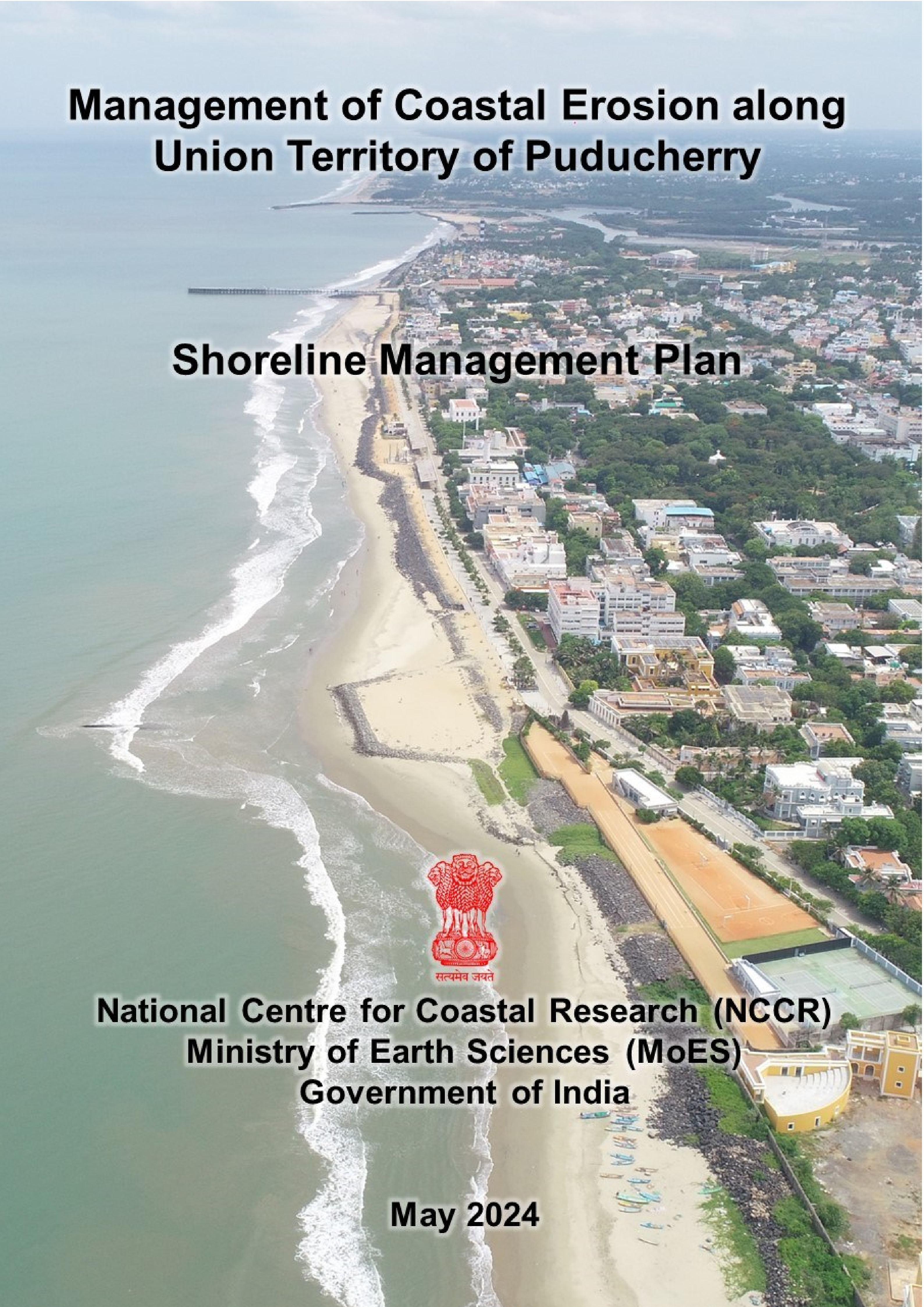
Management of Coastal Erosion along Union Territory of Puducherry



Shoreline Management Plan

सत्यमेव जयते

National Centre for Coastal Research (NCCR)
Ministry of Earth Sciences (MoES)
Government of India

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Abstract: *The coastal expanse of India faces dynamic challenges, particularly erosion, threatening ecosystems, infrastructure, and tourism. Puducherry emerges as highly vulnerable. This report by the National Centre for Coastal Research assesses 32 years of data, identifying erosion hotspots and proposing shoreline management strategies. Utilizing satellite data and stakeholder engagement, it offers tailored policies to address coastal infrastructure, socio-economic factors, and ecosystem preservation. Recommendations aim at sustainable development, regulating land use, managing emergencies, and ensuring economic stability. With community input, this comprehensive strategy fosters resilience against climate change, safeguarding both human well-being and coastal ecosystems.*

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FOREWORD

Puducherry Union Territory, nestled along the southeast (Puducherry and Karaikal) and southwest (Mahé) coast of India, is a gem of cultural heritage, pristine beaches, and culinary delights. This report endeavours to address the intricate relationship between the dynamic coastal environment and human activities, emphasizing the need for a scientific approach to coastal management. The coastline of Puducherry Union Territory is not merely a geographical boundary; it represents a shared heritage, a reservoir of biodiversity and a bastion against natural forces. Through meticulous examination, this report highlights the current status of the coastline, areas of erosion and accretion and advocating for strategies that align with the natural order to ensure sustainable stewardship.

Recognizing the multifaceted role of the coastline, there is an urgent need for a holistic Shoreline Management Plan (SMP) for Puducherry. This plan aims to integrate economic aspirations with environmental sustainability, safeguarding coastal ecosystems amidst challenges such as climate change, population growth and economic development. The Coastal Processes and Shoreline Management group, spearheaded by NCCR, takes up the responsibility of formulating the SMP for Coastal States and Union Territories. This collaborative effort brings together government bodies, scientific communities and local stakeholders to create a blueprint for resilience, ensuring the preservation and nurturing of livelihoods dependent on the coast for generations to come.

The SMP for Puducherry is a synergy of modern scientific approaches and the aspirations of local fishermen for sustainability. It goes beyond being a mere document, serving as a call to action to protect, preserve and thrive along the prosperous coastline of Puducherry Union Territory. This report signifies, not just the collection of data and recommendations but a commitment to action. The Comprehensive Shoreline Management Plan for Puducherry Union Territory endeavours to safeguard invaluable coastal resources, ensuring a harmonious coexistence between nature and human endeavours.

Dr. M. Ravichandran

Secretary, MoES

EXECUTIVE SUMMARY

India having coastline of about 7500 km has been subjected to dynamic changes leading to erosion, that threaten the habitats, public and private infrastructure, and tourism industry. Erosion is attributed to natural changes (sea level rise, storms, and more recently persistent low pressures due to climate change) and man-made activities (harbours, jetties, seawalls, groynes, dredging of tidal inlets and damming of rivers). Shoreline change analysis carried out for a period of 28 years (1990-2018) indicates that about 33.6% of the Indian coast is eroding, 39.6% is stable and about 26.9 % is accreting (NCCR, 2022). Puducherry is distributed along four parts namely, Puducherry, Karaikal, Mahé and Yanam. Puducherry and Karaikal are situated along the East coast surrounded by Tamil Nadu while Mahé is situated in the West coast encompassed by Kerala. Yanam is not along the coast but is encompassed by Andhra Pradesh.

Puducherry also known as Pondicherry rose to prominence after the advent of French colonization leading to the famous term "French Rivera of East". It was colonized, famously, by the Portuguese, Dutch, British and the French leading to the rich cultural heritage of the city, through the visible opulence of the heritage buildings. This in turn brought flocks of tourists that not only enjoy the rich heritage but also lazed along the wide beaches. It comes as no surprise that tourism has witnessed significant growth, attracting visitors from across the globe to explore its rich coastal heritage.

The developments have, in turn, spurred infrastructure growth along the coast, which currently encompasses three ports and three fishing harbours. In specific, the implementation of the Puducherry port led to erosion of the famous Promenade beach. The implementation of various coastal protection strategies along Puducherry solved the erosion problem of the region but shifted the erosion further North. It led to further extension of the coastal protection structure along the coast. The erosion problem then shifted to Tamil Nadu, which shares a political boundary creating inter-State issues with its neighbouring States. The implementation of the hard solution resulted in the loss of the beach along the coasts of Puducherry leading a loss of tourism for the Union Territory. Considering the issue, SMP was prepared by MoES for this stretch and as a part of this SMP, a hybrid solution was implemented with Northern wedge-shaped reef and nourishment that has restored the beach then. The success of this beach restoration and by recognizing the challenges posed by coastal erosion with concurrent urbanization, the Puducherry Government has requested the Ministry of Earth Sciences (MoES), to update and expand the Shoreline Management Plan (SMP) prepared in 2015 for the

entire Union Territory's coastline.

NCCR has taken up the task of developing SMP for protection of the coast with the objectives: 1) To assess the status of existing geomorphological setting of coast, existing coastal infrastructure and developmental activities (ports, harbours and tourism), 2) To understand the processes responsible for shoreline changes through waves, tides, currents, sediment characteristics and coastal morphology based on secondary data, 3) To study long/short term trends of shoreline along the coast for identifying hotspot erosion sites, 4) Understand the role of interconnectivity between the States, 5) To understand stakeholder/ community requirement through stakeholder interaction and field survey and 6) To develop shoreline management strategy, conceptually.

Shoreline change analysis was conducted utilizing 17 temporal satellite datasets (spanning 34 years, from 1990 to 2024) along the coast. The findings were categorized into seven classifications: low erosion, moderate erosion, high erosion, stable with low accretion, moderate accretion, and high accretion. Overall, about 46% of the coastline experiences varying degrees of erosion, while 11% exhibits accretion and remaining 43% in a stable condition. Notably, erosion surpasses 80% along the Karaikal coast. Approximately 20% of the coastline is occupied by coastal infrastructure, with UT Puducherry (5.5 km) leading the list, closely followed by Mahé (1.3 km), where the entire coast is covered by structures. Apart from this, the status of the coastal structure has also been assessed to determine its long-term performance and suitable reformation also suggested, wherever necessary.

Puducherry is blessed with a varied geomorphology due to its strategic locations on both the West and the Eastern coast of India. The coastal geomorphology is characterized by a predominantly coastal plains with inlets and deltaic plains with mangrove ecosystem propagated along the inlets of Puducherry. Noticeable dunes are present along Nallavadu, Kalipukupam beach, Karaikal beach, and Karukalacherry beach. This geomorphology has also been taken into consideration while proposing suitable strategies.

The results from the above studies were then validated during field interactions with stakeholders that was taken up at about 25 locations along the coast as a part of SMP. The entire coast of Puducherry has been split into policy units and each policy unit explains the strategic vision custom-delivered based on the socio-economics, tourism potential, stakeholder interaction, oceanographic parameters, coastal infrastructure and sediment characteristics.

Further, recommendations to be followed while implementing any new proposals, if needed, have been made as part of this report. This report will provide a roadmap for sustainable development, helping to protect the coastal villages, infrastructure and natural resources from shoreline change. It will help the Government to plan a comprehensive strategy in a holistic approach towards long-term economic stability.

I hope the report prepared by NCCR involving community inputs, ensures that it addresses the diverse needs of the Government, fostering resilience against climate change impacts and promoting the well-being of both human and nature along the coast.

Dr. M. V. Ramana Murthy
Director, NCCR

ACKNOWLEDGEMENTS

As the Group Head of Coastal Processes and Shoreline Management (CP&SM) at the National Centre for Coastal Research (NCCR), I am honored to extend my gratitude for the extensive collaboration that has culminated in the Shoreline Management Plan (SMP) for the Union Territory of Puducherry. This plan signifies far more than a mere document; it stands as a tangible manifestation of collective expertise and coordinated efforts aimed at promoting sustainable coastal management practices.

I wish to convey my sincere appreciation to the Government of Puducherry for engaging NCCR in preparing the SMP. Their foresight and proactive approach have been instrumental in the successful inception and development of the plan. Special thanks are extended to the

1. Department of Science, Technology and Environment (DSTE)
2. Puducherry Coastal Zone Management Authority (PCZMA)
3. Public Works Department (PWD)
4. Puducherry Port Department
5. Karaikal Port Private Limited
6. Department of Fisheries and Fishermen Welfare
7. Department of Tourism
8. Pondicherry Citizen's Action Network (PondyCAN)

as well as the officials of the Puducherry Government, for their pivotal role in coordinating with various departments and offering valuable support.

The invaluable insights and proactive contributions from field officials of different line departments and local representatives have greatly informed the SMP. We are particularly grateful to those who accompanied our survey teams and facilitated local stakeholder meetings, providing invaluable understanding of ground realities. Their active involvement and willingness to share profound knowledge have been crucial in ensuring the SMP's alignment with practical coastal management needs, setting a new standard for environmental governance.

I extend heartfelt thanks to Dr. M. Ravichandran, Secretary, Ministry of Earth Sciences, for entrusting NCCR with this significant task. The continuous guidance, support, expert supervision and encouragement provided by Dr. M. V. Ramana Murthy, Director, NCCR, have been pivotal in steering this project to successful completion.

Furthermore, I express deep appreciation for the dedicated team at NCCR, whose tireless efforts behind the scenes have been the foundation of this project. In conclusion, I am grateful to every individual and entity that has contributed, directly or indirectly, to the SMP. Our collective expertise and commitment to coastal management are what enable such ambitious projects. Through such partnerships, we can ensure the sustainable development and protection of our coastal heritage for present and future generations.

Shri. V. Ramanathan
Group Head, CP&SM, NCCR

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ACOUSTIC DOPPLER CURRENT PROFILER: ADCP

C

CENSUS TOWN: CT
COASTAL PROCESSES AND SHORELINE MANAGEMENT: CP&SM
COASTAL REGULATION ZONE: CRZ

D

DEPARTMENT OF SCIENCE, TECHNOLOGY AND ENVIRONMENT: DSTE
DIGITAL SHORELINE ANALYSIS SYSTEM: DSAS

E

EAST INDIA COASTAL CURRENTS: EICC
EAST-NORTH-EAST: ENE
EAST-SOUTH-EAST: ESE
ENHANCED THEMATIC MAPPER: ETM

F

FISH LANDING POINT: FLP

G

GEOGRAPHIC INFORMATION SYSTEM: GIS

H

HIGH TIDE: HT

I

INDIAN METEOROLOGICAL DEPARTMENT: IMD
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: IPCC

L

LINEAR IMAGINE SELF SCANNING SENSOR: LISS
LOW TIDE: LT

M

MEAN WAVE PERIOD: T_m
MINISTRY OF EARTH SCIENCES: MoES

N

NATIONAL CENTRE FOR COASTAL RESEARCH: NCCR
NATIONAL REMOTE SENSING CENTRE: NRSC
NORTH-EAST: NE
NORTH-NORTH-EAST: NNE
NORTH-NORTH-WEST: NNW

P

PEAK WAVE PERIOD: T_p

R

REPRESENTATIVE CONCENTRATION PATHWAYS: RCP

S

SEA LEVEL RISE: SLR
SHORELINE MANAGEMENT PLAN: SMP
SIGNIFICANT WAVE HEIGHT: H_S
SOUTH-EAST: SE
SOUTH-SOUTH-EAST: SSE
SOUTH-SOUTH-WEST: SSW
SOUTH-WEST: SW
SURVEY OF INDIA: SoI

U

UNION TERRITORY: UT
UNITED STATES GEOLOGICAL SURVEY: USGS

W

WAVE DIRECTION: Dir
WEIGHTED LINEAR REGRESSION RATE: WLR
WEST-NORTH-WEST: WNW
WEST-SOUTH-WEST: WSW

1 INTRODUCTION

The coastal zone, a dynamic interface between land and sea, plays a crucial role in supporting diverse ecosystems, economic activities and human communities. In the rapidly evolving landscape of urbanization, the role of coast is a multifaceted and critical component that significantly influences both the development of human settlements and the health of surrounding ecosystems. A coast, often synonymous with a protective layer, serves as a metaphor for the interface between urban environments and the natural world, encapsulating the dynamic interplay between infrastructure, biodiversity, and sustainability. They are particularly vulnerable to the impacts of climate change, including rising sea levels, more frequent and severe storms, and changing ocean conditions. Human activities such as urbanization, industrialization, and improper waste management further exacerbate these challenges, posing threats to the health of coastal ecosystems and the welfare of communities reliant on them.

"Our exotic coasts marked by its complexity and interconnectivity, necessitating a comprehensive and sustainable approach to address these challenges. This involves the intricate relationships between urbanization, biodiversity, and climate change, highlighting the need for a Shoreline Management Plan

Environmental-friendly solutions that align with the evolving needs of society are the crucial challenges in coastal zone management. It is imperative to consider political, social, and technical issues ensuring that potential solutions must balance the anticipated positive and negative impacts. For centuries, the coastline has been a focal point for diverse activities including industry, agriculture, recreation, and fisheries. These national economic assets have been developed and flourished despite constant changes in the physical characteristics of the coast. The coastline represents a national heritage, and thus to ensure its preservation for future generations, proper management and restoration of the coastal zone is essential. The coast serves various functions and offers essential ecological services such as - i) infrastructure development, ii) filter and barrier to salt-water intrusion, iii) provision of natural habitat, iv) support for livelihood activities, v) space for recreational activities and well-being, etc. The term 'coastal restoration' refers to the process of rejuvenating damaged natural sandy beaches, along with reinstating their inherent functions and services. The maintenance of a healthy sandy beach is crucial for safeguarding the coastline against the sea, protecting the low-lying areas from flooding, and securing the present and future livelihoods of coastal communities.

The coastal areas of Puducherry located along the southern coastline of India, features a diverse landscape shaped by the dynamic forces of geomorphology. Situated at three distinct locations, The UT of Puducherry encompasses the Puducherry and Karaikal sections along the eastern coast, where the Bay of Bengal exerts its influence, while Mahé lies on the western coast, bordered by the Arabian Sea.

The Union Territory (UT) of Puducherry comprises two revenue districts with a total coastal length of about 45 km (SoI), encompassing Puducherry, Yanam and Mahé in Puducherry revenue district and Karaikal. UT Puducherry shares its coast with States like Tamil Nadu, Kerala and Andhra Pradesh. Puducherry is the most populous district while Mahé has the highest population density. The complexity of the denudation process has been heightened by the proliferation of urbanized coastal infrastructures along the coast. To mitigate continuous denudation and restore the existing coastal belt, a comprehensive analysis of shoreline history and characteristics is conducted using remote sensing and field measurements. This observation identifies significant zones of coastal erosion and accretion, with detailed descriptions provided for the protective measures implemented along the coast.

The flat plains of Puducherry along the Bay of Bengal to the low-lying terrain of Karaikal influenced by the Cauvery River delta and the harbour-dominated coastline of Mahé on the Arabian Sea, each area showcases unique features and processes of coastal geomorphology. Historically, the UT was under the influence of colonization which has shaped the fundamental heritage of the place. As a reason, tourism has flourished owing to its distinctive heritage that stands out from the rest of the locations. The Eden beach at Puducherry boasts its status as a blue flag beach, which attracts hundreds of tourists every day. The development of this coast lies in a blend of ecological preservation and diverse urban needs emphasizing the importance of ecosystem conservation. These plans for sustainable development aim to minimize the impact on the coast, while meeting urbanization demands.

The coastal infrastructures form the major economic boost for the UT of Puducherry and host three ports and three fishing harbours. Additionally, 22 fish landing points promote the fishing sector in terms of economy and livelihood. These infrastructure developments were carried out in a piece-wise manner and was not integrated leading to adverse impact on the coast and the livelihood that is dependent on it. Realizing this, the beach restoration along with site-specific reefs and nourishment has been designed and the Northern reef and beach nourishment has successfully been implemented, which has significantly restored the beach as a part of the same project leading towards a sustainable development principles.

In terms of shoreline change analysis, it was observed that about 46% of coast is under erosion, about 43% is stable and about 11% is under accretion [1]. A total of 20 % of coast with engineering structures are observed along the coast which are comprised of seawalls, training walls, and groynes. Resorting to hard measures may not align with sustainability principles, and therefore natural measures shall be given priority. The exploration of safeguarding the coastline through bio-shields not only improves ecological balance but also enhances the overall beauty of the ecosystem by promoting tourism. Nevertheless, areas experiencing severe erosion may be unsustainable for natural methods due to their time-consuming nature and the limitations posed by existing coastal structures. Combining natural and hard measures into hybrid strategies, can effectively protect the coast from sea erosion while harnessing available natural resources concurrently.

Historically, emphasis has primarily been placed on protection rather than restoration, resulting in the fragmented implementation of coastal and flood protection measures. These initiatives have typically been reactive, responding to identified threats to existing settlements or incorporated into new development projects. Oftentimes, whilst operating within narrow boundaries, these measures may inadvertently impact adjacent coastal areas negatively. Hence, there is a critical need for a comprehensive plan that tackles shoreline concerns and erosion issues in an integrated, sustainable, and strategic manner.

Achieving this goal can be facilitated through the implementation of a Shoreline Management Plan (SMP), which addresses concerns at an appropriate scale. The chosen policy must guarantee that the restoration of eroded sandy beaches is executed in a manner that is technically, environmentally, and economically viable, both at the time of implementation and in the long term. A SMP has already been published for Puducherry in 2015, however, it was for a stretch of about 10 km which covered only the area of interest, at that time. There is also a need to update SMPs at regular intervals, and seeing the potential impact of SMP, it has now been extended to the entire UT Puducherry. For the preparation of an SMP, the boundaries of the region are to be identified properly to avoid potential adverse impacts resulting from the planned interventions. The processes along the shoreline exhibit spatial and temporal variations. A meticulous assessment of inputs and outputs within the region is necessary, considering the underlying process. Consequently, several questions still need to be answered by scientific experiments. They are

a) The coastal stretch considered to be dominated by onshore- offshore transport or along shore transport.
b) The magnitude of the sediment transport in the onshore, offshore, and alongshore.
c) The modification of sediment pathways along the coastal stretch resulting from manmade interventions. These include construction of dams on upstream of the river, major harbour installation along the coast, coastal protection structures, and sand mining etc.
d) Impact of extreme events and sea level rise on shoreline.
e) Change in the monsoon cycle or climate change events and
f) Sediment budget through the concept of sediment cells.

The development and implementation of a robust shoreline management plan is imperative for safeguarding the delicate balance between urbanization and the health of coastal ecosystems. As we navigate the challenges posed by climate change, population growth, and economic demand, a strategic and adaptive approach becomes essential. By embracing the principles of sustainable development, ecosystem preservation, and community engagement, we pave the way for resilient coastlines that not only support thriving urban centres but also nurture the diverse ecosystems that make these areas unique. To develop a holistic approach various parameters such as geomorphology, socio-economics, shoreline vulnerability, ecology, met-ocean parameters, sediment availability and the existing coastal infrastructure at the location have been analyzed in the consecutive chapters.

Manapad Dunes

2 GEOMORPHOLOGICAL SETTING

Physical characteristics such as geology and geomorphology are among the important key aspects of the shoreline management plan. Increasing natural and human disturbances will disturb the spatial and temporal balance of the natural processes and alter the geomorphology of the region. It is essential to understand the evolution of the coastal morphology and its influence on shoreline erosion and flood risk. Assessment of the geomorphological changes is important to manage coastal resources sustainably. A comprehensive understanding of how waves, tides, streams, and human activities interact provides a perspective on the processes shaping these environments. This knowledge holds practical significance for coastal management and sustainable development.

> **"Coastal geomorphology is essential to understand the dynamic processes shaping coastal regions, offering insights crucial for both sustainable development and the effective mitigation of hazards**

2.1 Geology

The geological formations of the Puducherry and Karaikal regions exhibit a predominance of sedimentary deposits, encompassing a range of geological periods including the Cretaceous, Palaeocene, Mio-Pliocene, and Quaternary epochs. The structural framework of this area is notably defined by the presence of the Cauvery rift basin, which extends in a NE-SW direction and encompasses geological time from the Late Jurassic to the Early Cretaceous periods [2]. Particularly noteworthy is the exposure of a comprehensive section spanning from the upper Cretaceous to the Paleocene era within the Ariyalur – Puducherry sub basin [3].

Within Puducherry, the geological formations are characterized by the Valudavur, Mettuveli, Karasur, Manaveli, and Cuddalore formations, arranged in chronological succession. These formations predominantly belong to the Quaternary period, marking significant geological activity in the region during this time [4]. Karaikal, situated within the Cauvery basin, exhibits Quaternary formations that originate from fluvial and semi-marine processes, covering the entirety of the region [5]. In contrast, Mahé, positioned along the we, stern coast of India, showcases Archean formations composed of the Southern Granulitic Terrain. These formations are primarily comprised of a migmatitic complex [6].

2.2 Geomorphology

Coastal areas, characterized by the interactions of natural and anthropogenic forces, undergo dynamic development over time. A coastal environment represents a unique intersection where terrestrial materials transition to marine domains, subsequently transforming erosion and other geomorphic processes. Coastal geomorphology focuses on the formation and evolution of coastal regions. Specifically, it examines the intricate processes involving waves, tides, and streams, which contribute to the creation of diverse coastal landforms such as cliffs, headlands, coral reefs, sand dunes, rocky and sandy beaches and many more. The study of coastal geomorphology offers valuable insights into the dynamic nature of coastal regions. By comprehending the interplay of waves, tides, streams and human activities, we gain a holistic perspective on the processes that shape these environments. This knowledge has practical implications for coastal management and sustainable development.

Coastal geomorphology encompasses the study of landforms influenced by larger water bodies and the processes (wave, wind, current, and tide) that act on them. A detailed survey of geomorphological landforms and their functions is essential to understand the biophysical system and assess the consequences of the proposed coast activities and possible solutions. Coastal regions, shaped by the dynamic interplay of natural and human-induced forces, undergo continuous transformation. These areas serve as a unique interface, where terrestrial materials transition into marine realms, experiencing alterations through erosion and various geomorphic processes. The scientific discipline of coastal geomorphology is dedicated to studying the formation and evolution of these dynamic coastal landscapes. The exploration of coastal geomorphology yields valuable insights into the dynamic nature of coastal regions.

The Union Territory of Puducherry, features a diverse landscape shaped by the dynamic forces of geomorphology. Situated at three distinct locations, The UT of Puducherry encompasses the Puducherry and Karaikal sections along the eastern coast, where the Bay of Bengal exerts its influence, while Mahé lies on the western coast, bordered by the Arabian Sea.

2.2.1 Puducherry

The Puducherry coastline along the Bay of Bengal is characterized by a flat plain with an average elevation of approximately 20-25 meters above mean sea level. These marine plain features gently sloping lands interspersed with sand dunes, contributing to a diverse and dynamic coastal environment. Notably, Nallavadu exhibits sand dunes reaching heights of 2-3 meters, while Pudukuppam showcases shallow, continuous dunes stretching for around 700 meters. The region is renowned for its major sandy beaches, including Pondy-Marina beach, Veerampattinam beach, Eden beach, Paradise beach, and Pudhukuppam beach. In addition to sandy beaches and dunes, the coastal area is characterized by features such as rivers and lagoons. Estuaries, such as Thengaithittu near Veerampattinam, play a significant role in shaping the coastline and serve as a notable habitat for mangroves. A paired spit is found at the mouth of the Chunnambar River, while the Mullodai lagoon runs parallel to Nalavadu with the presence of mangroves. The geomorphology map of Puducherry is shown in Figure 1.

2.2.2 Karaikal

The Karaikal Region, situated within the deltaic expanse of the Cauvery River basin is characterized by low-lying terrain and subtle undulations. With elevations seldom exceeding five meters above mean sea level. Karaikal's coastal landscape is marked by the noticeable effect of wind on its shoreline, with large sand dunes and mounds formed by the constant action of the wind over time. Moreover, Karaikal's coastal region hosts a variety of geomorphic formations, including tidal inlets, spit bars and sandy beaches. The geomorphology map of Karaikal is shown in Figure 2. Sand dunes are notable features along the coastline, particularly at Kalipukupam beach, Karaikal beach, and Karukalacherry beach, where they reach heights ranging from 1.3 to 2.2 meters. However, erosion affects some dunes, particularly at Kakalachery Beach. North of Karaikal Port, a significant dune rises to 6.8 meters in height. Karaikal's coastal landscape is segmented by river channels of Kottucherry inlet, Arasalar river, Thirumalairajan river and Vanjur River. Sand bar formations within the river mouth and spit formations in the southern river mouth have been observed for the Thirumalairajan river. Additionally, spit formation is evident in the Vanjur River.

Figure 1. Geomorphology of Puducherry

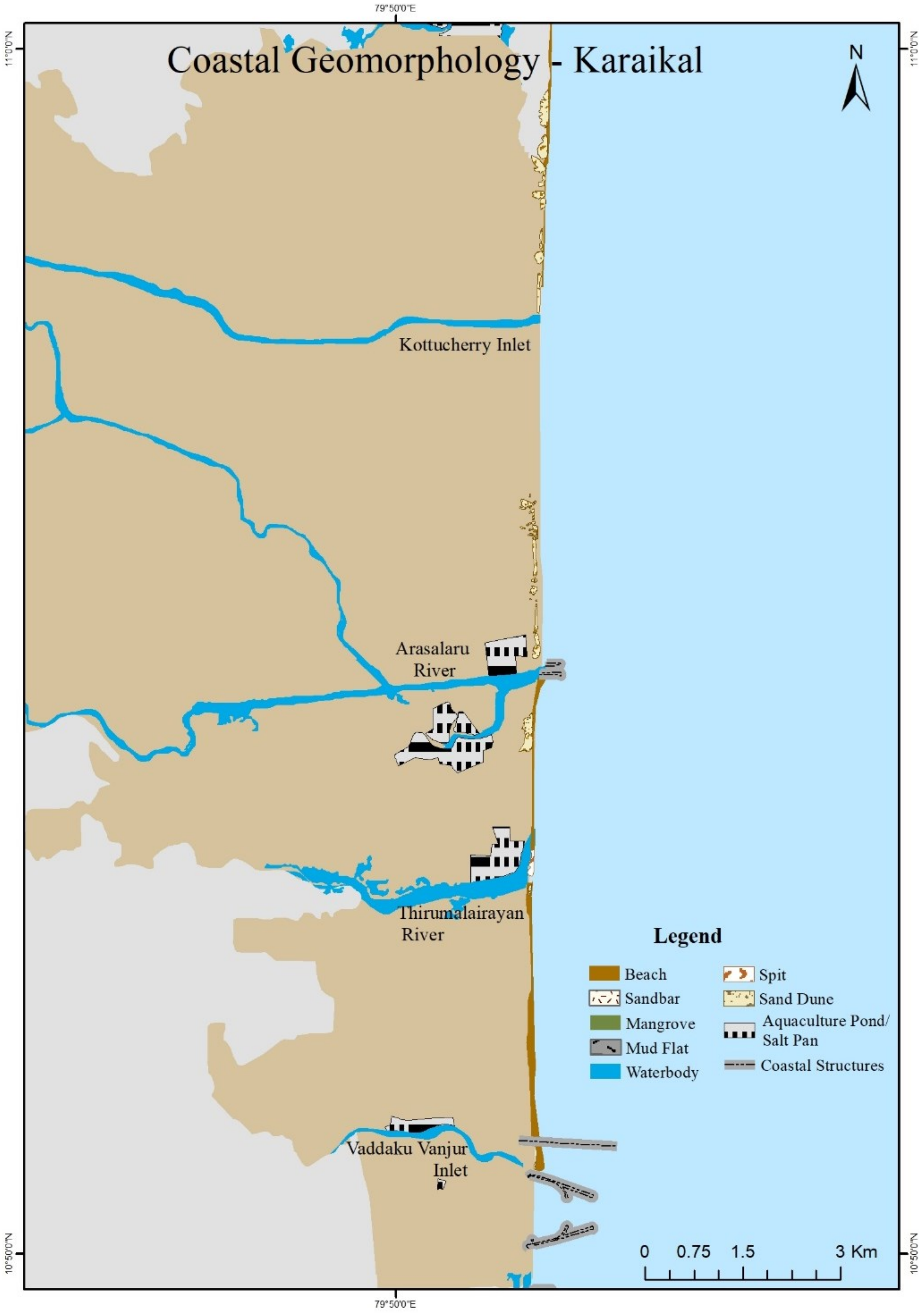


Figure 2. Geomorphology of Karaikal

2.2.3 Mahé

Mahé, is situated on the West Coast of Kerala, on the Malabar coast of the Arabian Sea, positioned towards the south of the Mayyazhi River. The majority of the 2 km stretch of coastline is dominated by the Mahé harbour, with a small segment occupied by Poozhithala Beach. The geomorphology map of Mahé is shown in Figure 3.

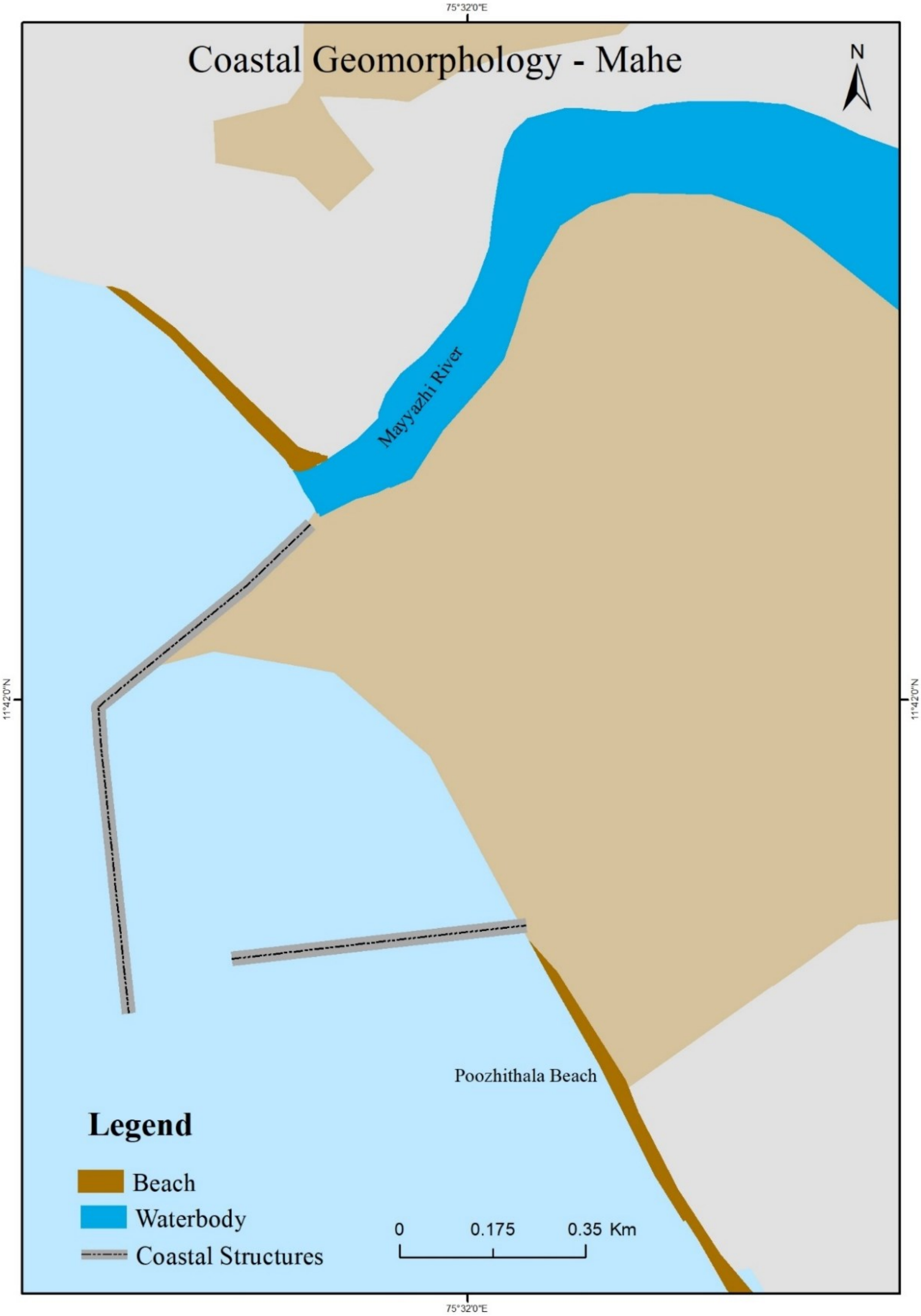


Figure 3. Geomorphology of Mahé

The coastal regions of the Union Territory of Puducherry offer diverse geomorphological settings shaped by natural forces and human activities. From the flat plains of Puducherry along the Bay of Bengal to the low-lying terrain of Karaikal influenced by the Cauvery River delta, and the harbour-dominated coastline of Mahé on the Arabian Sea, each area showcases unique features and processes of coastal geomorphology. Recognizing and conserving these dynamic environments is essential not just for preserving the natural habitat but also for facilitating sustainable coastal development.

2.3 Thengaithittu Estuary

Thengaithittu Estuary, lies within the boundaries of Union Territory of Puducherry district of latitudes $11^0$46’03” to $11^0$53’40” North and longitudes $79^0$49’45” to $79^0$48’00” East. It is encircled by three villages viz. Ariankuppam, Murungapakkam and Veerampattinam, and two islets namely, Thengaithittu and Ashramthittu. Mangrove exists as fringing vegetation over 168 Hectares distributed along the sides of Ariankuppam estuary, which empties into the Bay of Bengal at Veerampatinam on the southeast coast of India (Figure 4). There are seven mangrove species belonging to 3 families, 16 mangrove associate plants belonging to 12 families were recorded in this area [7].

Avicennia zone – It forms very small patch of Avicennia marina and A. officinalis dense stand to the mouth region of estuary of Veerampattinam (Figure 5), Rhizophora zone - they are four patches of Rhizophora mucronata and R. apiculata on the southern part of Thengaithittu and four patches of R. mucronata and R. apiculata near the mouth of river. Acanthus zone – Acanthus ebracteatus and A. illicifolius forms dense stand to the western and northern side of Ariyankuppan and Murungapakkam Bruguiera cylindrica spreads from the western end of Murungapakkam up to eastern end of Ashram Islet. Avicennia and Rhizophora mixed zone spreads near the bridge [8]. Additionally, 15 species of mollusks, 15 species of decapod crustaceans, 39 species of fishes belonging to 24 family under 7 orders have been identified in the water ways and 14 species of birds were identified in the Estuary [7]. All together 23 species of flora and 80 species of macrofauna were identified from this pristine Puducherry mangrove ecosystem. However, the figure is too small when compared to that of the other nearby mangrove ecosystems like Pitchavaram, it is quite considerable as rich in biological diversity as of Puducherry is concerned.

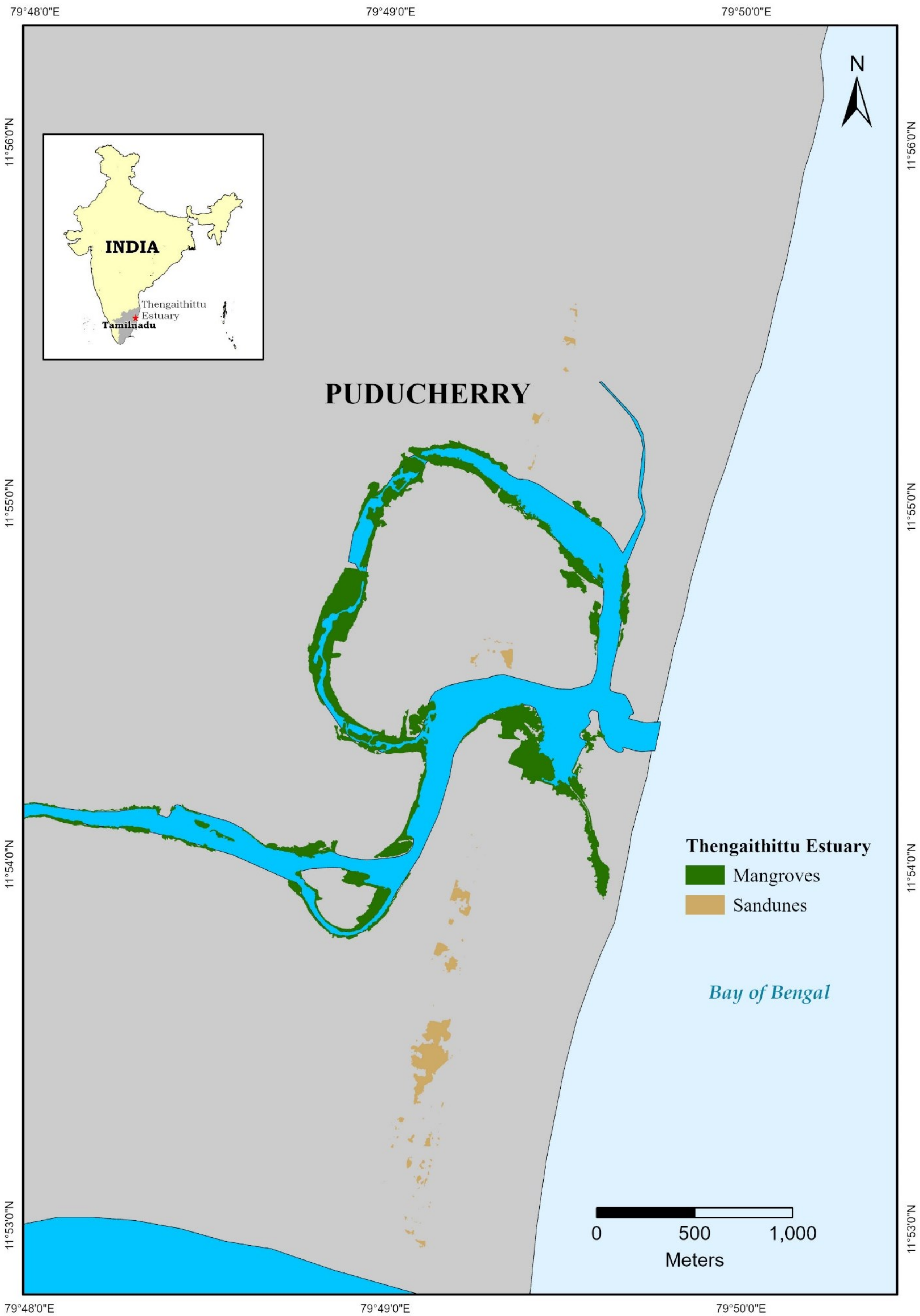


Figure 4. Thengaithittu Estuary and its Environments

Figure 5. Mangroves in Thengaithittu Estuary

The coastal regions of Puducherry, Karaikal and Mahé boast diverse geological and geomorphological features shaped by natural processes spanning geological epochs. These areas showcase unique landscapes, from sedimentary deposits to dynamic coastal interactions like waves and tides. Understanding coastal geomorphology is crucial for effective management and sustainable development, emphasizing conservation efforts to preserve their ecological integrity. Holistic approaches to conservation and management are essential to ensure the resilience and vitality of these coastal environments for future generations.

Shoreline Management Plan (SMP) acts as a guiding framework for understanding the areas at higher risk and implementing suitable measures to mitigate these hazards. Hence, the integration of geomorphology into SMP is crucial for preserving the diverse and dynamic landforms. SMPs provide a strategic framework to align developmental efforts with the natural environment, ensuring the sustainable management of coastal ecosystems and features.

3 TIDAL INLETS

Coastal inlets and rivers serve as vital conduits, connecting terrestrial and marine environments while influencing local ecosystems and human activities. Understanding their dynamics, particularly regarding opening and closing phenomena, infrastructure presence, and siltation, is paramount for coastal management and development. These water bodies often exhibit dynamic behaviour, characterized by fluctuating openings that can impact navigation, water quality, and ecological processes. Additionally, the presence of infrastructure, such as harbours or training walls, profoundly influences the stability and accessibility of these waterways. Moreover, siltation, the gradual accumulation of sediment, poses challenges to navigation and ecosystem health, necessitating continual monitoring and management efforts.

> **"Tidal inlets profoundly influence shoreline management plans by regulating sediment transport, coastal erosion rates, and ecological processes, necessitating their integration into management strategies**

In the coastal region of the Union Territory of Puducherry, a total of 7 rivers/inlets are present, along with one permanently closed lagoon. Of these, 6 rivers drain into the Bay of Bengal, while one river flows into the Arabian Sea. The inlets have been classified as open/ intermittently open. The inlets that are trained by means of a training wall have also been indicated. Additionally, the Madalapattu Inlet, flowing through Puducherry and Tamil Nadu, impacts the nearby coast of Puducherry with its estuary situated in the Cuddalore district of Tamil Nadu.

3.1 Puducherry

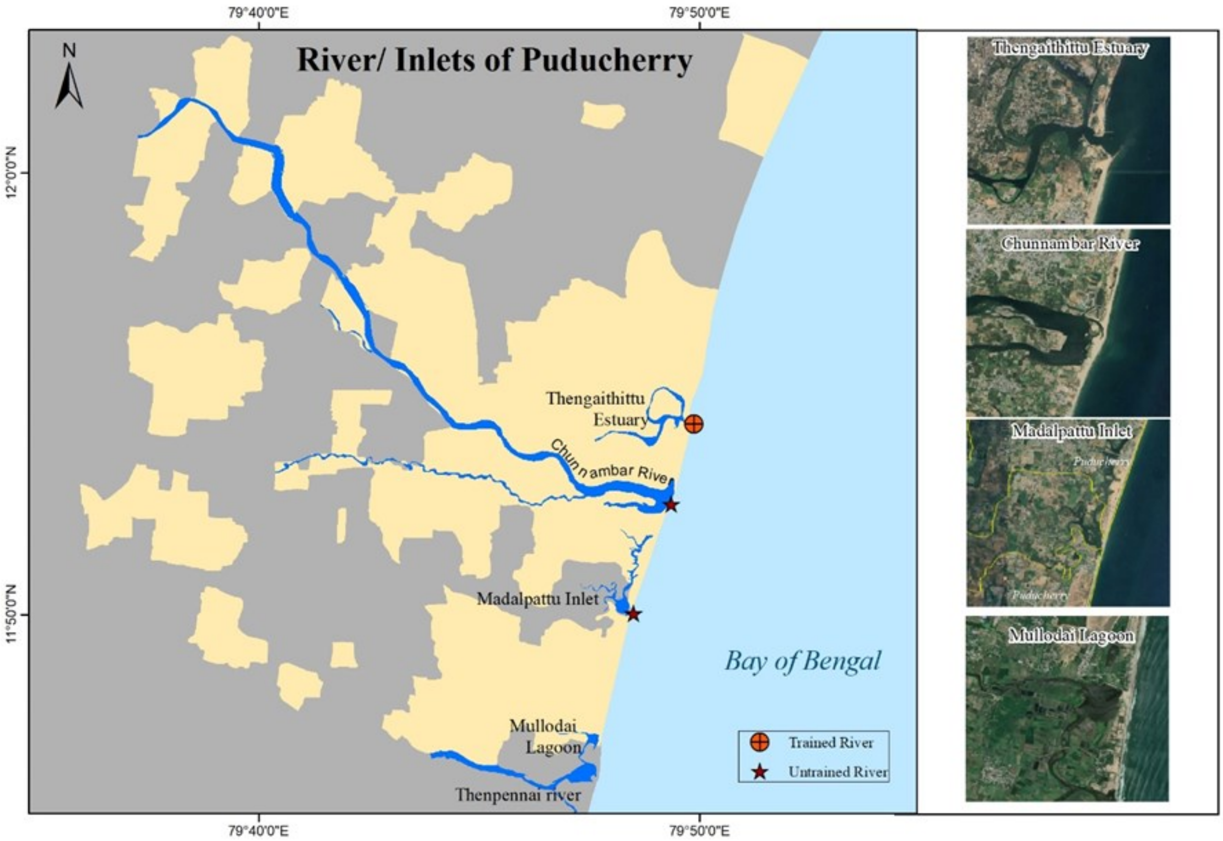


Figure 6. Map showing the Inlets along Puducherry Coast

Table 1. Status of Inlets in Puducherry

No.	Name	Status	Remarks
1	Thengaithittu Estuary	Open	Puducherry Harbour with infrastructure present
2	Chunnambar River	Intermittently Opened	
3	Madalapattu Inlet	Intermittently Opened	The river has tributaries flowing through Puducherry and Tamil Nadu, with the estuary located in the Cuddalore district of Tamil Nadu. The heavy siltation observed in the inlet's mouth significantly affects the nearby coast of Puducherry.
4	Mullodai Lagoon	Closed	The Mullodai Lagoon drains into the Thenpennai River in the south. The mouth of the lagoon has been observed to remain closed for an extended period due to significant siltation buildup.

3.2 Karaikal

Figure 7. Map showing the Inlets along Karaikal Coast

Table 2. Status of Inlets in Karaikal

No.	Name	Status	Remarks
1	Inlet in Kottucherry	Intermittently Open	-
2	Arasalaru River	Open	Training wall is observed on either side of the mouth. Mangrove patches are observed a the back side
3	Thirumalairajan River	Intermittently Open	Back side of the river mouth, is covered by Mangroves
4	Inlet in Vadakku Vanjur	Open	Back side of the river mouth, is covered by Mangroves

3.3 Mahé

Figure 8. Map showing the Inlets along Mahé Coast

Table 3. Status of Inlets in Mahé

No.	Name	Status	Remarks
1	Mayyazhi River	Open	Southern part of River is partially trained by the northern breakwater of the Mahé harbour

In the Union Territory of Puducherry, the landscape is characterized by a network of seven rivers, each contributing to a diverse array of waterways. While three rivers remain consistently open year-round, benefiting from protective infrastructure, three inlets face vulnerability to seasonal shifts, resulting in the formation of sandbars and periodic closure of their mouths. This contrast underscores the dynamic nature of coastal environments and highlights the necessity for strategic management practices to ensure the sustainable preservation of these vital water bodies amidst fluctuating conditions.

Tidal inlets are vital for coastal ecosystems, facilitating the exchange of water, sediment, nutrients, and organisms, regulating hydrodynamics, sediment transport, ecological connectivity, shoreline stability, erosion rates, habitat diversity, and supporting economic activities. Status of the inlet drives the coastal dynamics. Training the inlets will keep the inlet open but affect the coastal processes. If the inlet is planned to be trained, design should be carried out so as to have minimal effect on the downdrift side. Suitable management strategies shall have to be adopted.

4 MET-OCEAN PARAMETERS

Meteorological and oceanographic (met-ocean) parameters, such as wind, wave, and tides, play a pivotal role in influencing nearshore coastal processes. The interaction between meteorological elements and ocean dynamics is crucial for shaping nearshore features, sediment transport, and overall coastal geomorphology. Understanding met-ocean parameters is essential for predicting and managing nearshore processes. For example, wind contributes to wave generation, impacting coastal erosion and sedimentation patterns. Tidal currents play a vital role in shaping nearshore bathymetry, affecting sediment transport and distribution. The characteristics of waves influence the energy reaching the coastline, affecting erosion and deposition processes.

> **"They are crucial in shaping nearshore coastal processes, influencing features, sediment transport and geomorphology of coast. Comprehensive understanding of these are essential for devising sustainable measures to mitigate risks and protect coastal communities**

As waves approach the coast, processes such as shoaling, refraction, breaking, and energy dissipation lead to significant changes in nearshore areas, influenced by factors like beach slope, angle of approach, and morphology. Nearshore processes, particularly sediment transport, influence the dynamic nature of the coast. Wave breaking induces longshore and cross-shore currents, facilitating the transportation of sediment parallel to the coastline and perpendicular to it, respectively. These currents drive ongoing alterations in bathymetry, thereby impacting hydrodynamics and the dispersion of energy. The thorough comprehension of coastal geomorphology, wind and wave climate, and their intricate interactions with sediment particles, coupled with an understanding of underlying coastal processes across different spatial and temporal scales, enhances the predictability of coastal evolution. By monitoring and analysing met-ocean parameters offer valuable insights into nearshore coastal dynamics, aiding the development of effective coastal management strategies. This information, considering both natural environmental factors and human activities impacting coastal regions, empowers coastal planners and managers to implement sustainable measures for risk mitigation, community protection, and preservation of the nearshore environment. Winds, waves, currents and tides are few among the main influential parameters and storm surge, rainfall and cyclonic events pivots the climate change effects on coastal processes. The following are the parameters considered: bathymetry, tide, wave, current, wind, rainfall, and Sea Level rise.

The Union Territory of Puducherry comprises of four French colony districts namely Puducherry, Karaikal, Mahé and Yanam, which are not geographically contiguous. Off these Puducherry and Karaikal lies in East coast of Tamil Nadu state and Mahé lies in West coast near Kannur district of Kerala State, and hence experience distinct Met Ocean parameter characteristics. The locations of the data collected in Puducherry UT are shown in the Figure 9.

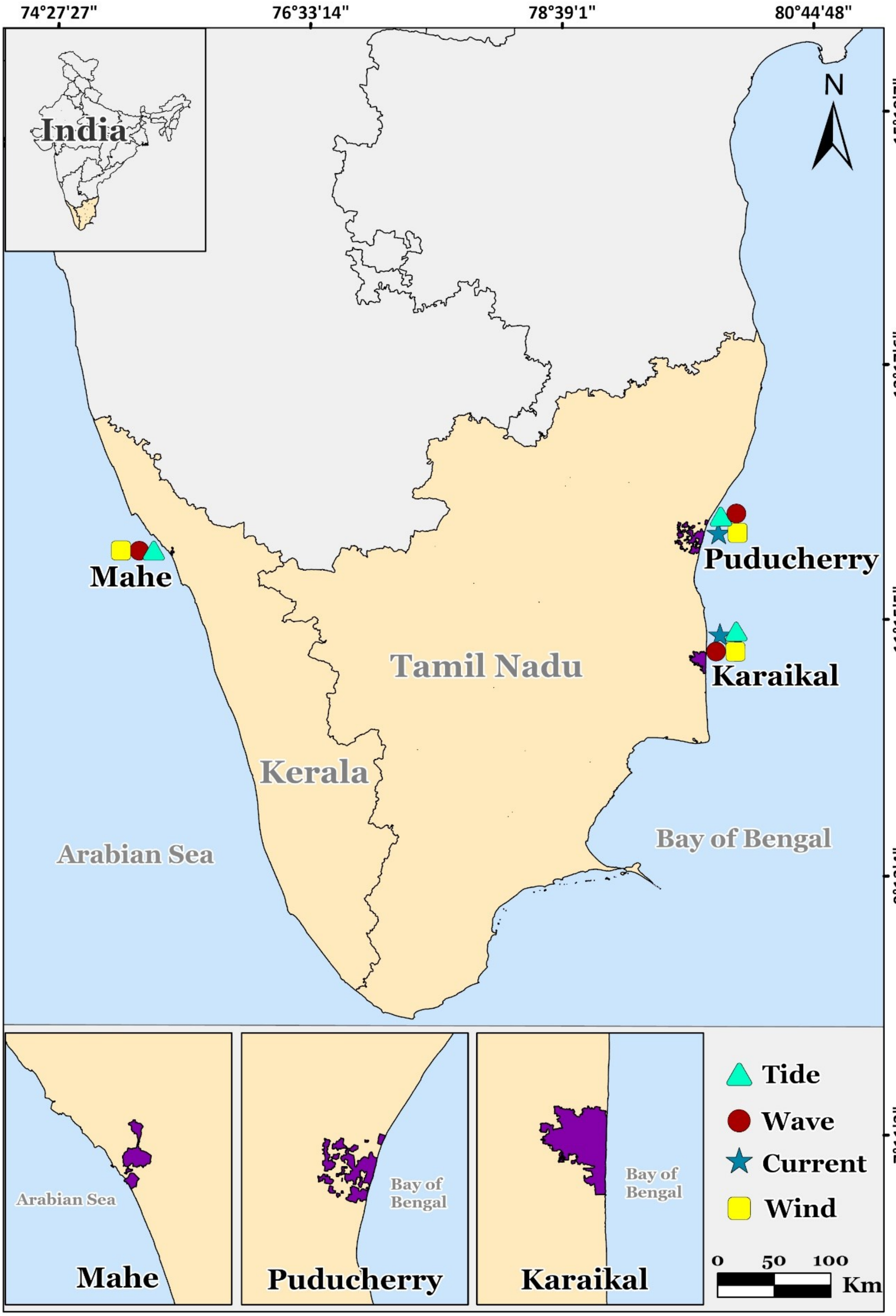


Figure 9 Locations for measurement of wave, tide, current and wind in Pondicherry UT

4.1 Annual Rainfall

The historical trend of precipitation in Puducherry UT provides valuable insights into the changing climate dynamics of the region. UT experiences two distinct periods of monsoon rainfall, which are, SW monsoon, prevailing from June to September, characterized by robust SW winds. Subsequently, the NE monsoon dominates from October to December, driven by prevailing NE winds and few intermittent summer showers.

According to data from the Departments of Economic and Statistics of Puducherry UT, the rainfall data from the year 2001 to 2021 is given in Figure 10. It is evident that Mahé records higher rainfall compared to all other districts of UT as prevailing in West coast. The average rainfall in Mahé is 3530 mm [www.Mahé.gov.in/economy]. Most of this, about 80 % occurs during June to September and about 10 % during October to November. July is the rainiest month which alone accounts for about one third of the annual total rainfall.

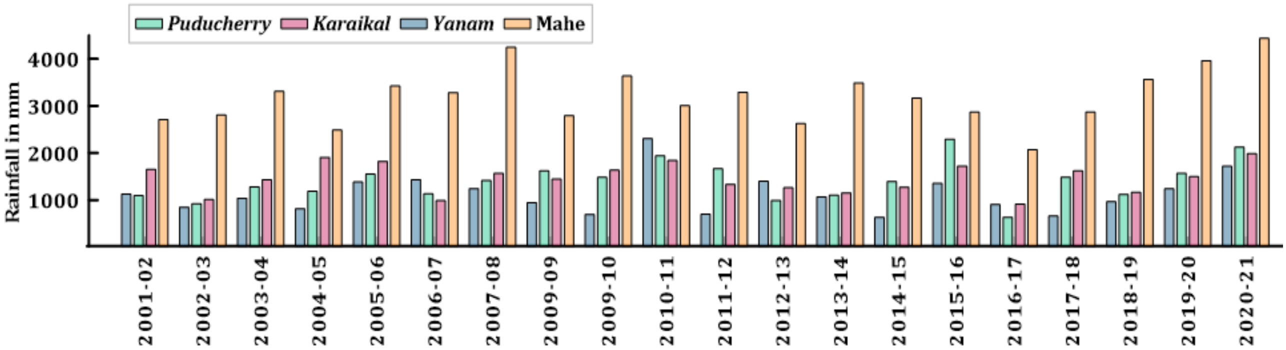


Figure 10. Annual Rainfall for Puducherry UT from 2001 to 2020

As per Department of Science, Technology and Environment, Government of Puducherry, the rainfall trend for the region of Puducherry is almost consistent with the average annual rainfall between the years 1976 to 2020 being 1310 mm. The mean SW monsoon rainfall for Puducherry is 348.4 mm which forms 27.2% of the mean annual rainfall. The NE monsoon plays a dominant role with a mean rainfall of about 803.8 mm which is nearly 62.7 % [9].

Monthly rainfall along Puducherry UT for the year 2020 to 2021 is tabulated in Table 4 [Statistical handbook 2020-2021, Directorate of Economics and Statistics]. It is inferred that SW monsoon accounts for about 76% of total annual rainfall for Mahé, followed by 52% for Yanam and the least having 17% and 24% for Puducherry and Karaikal. On the contrary NE Monsoon accounts for about maximum of 68% and 72 % for Puducherry and Karaikal, followed by Yanam having 44% and the least having 8% in Mahé for total annual rainfall. Puducherry and

Karaikal being in East coast have NE Monsoon dominance and Mahé prevailing in West coast have SW monsoon dominance.

Table 4. Monthly Rainfall in Puducherry UT

No.	Month	Puducherry	Karaikal	Mahé	Yanam
1	Jun-20	30.0	36.3	1122.0	199.8
2	Jul-20	115.6	192.8	823.2	267.6
3	Aug-20	96.4	109.1	655.8	170.8
4	Sep-10	116.2	132.3	797.2	271.4
5	Oct-20	181.4	58.6	206.4	509.6
6	Nov-20	512.4	352.9	43.6	247.4
7	Dec-20	601.8	739.3	66.0	0
8	Jan-21	153.2	284.3	51.0	0
9	Feb-21	259.4	37.4	23.6	0
10	Mar-21	0.0	0.0	24.6	0
11	Apr-21	17.2	0.8	21.8	35.6
12	May-21	41.0	41.6	599.6	17.6
	Total	**2124.6**	**1985.4**	**4434.8**	**1719.8**

4.2 Wind

Climatological data on surface winds during the Non-Monsoon (February-May, FMAM), SW Monsoon (June-September, JJAS), NE Monsoon (October-January, ONDJ), and annual scales of the wind data sets observed from Indian Meteorological Department (IMD) for a period of 11 years from 2012 to 2022 has been plotted to understand the wind. The wind data set collected at every 3-hour intervals has been described for all 3 coastal districts of Puducherry UT.

4.2.1 **Puducherry**

Time series plot for the wind prevailing at Puducherry coast from the year 2012 to 2022 is shown in Figure 11. Mean wind speed of 4 kmph is observed with the maximum wind speed > 15 kmph generally occurring in monsoon months. As observed wind velocities are much more intense in the span from 2012 to 2017 with ranges exceeding 10 kmph in all their months in time series graph and more peaks also observed. In the span from 2017 to 2022 wind peaks are observed in last quarter of the years 2018 and 2020 indicating the dominance of NE monsoon, cyclones and depressions. Puducherry recorded the highest wind speed of 46 kmph during to the month of November 2015 during a deep depression over the Bay of Bengal (Figure 11).

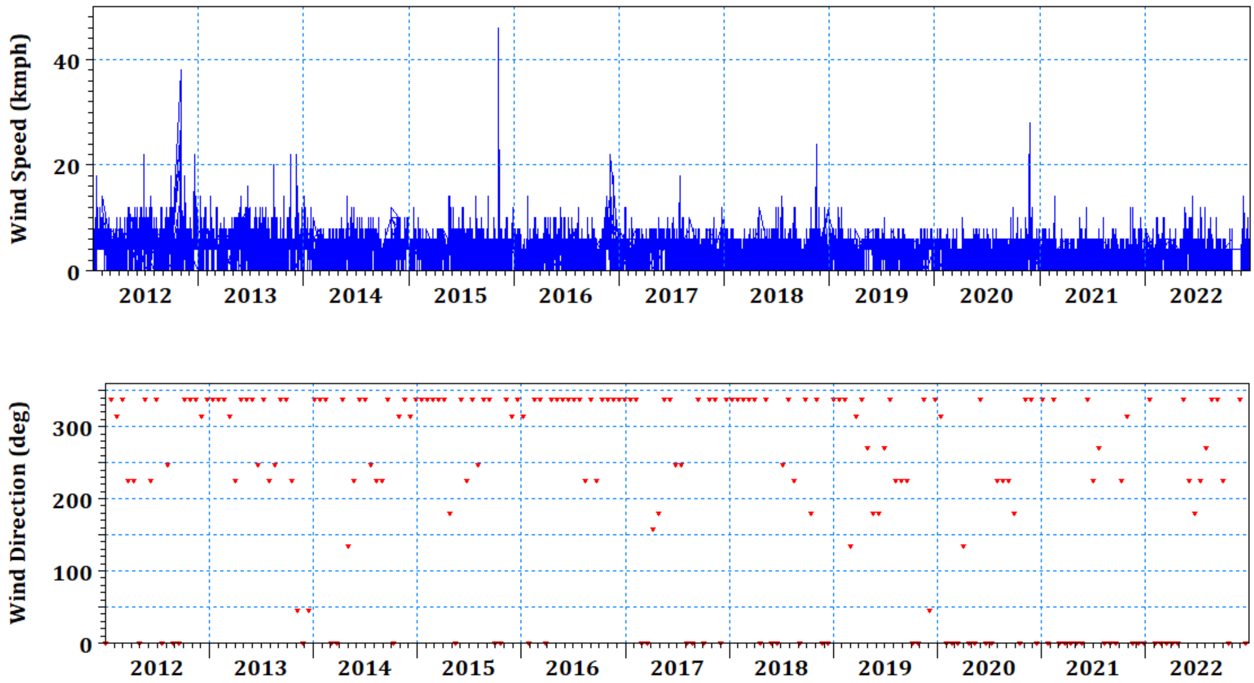


Figure 11 Time Series of Wind Speed and Direction at Puducherry coast

On an annual scale, winds predominantly approach from NNE direction with a directional split among NNW, WSW and SSE directions. In this predominant direction, winds with velocity less than 1 kmph occurs for approximately 35% of the time and in velocity range from 2 to 5 kmph for 5% of the time. Wind speeds ranging from 2 to 5 kmph cumulatively account for approximately 35 % time in all directions (Figure 12 a). During the SW monsoon, the predominant wind directions are WSW and NNE direction. Winds exceeding 10 kmph occurs approximately 2 % of the time in WSW direction. Winds in the velocity range from 2 to 5 kmph cumulatively account for more than 40 % of the time (Figure 12 b).

During the NE monsoon, predominantly wind approach from NNE and NNW quadrant. In this predominant direction, Winds with a velocity range of less than 1 kmph occur approximately 50 % of the time. Winds exceeding 10 kmph occur at about 2 % of the time in the NNW quadrant (Figure 12 c). During non-monsoon months, predominant wind direction occurs in the NNE and SW direction. In this predominant direction, winds with velocity range less than 1 kmph occurs for approximately 30 % of the time. Winds with a velocity range of less than 5 kmph occur cumulatively account for 60 % of the time in all directions. Winds with velocities ranging from 5 kmph to 10 kmph occurs approximately 25 % of the time. Approximately 90% of the observed data indicate low intensity winds within the 10 kmph range during the non-monsoon season (Figure 12 d).

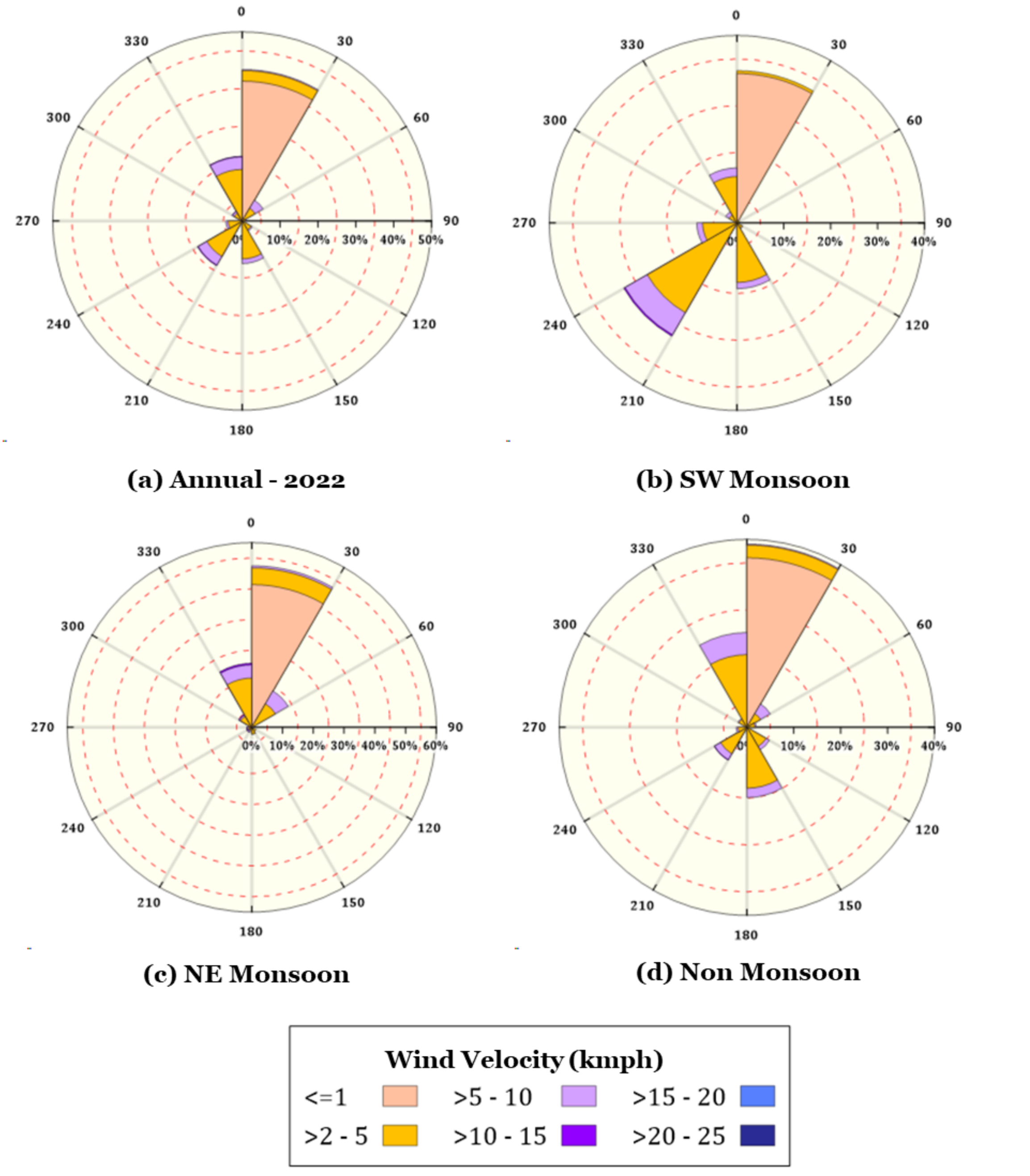


Figure 12 Annual & Seasonal Rose Plots for Wind Speed and direction along Puducherry Coast

4.2.2 Karaikal

Time series plot for the wind prevailing at Karaikal coast from the year 2012 to 2022 is shown in Figure 13. Mean wind speed of 10.5 kmph is observed with the maximum wind speed exceeding 20 kmph generally occurring all the seasons throughout the year. Winds with velocities ranging from 5 kmph to 30 kmph predominantly occur during this period. Wind peaks were observed more frequently from 2012 to 2019, with almost seven events of winds exceeding 50 kmph, while no wind peaks above 50 kmph is observed from 2020 to 2022. Karaikal recorded a highest wind speed of 80 kmph in October 2012 during a deep depression in the Bay of Bengal (Figure 13).

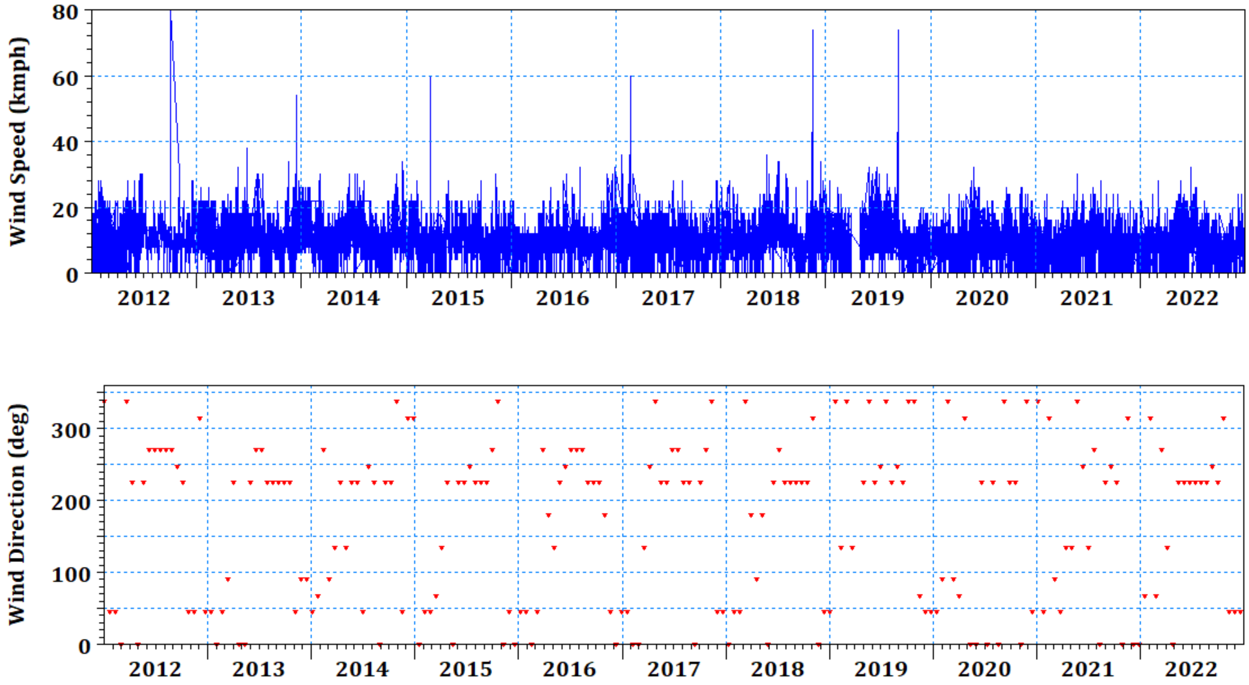


Figure 13 Time Series of Wind Speed and Direction at Karaikal coast

On an annual scale, the winds approach from all the directions, with all directional sectors having velocities exceeding 10 kmph. Winds exceeding 10 kmph occur predominantly in all directions and cumulatively account for 40 % of the time. Winds with velocity less than 1 kmph occur in the NNE direction. Wind speeds exceeding 20 kmph occur about 5 % time of the time throughout the year, almost in all directional sectors (Figure 14 a).

During the SW monsoon months, the predominant wind direction is SW. Winds exceeding 15 kmph occur for almost 10 % of the time in SW and WSW direction. Winds with velocities ranging from 5 to 10 kmph cumulatively account for more than 25% of time in the quadrant from 210^0 to 240^0 (Figure 14 b).

During the NE monsoon months, the predominant wind direction is NNE, with a directional split towards NNW. Winds with velocities less than 1 kmph occur about 15 % of the time in the NNE direction. Winds exceeding 10 kmph occur about 30 % of the time in the NNW and NNE quadrant, indicating the NE monsoon dominance with high wind speeds (Figure 14 c). During non-monsoon months from February to May, winds approach from all e directions, predominantly ranging from 1 to 15 kmph, with very few occurrences of velocities exceeding 15 kmph (Figure 14 d).

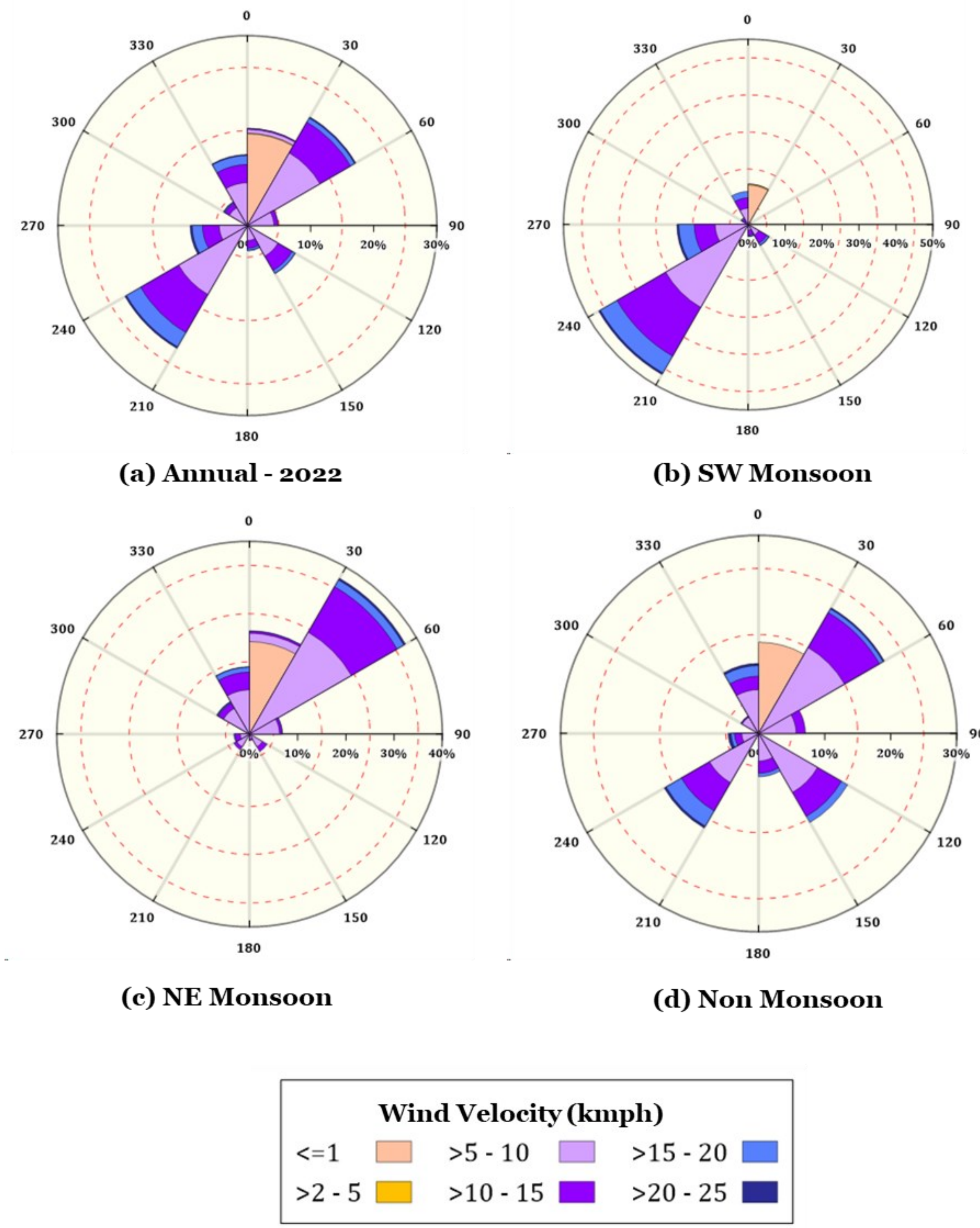


Figure 14 Seasonal Rose Plots for Wind Speed and direction along Karaikal Coast

4.2.3 Mahé

Time series plot for the wind prevailing along Mahé coast from the year 2012 to 2022 is shown in Figure 15. Mean wind speed of 4 kmph is observed with maximum wind speeds exceeding 20 kmph generally occurring during the SW monsoon. Wind velocities were notably higher in 2017 and 2018, with speeds exceeding 25 kmph at the beginning of the year. Mahé recorded its highest wind speed of 36 kmph in January 2017 (Figure 15).

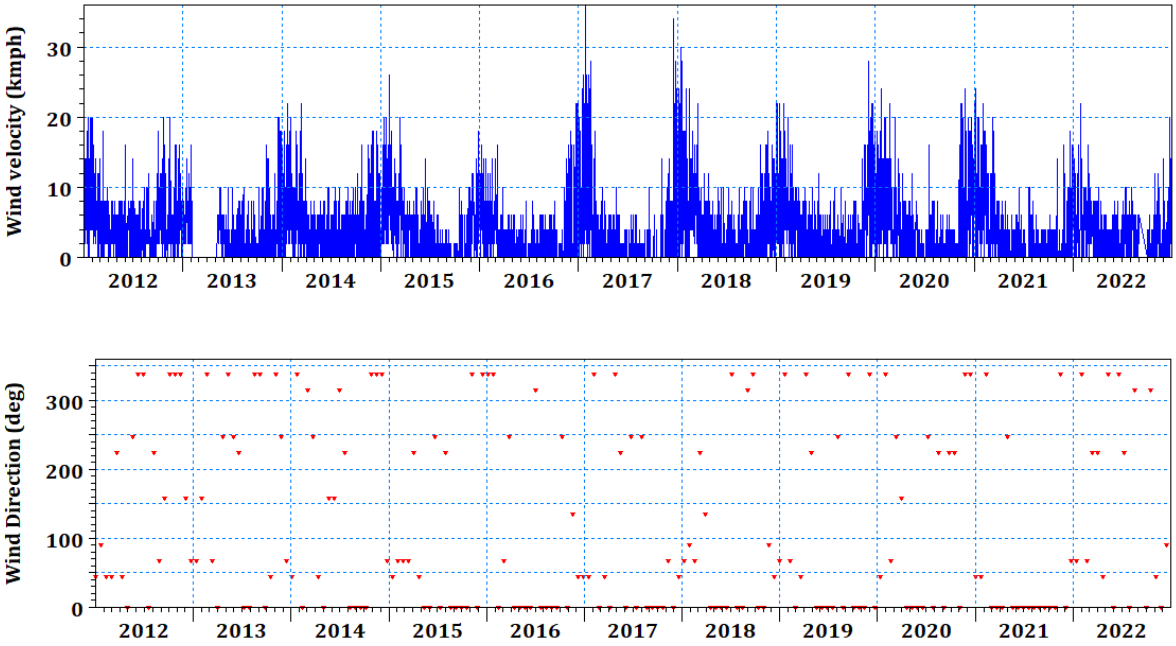


Figure 15 Time Series of Wind Speed and Direction along Mahé Coast

On an annual scale, the winds are approaching from all directions, predominantly from the SW, NE and WSW. Winds with velocities exceeding 10 kmph occur approximately 20% of the time. Wind velocities in the range of 2 to 5 kmph occur in the NNE direction about 10 % of the time. Winds with velocities between 5 to 10 kmph occur about 35 % of the time in all directions. Winds with velocity exceeding 20 kmph were observed in the WSW and SW direction for about 3 % of the time (Figure 16 a). During the SW monsoon, the predominant wind direction is SW and WSW. Winds exceeding 10 kmph occur for almost 35 % of the time, predominantly in SSW and WSW directions, indicating the dominance of high intensity winds during the SW monsoon. Winds in the velocity range of 1 to 5 kmph occur very minimally in all directions (Figure 16 b).

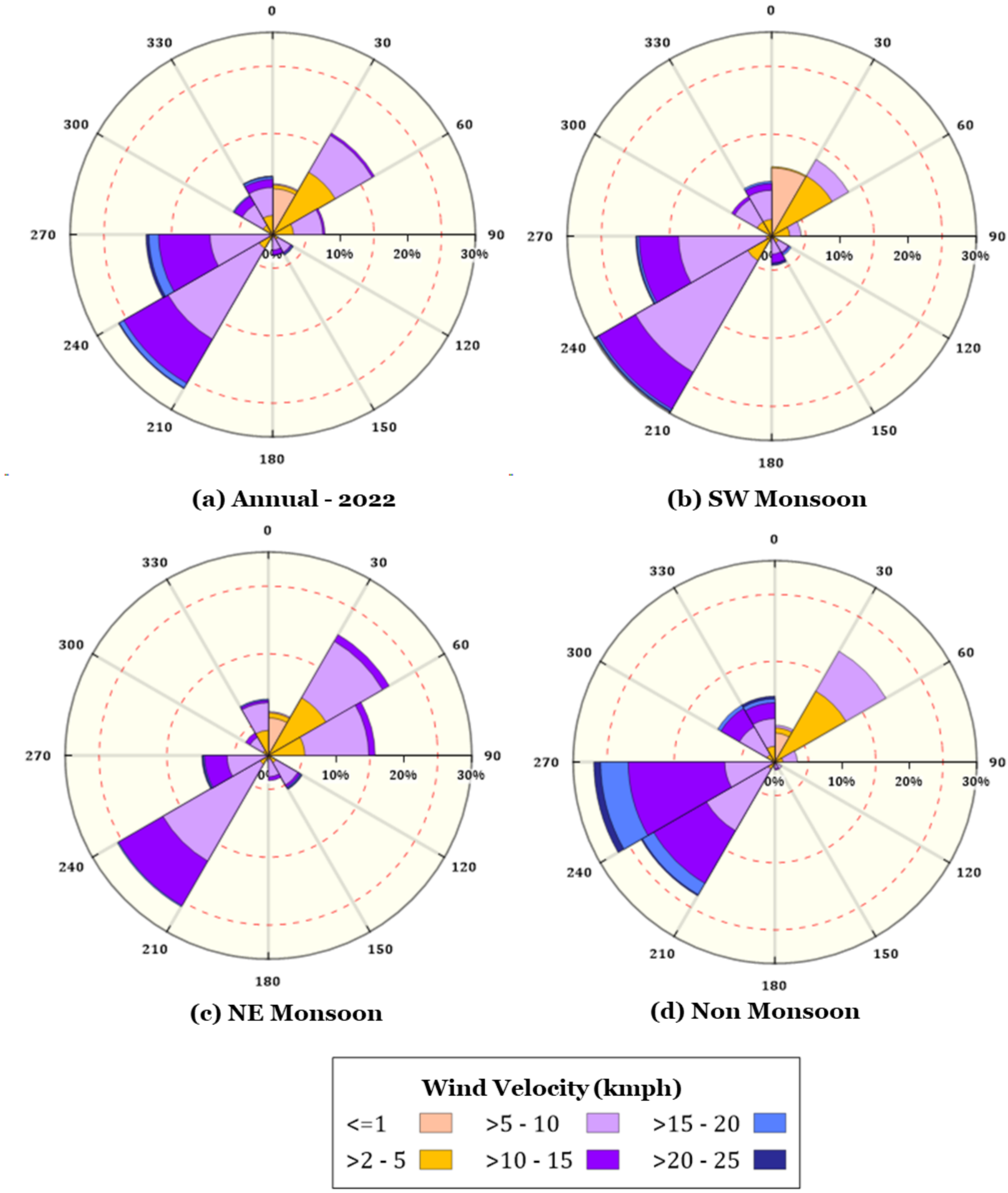


Figure 16 Seasonal Rose Plots for Wind Speed and direction along Mahé Coast

During NE monsoon months, winds approach in all directions with predominant directional split in the SW and NE directions. Winds with velocities less than 5 kmph occur about 10 % of time in NE direction. Winds exceeding 10 kmph cumulatively accounts for 20 % of the time in all directional splits. This season experiences winds exceeding 15 kmph in the SSW direction, though such occurrences are minimal (Figure 16 c). During the non-monsoon months, winds approach from the SW, WSW, NW, and NE quadrants, ranging from 210 to 60˚, with dominance in the WSW direction. Predominantly, winds are in the velocity range of 10 to 15 kmph, indicating the imminent onset of SW monsoon in May (Figure 16 d).

The Annual wind rose indicates that large wind speeds (> 20 kmph) are seen in Karaikal and Mahé where Puducherry is observed to have lowest wind velocities among all [Figure 12 (a) ,Figure *14* (a) and Figure *16* (a)].

4.3 Tide

Tide is defined as the rise and fall of water level due to attraction between the celestial bodies. The rotation of the earth combined with the gravitational force of the Sun-Earth-Moon influence the water to move in a cyclic action with an amplitude. Tides can therefore be represented by the "tidal range" which is the vertical distance between high tide and low tide value and "period" which is the time for occurrence of consecutive high tide (HT) or low tide (LT) levels.

The tides are classified into micro, meso, and macro tides based on their tidal range. Tides with a range less than 2 m are considered micro tides and those between 2 m and 4 m are considered meso-tide while those larger than 4 m are considered macro-tides. The type of tidal range determines the distribution of wave energy. The tides can also be classified based on their waveform (Form number) and also on their magnitude. In order to study the waveform of tides, harmonic analysis is carried out which gives an understanding of the variation of tides. It identifies the major tidal constituents, their frequencies, and amplitudes which help in understanding the influence of each tidal constituent and also in the prediction of the future tidal variations. Based on the frequency and tidal range, tides can be classified as diurnal tides (1 HT & 1 LT per lunar day), semi-diurnal tides (2 HT & 2 LT per lunar day), and mixed tides (2 HT & 2 LT with unequal range per lunar day). Therefore, the type of tide based on the waveform can be classified based on tidal form number (F) which is defined as the ratio of major diurnal to semidiurnal tidal constituents using the following expression:

$$F = \frac{(K1 + O1)}{(M2 + S2)}$$

$F < 0.25$ - semi diurnal tide
$0.25 < F < 1.50$ - mixed semi diurnal tide
$1.50 < F < 3.00$ - mixed diurnal tide
$F > 3.00$ - diurnal tide

The M_2 is the largest lunar constituent and mostly has the largest influence on the tidal levels. The S_2 constituent is the largest solar gravitational effect on the tidal levels. The constituents K_1 and O_1 show the influence of the moon's declination on the water levels. K_1 and O_1 together introduce the diurnal effect on the tidal levels. If the sum of these constituents is larger than the solar and lunar effects, then the diurnal behaviour of the water levels is experienced. The combination of all these effects constitutes mixed tides. Tides along all the three coasts are of Mixed Semi-diurnal types (Table 5).

Table 5 Type of tide based on Form Number

Location	Form Number	Type
Puducherry	0.26	Mixed Semi-diurnal
Karaikal	0.32	Mixed Semi-diurnal
Mahé	0.67	Mixed Semi-diurnal

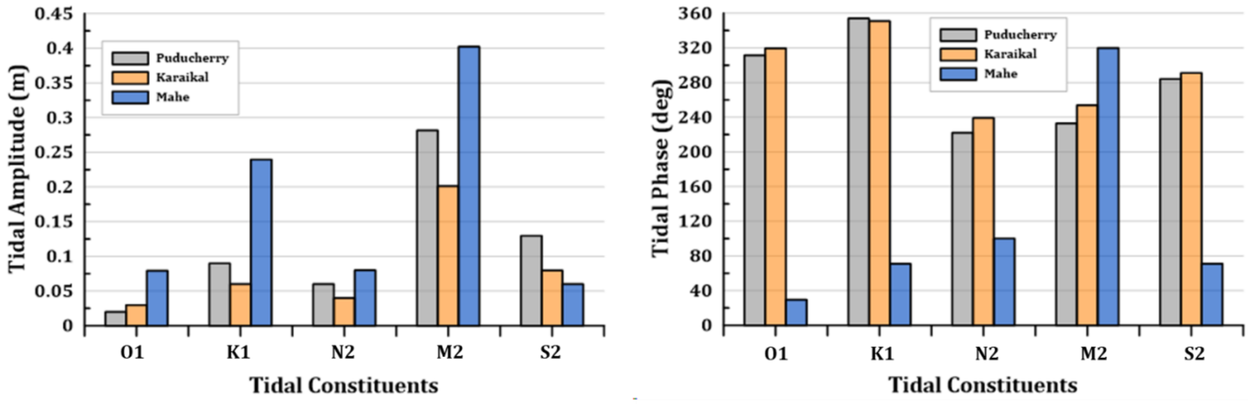


Figure 17 Tidal Amplitude and Phase for Pudhucherry UT

Tidal harmonic analysis for the Puducherry UT coast has been carried out to determine the amplitudes and frequencies of the major tidal constituents. The locations of observed water levels for the analysis as indicated in Figure 9. The major tidal constituent identified from the analysis is M_2, which represents the principal lunar constituent (Figure 9). It is observed to vary across all three coastal areas. The tidal amplitudes of all coefficients are higher in Mahé compared to Puducherry and Karaikal, except for S_2. Diurnal constants occur in NE quadrant along Mahé. Additionally, the lunar constituent is the largest among all three coasts when compared to solar and diurnal constituents. Along Puducherry and Karaikal coast diurnal constituents occur in phase angle of 300° to 350°. Semi diurnal constituents in these coasts occur only in SW and WNW quadrants (Figure 17).

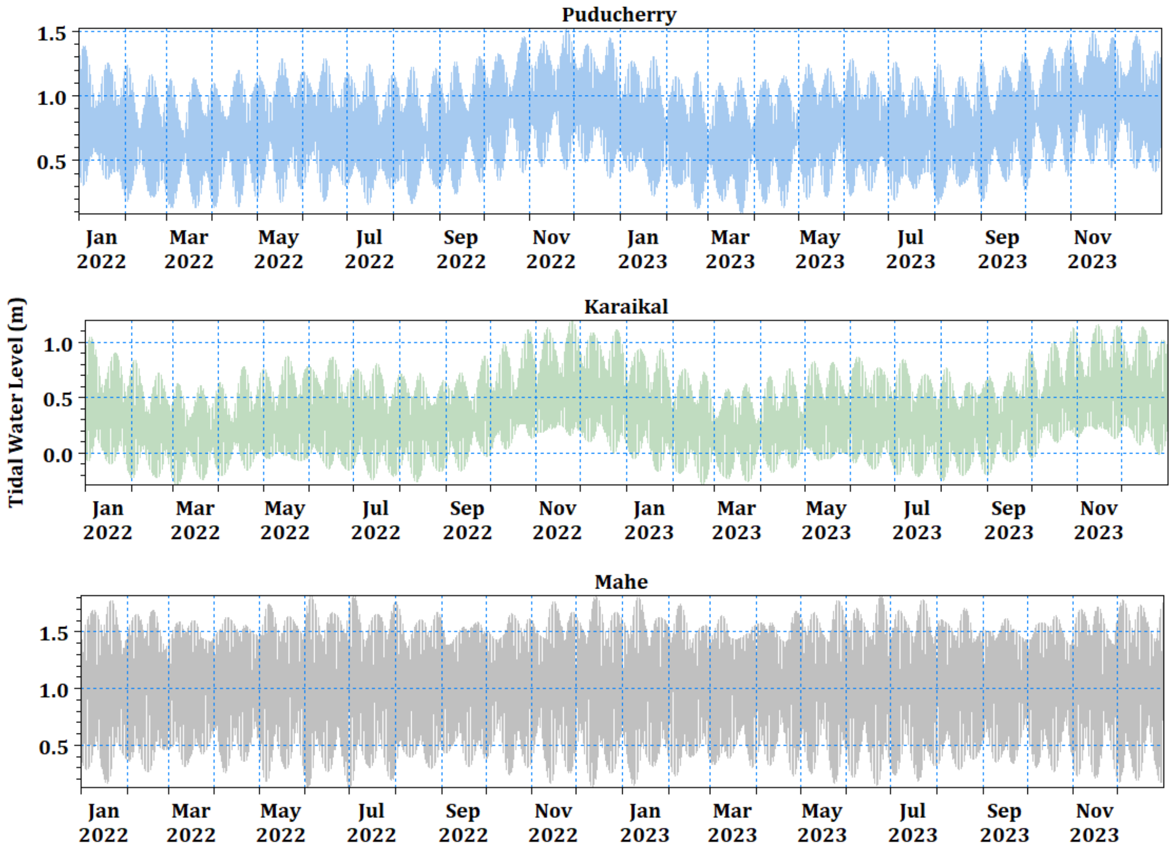


Figure 18 Time series tide data along Puducherry UT

The time series of the water level for a period of two years from January 2022 to December 2023 for the three locations are plotted in Figure 18. The tidal range was found to be in the order of 1.25 to 2.0 m range for all three locations. The tidal range is approximately 1.25 m for the coasts of Karaikal and Puducherry while the tidal range for Mahé is about 1.8 m. Thus, it can be concluded that the Puducherry UT coast falls under the category of micro-tidal (< 2m) range. The distribution and frequency of wave energy are more concentrated within the intertidal region in the micro-tidal areas than in macro tidal range.

4.4 Wave

Wave parameters such as significant wave height (H_s), mean wave period (T_m), peak wave period (T_p), and wave direction (Dir) were analysed using data collected from directional wave rider buoys. The buoys were deployed at 20 m water depth at, Puducherry (11.932°N, 79.854°E) and Kozhikode (11.31° N, 75.66° E) Coasts (Figure 9).

The wave climate of the North Indian Ocean (NIO) is categorised as the southwest monsoon (SW, June–September), north-east monsoon (NE, October–January) and pre-monsoon/ non-monsoon (February–May) [11]. The temporal variation of the wave climate is analysed using a wave rose and time series plot for all three locations.

4.4.1 Puducherry coast

The wave climate for the years from 2007 to 2022 has been analyzed for the Puducherry coast and represented as a time series plot (Figure 19). H_s predominantly lies in the range from 0.3 to 3.0 m from 2007 to 2022, with wave heights exceeding 2.5 m are observed in the last quarter of every year indicating the dominance of the NE monsoon winds along Puducherry Coast. More than 90 % of the waves occurs from 90^0 to 180^0 (Figure 19).

On an annual scale, the predominant wave direction along the Puducherry coast was is from the ESE direction. H_s is in range of 0 to 1 m for approximately 50 % of the time. Hs exceeds more than 2 m for approximately 5 % of the time in ENE and ESE directions (Figure 20 a). During the SW monsoon season, the H_s varied from 0.5 m to 2.0 m, with a mean value of 0.8 m. H_s is in range of 0 to 1 m for approximately 80 % of the time predominantly in SSE direction. The wave heights are comparatively lower than those of the NE monsoon (Figure 20 b and c).

During the NE monsoon season, the H_s varied from 0.5 m to 3.0 m, with an average value of 1.25 m. The H_s exceeds 1 m approximately at about 20% of all wave heights with these high-energy waves predominantly coming from the East direction. However, large waves (H_s>2 m) were observed from the East direction (70° to 110°) for more than ~3% of the time (Figure 20 c).

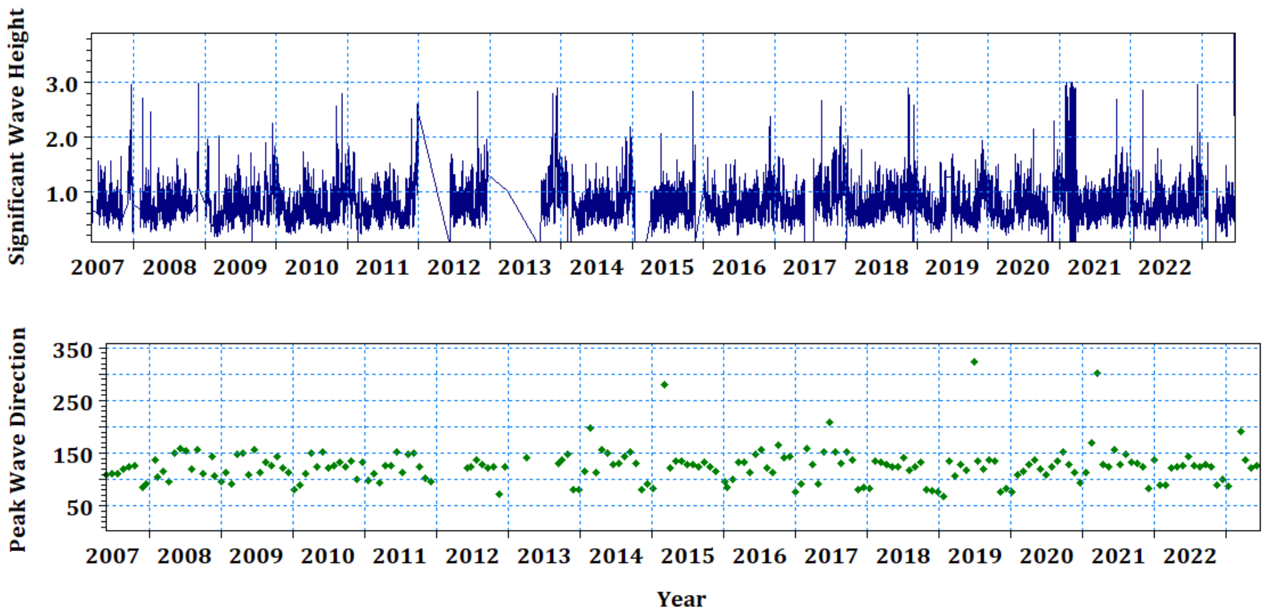


Figure 19 Time series of significant wave height (Hs) and peak wave direction for Puducherry

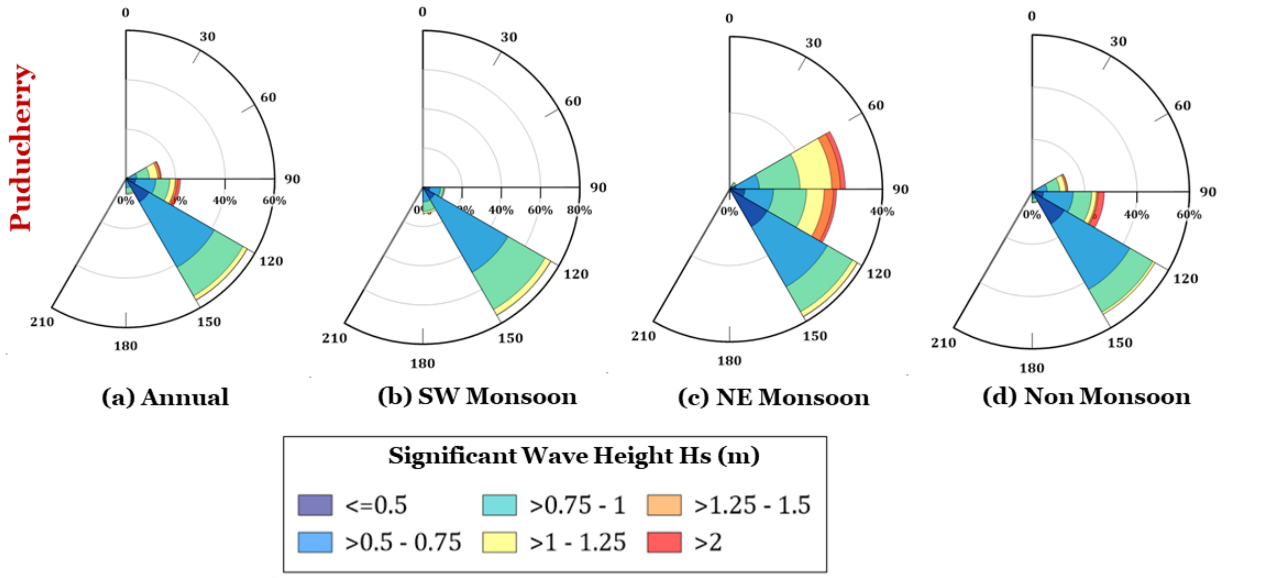


Figure 20 Annual and seasonal Wave Climate at Puducherry coast

During non-monsoon period, the H_s ranged from 0.4 m to 1.25 m, with a mean value of 0.6 m. During the non-monsoon periods, waves with H_s values ranging from 0.5 m to 1 m (Approximately 50% of the time) and 1 m to 1.5 m (more than 5% of the time) predominantly approaching from the ESE direction (90°-150°) (Figure 20 (d)).The peak wave direction during the NE monsoon varied from 60° to 120° and for the SW monsoon, it varies from 120° to 150° with the transition from monsoon to non-monsoon seen in between as shown in Figure 20.

The monthly wave rose plot for H_s are depicted in Figure 21. Waves from November to February predominantly approaching the coast from the East and NE directions, whereas from March to August, waves come from SE direction. The monthly wave roses of H_s and Peak Wave Direction clearly indicate the predominance of waves from the 60 to 150° direction along the Puducherry coast during non-monsoon months. In the SW monsoon, for all months, most waves come from the SE direction. Whereas from October to November predominant wave directions are in transition from SE to Easterly direction. During the NE monsoon, the dominance of Easterly waves (70-100°) with higher energy is observed along the Puducherry Coast.

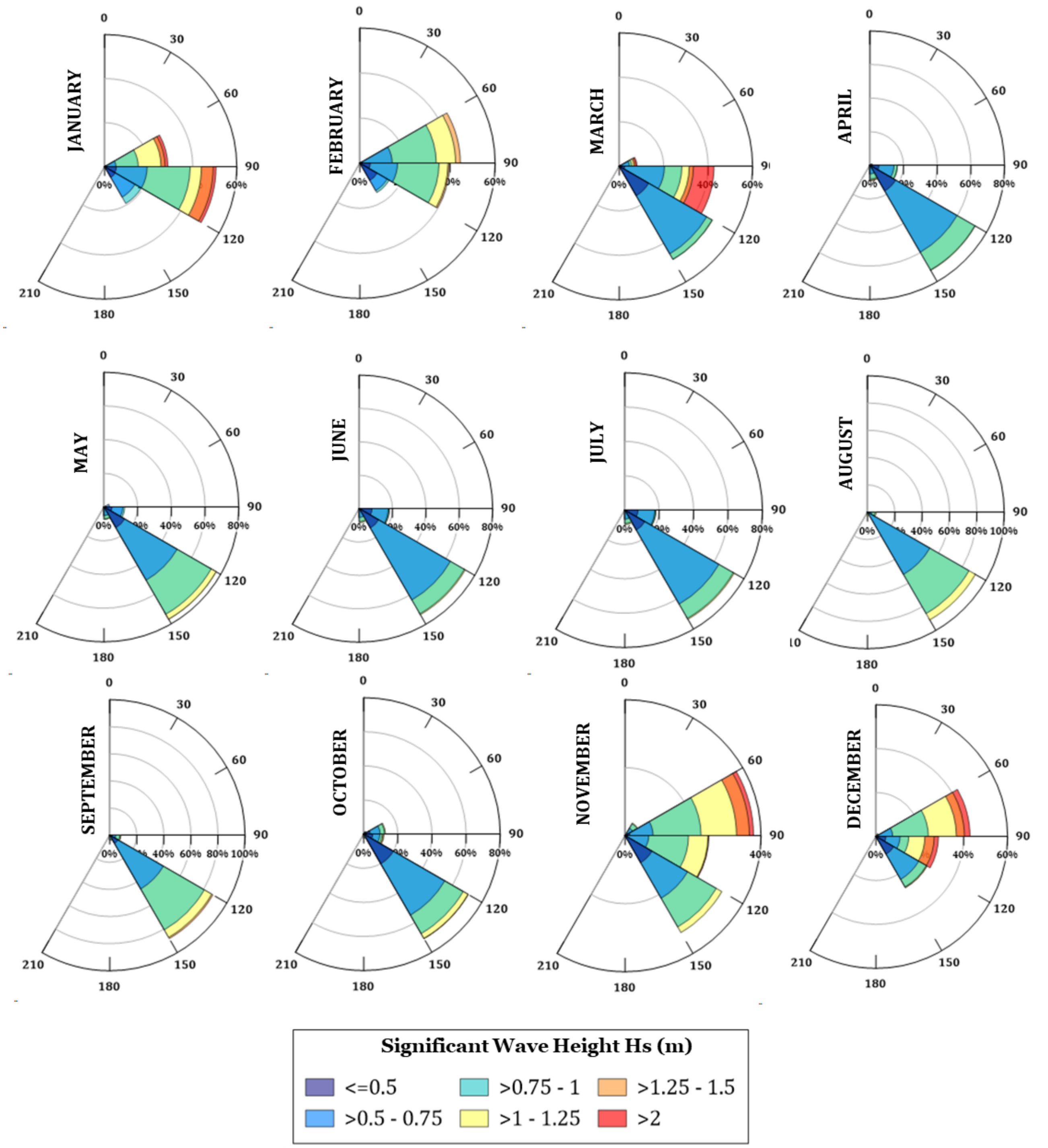


Figure 21 Monthly Variation of Puducherry Wave Climate (2021)

4.4.2 Karaikal coast

The wave climate in terms of Significant wave height, Peak Wave Direction and Peak wave period has been plotted for short term deployment duration from February to March months of 2013 (Figure 22). H_s predominantly fall withinrange from 0.3 to 1.61 m with a mean of 0.78 m. As inferred from the time series plot, February recorded higher H_s when compared to March. Swell waves with time period exceeding 10 seconds are observed in March . More than 90 % of the waves in the measurement period occur in the NE and ESE quadrant from 50^0 to

140^0 (Figure 22). During the observation period, H_s lies in the range from 0.5 to 1 m for approximately 65 % of the time, with H_s exceeding 1 m observed for about 25 % of the time. Peak wave direction is in ENE and ESE direction ranging from 60° to 120° Figure 23.

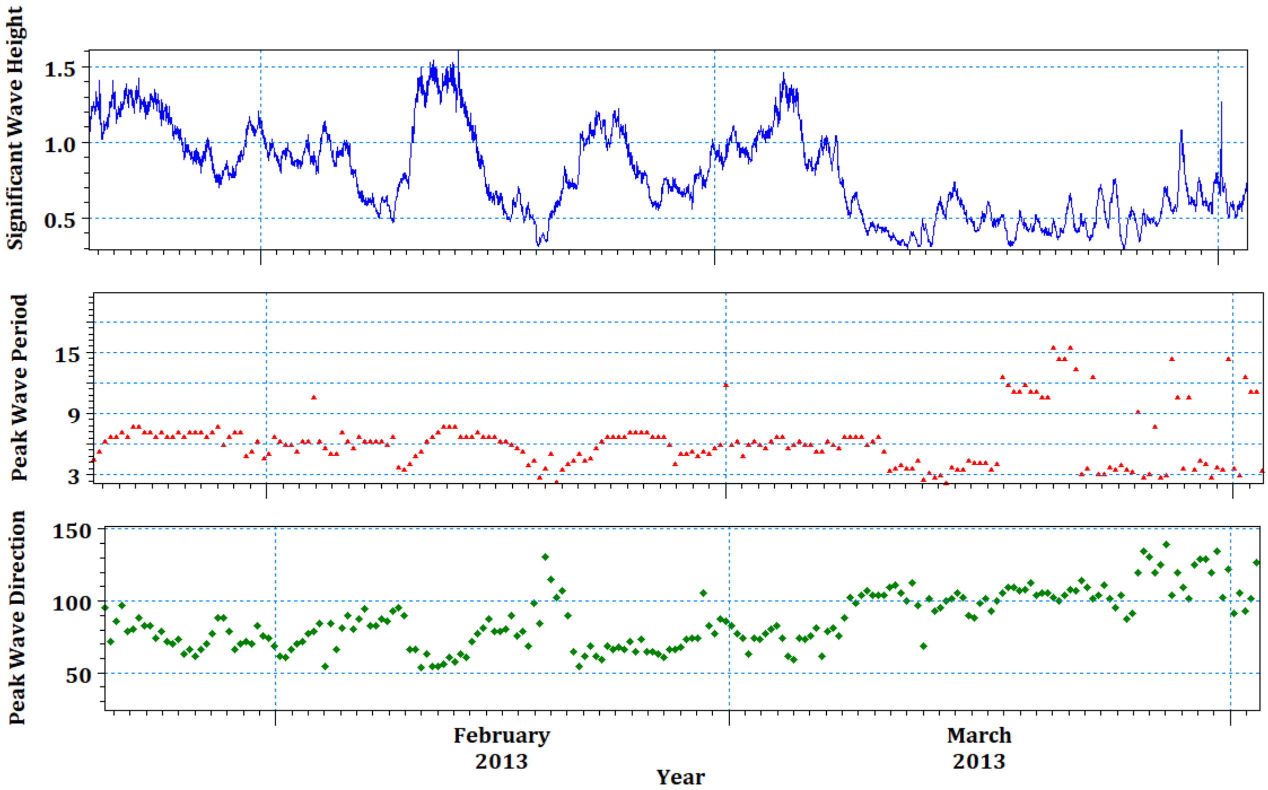


Figure 22 Time Series for Significant Wave Height (H_s), Peak wave Period (T_p) and Peak wave Direction at Karaikal Coast

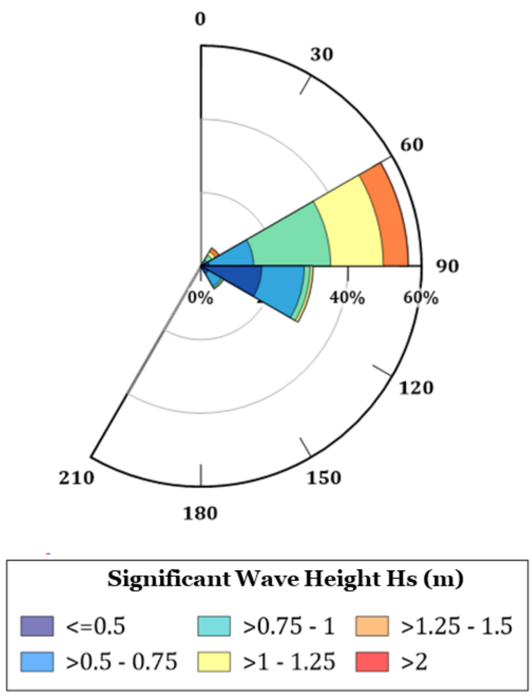


Figure 23 Wave Rose Plot for Karaikal (February to March 2013)

4.4.3 Mahé

Data spanning from 2013 to 2020, with some data gap,s was collected from a Wave rider buoy positioned off the Kozhikode coast and is represented for Mahé in the present study. The significant wave height (H_s) varied between 0.2 to5.27 m over this period, with a mean of 0.79 m. The highest H_s of 5.17 m were recorded on June 2016 along the West coast due to depression ARB 01 in the Arabian Sea (Figure 24).

On an annual scale for the year 2019, Hs ranged from 0.23 to 3.24 m, with an average of 0.92 m. The predominant wave direction is SW and WSW (more than 44% of the time), ranging from 210^0 to 270^0, with the direction of 220^0 almost 50% of the time (Figure 24 and Figure 25 a). Hs exceeding 1 m was observed for approximately 30% of the time, and these high energy waves are from the West direction (Figure 25 a).

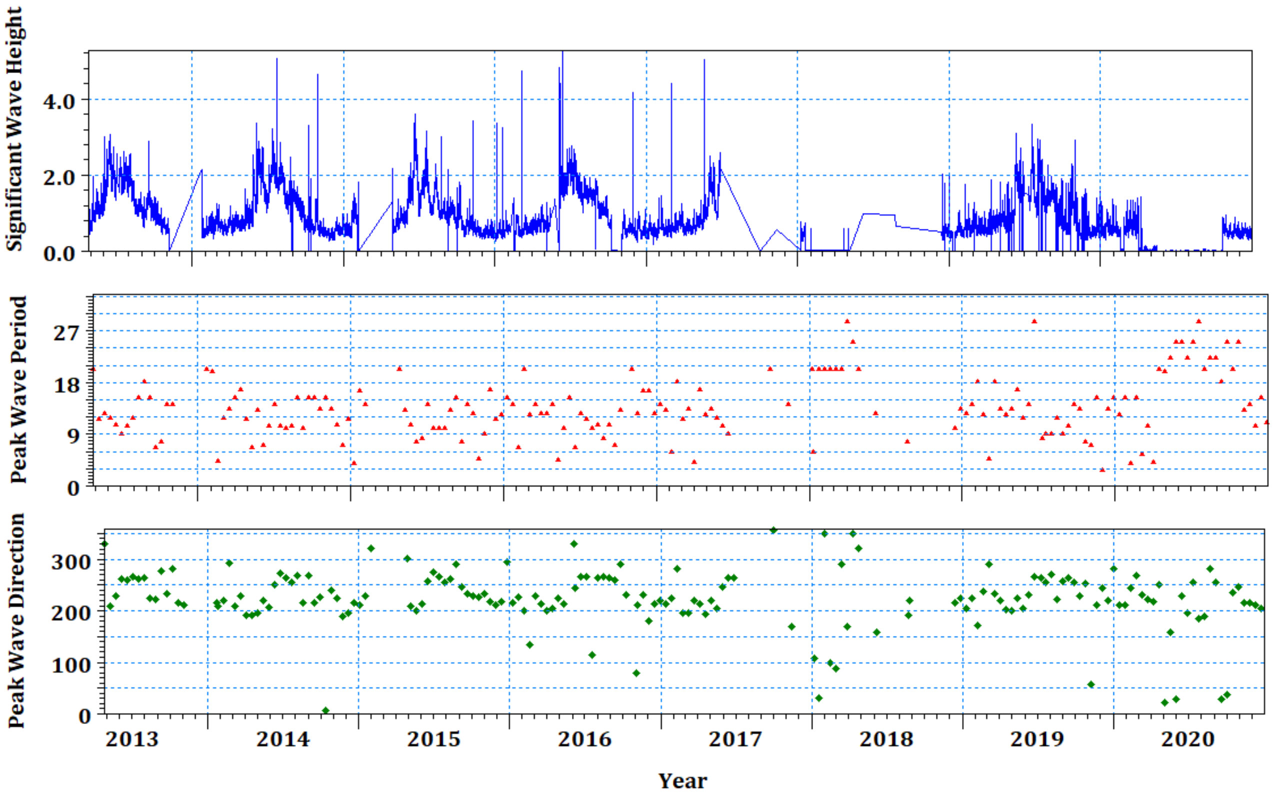


Figure 24 Time Series for Significant Wave Height (H_s), Peak wave Period (T_p) and Peak wave Direction at Kozhikode Coast from 2013 to 2020

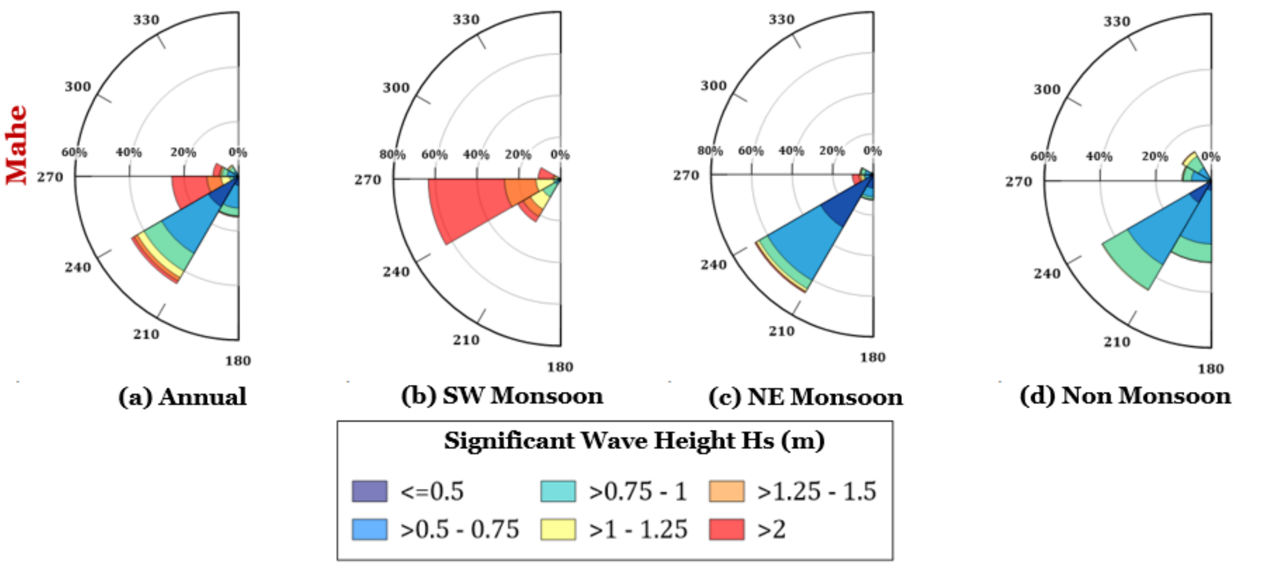


Figure 25 Annual and seasonal Wave Climate at Kozhikode coast (2019)

During SW monsoon season, the H_s varied from 0.5 m to 3.34 m, with a mean value of 1.47 m, indicating high energy waves in SW monsoon. Throughout the SW monsoon season, H_s exceeded 1 m most of the time, with these high-energy waves predominantly (more than 88% of the time) originating from the WSW direction. Moreover r, large waves (Hs>2 m) were observed from the WSW direction (240- 270°) for more than ~70% of the time (Figure 25 b).

During the NE monsoon season, the Hs varied from 0.23 m to 2.93 m, with a mean value of 0.638 m. Waves with H_s values ranging from 0.5 to 1 m occurs approximately 80% of the time and the predominant wave direction was the SSW direction (Figure 25 c). During the non-monsoon season, the H_s ranged from 0.37-1.87 m, with a mean of 0.67 m. During the non-monsoon periods, waves with H_s values ranging from 0.5 m to 1 m (more than 40% of the time) approached from the SSW direction (210-240°) (Figure 25 d).

Monthly wave roses of H_s and Peak Wave Direction (Figure 26) clearly indicate the predominance of waves from the 210 to 330° direction along the Kozhikode coast. For all months except during the SW monsoonal months (June to September), most of the waves were from the SW and SSW direction, including high energy and swell waves. During the SW monsoon months, particularly in June, July and August high energy waves approach from the West direction. During NE monsoon, low energy wave predominantly occurs along SSW direction..

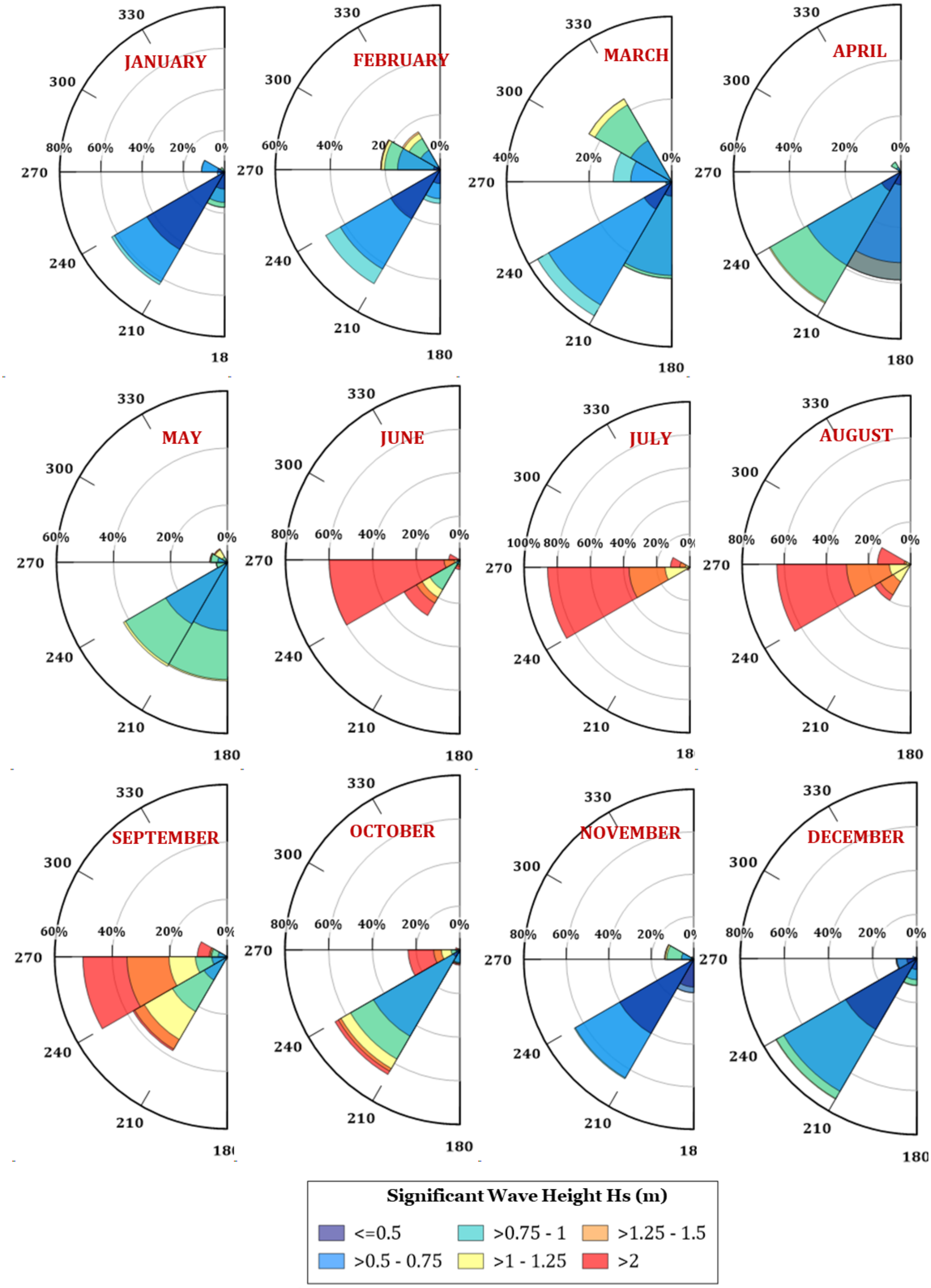


Figure 26 Monthly Variation of Mahé Wave Climate

4.5 Currents

Currents are widely classified as ocean and coastal currents. The major ocean current is the East India Coastal Currents (EICC) that reverses seasonally. The major driving mechanism for the EICC is the monsoon winds and remote forcing from barometric waves (equatorial Kelvin and Rossby waves and coastal Kelvin currents) [10]. The oceanographic currents are very difficult to track and model. However, the coastal processes are mainly influenced by the coastal currents. The coastal currents are driven by means of tides, storm surge, wave generated longshore currents and wave generated shore normal currents. The currents not only influence the complex dynamics of the tidal inlets but also on the sediment transport along and cross-shore.

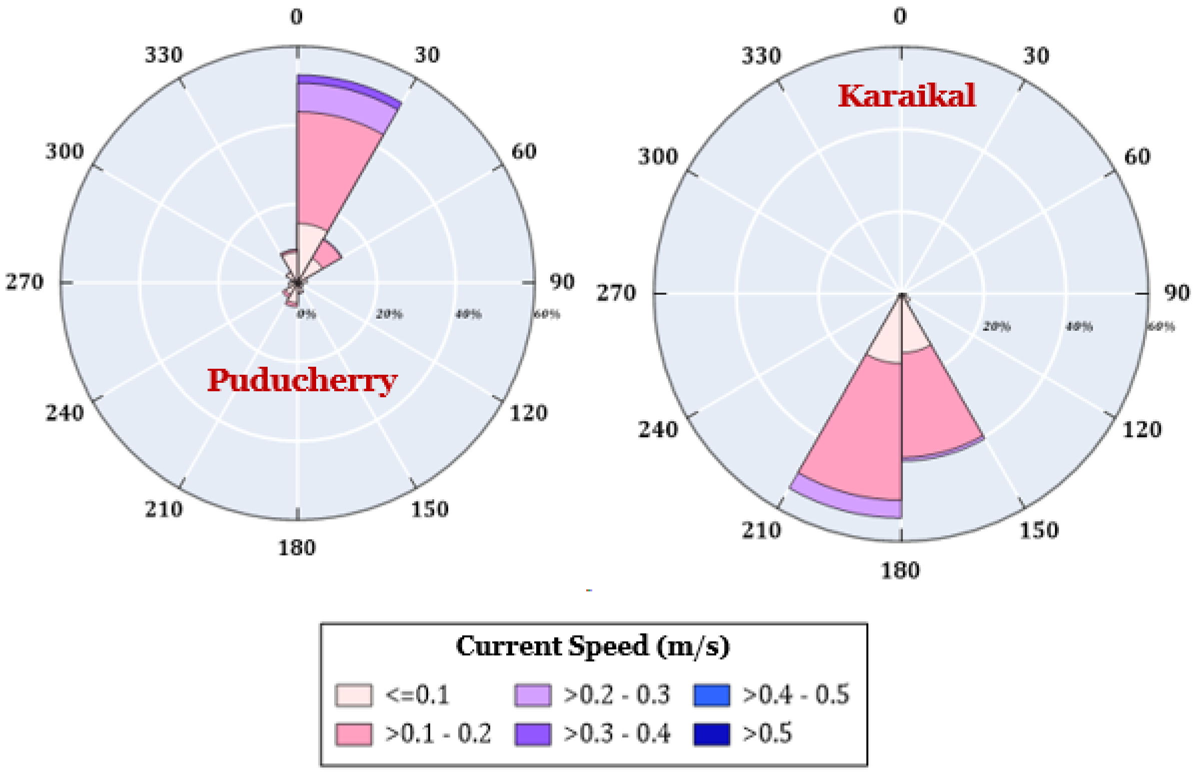


Figure 27 Current Rose for the two locations (a) Puducherry and (b) Karaikal

The Short-term current readings were observed along Puducherry and Karaikal through ADCP deployed in the region (Figure 19). The current rose plots of the locations indicate currents prevailing in Puducherry have a speed range from 0.1 to 0.3 m/s for approximately 80 % of the time, predominantly moving towards the NE direction. Currents at the Karaikal location have a speed range from 0.1 to 0.2 m/s for approximately 90 % of the time, predominantly moving towards the SSW and SSE directions (Figure 27).

4.5.1 Puducherry

Currents along the Puducherry coast (11.55° N, 79.50° E) were measured by deploying recording current meter. Data collected for fifteen days from 29th August 2023 to 12th September 2023 has been considered for analysis. The mean current speed was 0.10 m/s, with values ranging from 0.001 to 0.37 m/s. The highest current speed of 0.37 m/s was observed on 2nd September 2023 (Figure 28). The predominant Current direction for Puducherry coast is moving towards the NNE direction from 0 to 30°, with a less directional split in NNW and SSW quadrant.

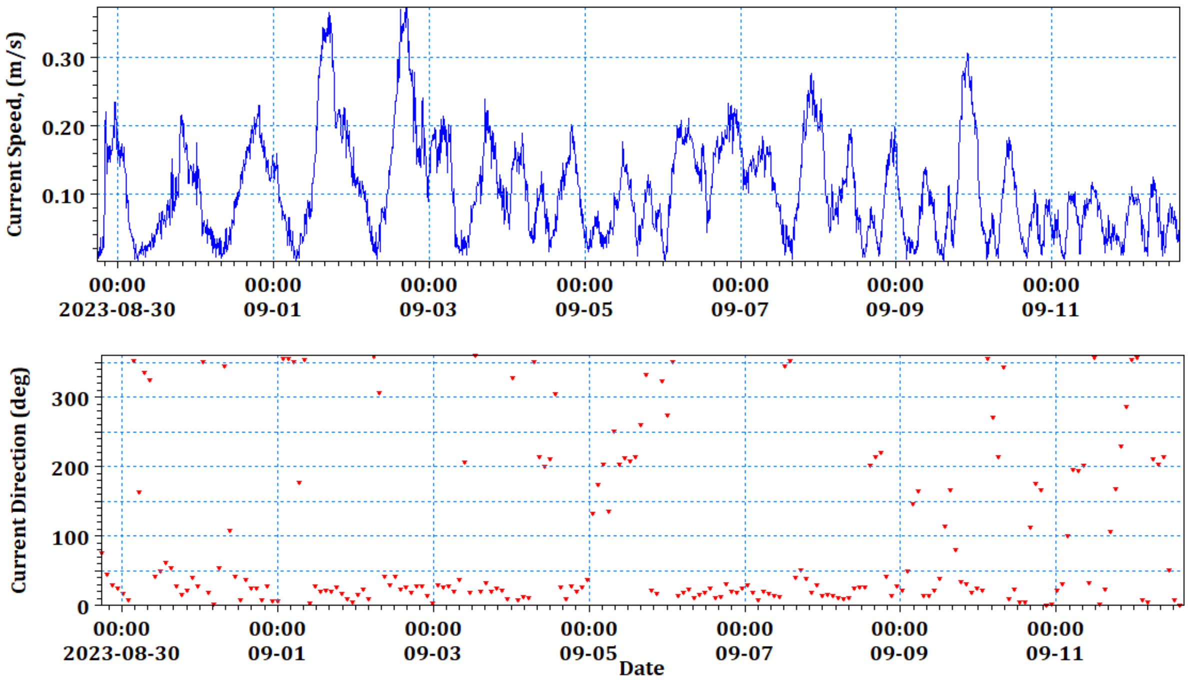


Figure 28 Time Series of current Speed and Current along Puducherry

4.5.2 Karaikal coast

Currents along the Karaikal Coast (10.54° N, 79.5° E), were measured by deploying recording current meter. The data was collected for seven days from 25 November 2022 to 1 December 2023 has been considered for analysis. The mean current speed was 0.12 m/s, with values ranging from 0.002 to 0.29 m/s. The highest current speed of 0.29 m/s was observed on 29 November 2022 (Figure 28). The Predominant current direction along the Karaikal coast is moving towards the SSW direction for annual observation from 180 to 210^0 (Figure 29).

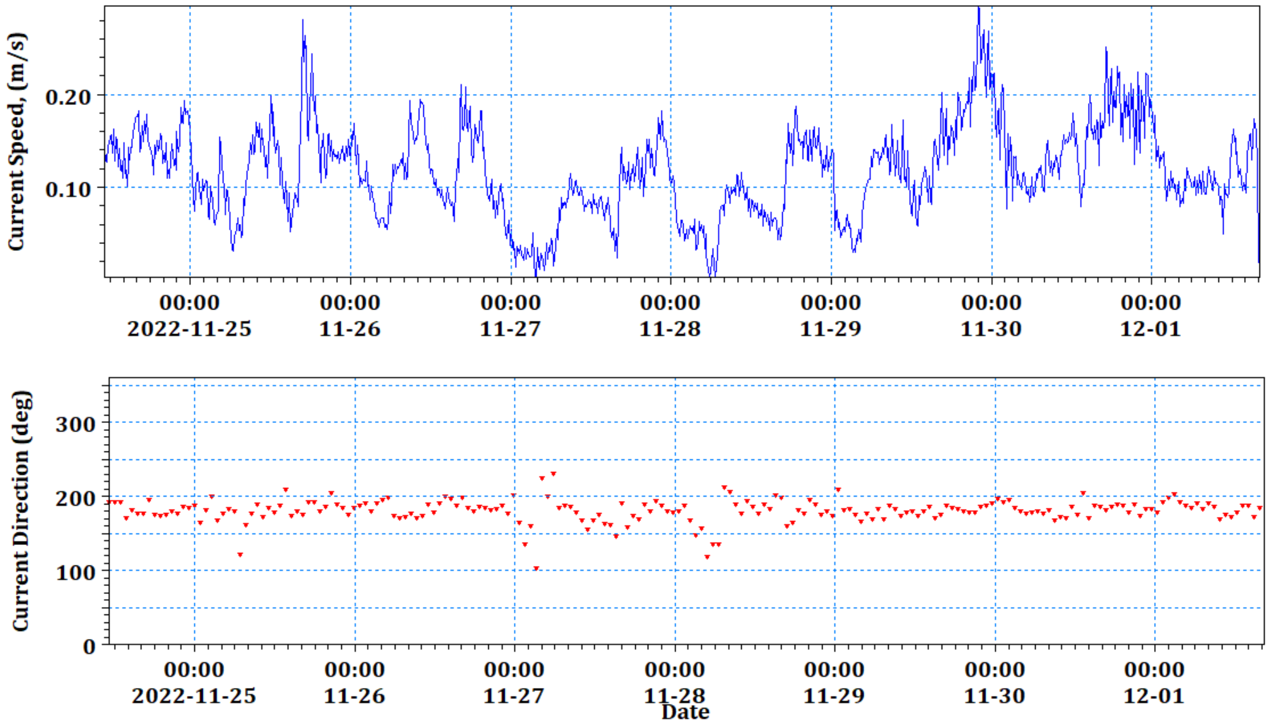


Figure 29 Time Series of current Speed and Current along Karaikal

4.6 Bathymetry

The bathymetry refers to the measurement and mapping of the depth and topography of the ocean floor. The Puducherry UT coast extends over a distance of approximately 29 km, having 25 km coastline in Bay of Bengal and 4 km coast line along Arabian Sea. The bathymetry of the coast is an important aspect of its coastal morphology and marine ecosystem. It provides valuable information for navigation, infrastructure development, and ecosystem management, and is essential for understanding the dynamics of the coastal environment. The steepness of the bed has a wide influence on the oceanographic parameters that affects the coast.

The nearshore bathymetry of the entire Puducherry UT coast is obtained from MIKE C-MAP and Figure 30 shows the depth contours along the coast.

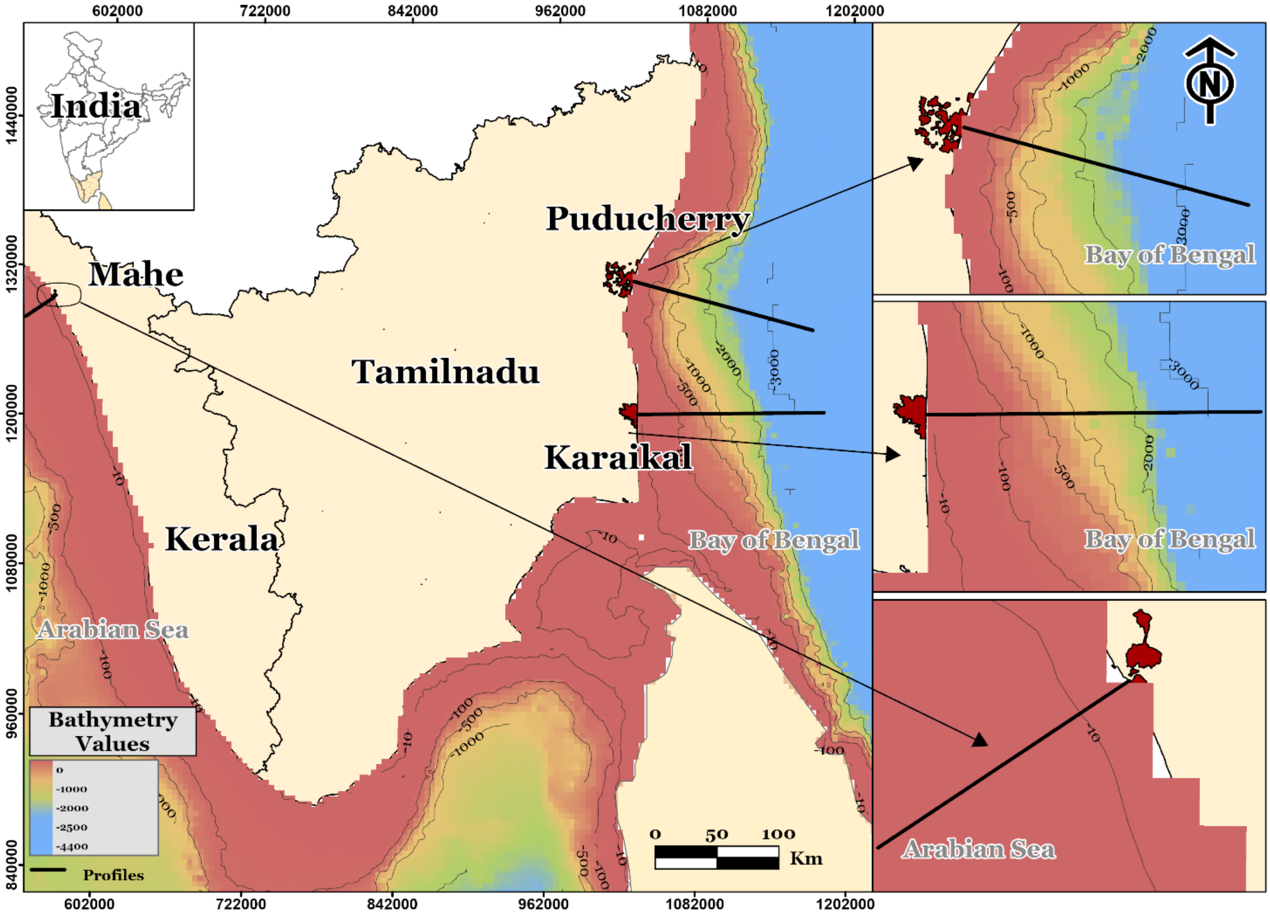


Figure 30 C-MAP bathymetry and cross-shore profile along Tamil Nadu

Table 6 Shelf widths at different depth levels

Depth	20	40	60	80	100	Bed Slope (1:value) between isobaths of			
Location	Shelf length (km) from Shoreline					20- 40 m	40- 60 m	60- 80 m	80- 100 m
Puducherry	5.87	8.89	11.43	13.96	15.82	151	127	127	93
Karaikal	2.41	9.08	13.74	16.73	22.35	334	233	150	281

The bathymetry data from MIKE C-MAP can provide a more complete and comprehensive understanding of nearshore environments, thereby enabling numerical models to accurately predict physical processes along the coast. The C-Map data for the Puducherry and Karaikal coast has been plotted for the depth ranging between 0 m to 4,500 m and for Mahé for the depth ranging from 0 to 32 m.

The bathymetry at Pondicherry was characterized by gently sloping topography from 0 to 25 m at 12 km from the shore line. The gradient increased significantly and at 21 km from the shore the maximum depth of 300 m was observed. This feature appeared to be a near shore submarine canyon [12].

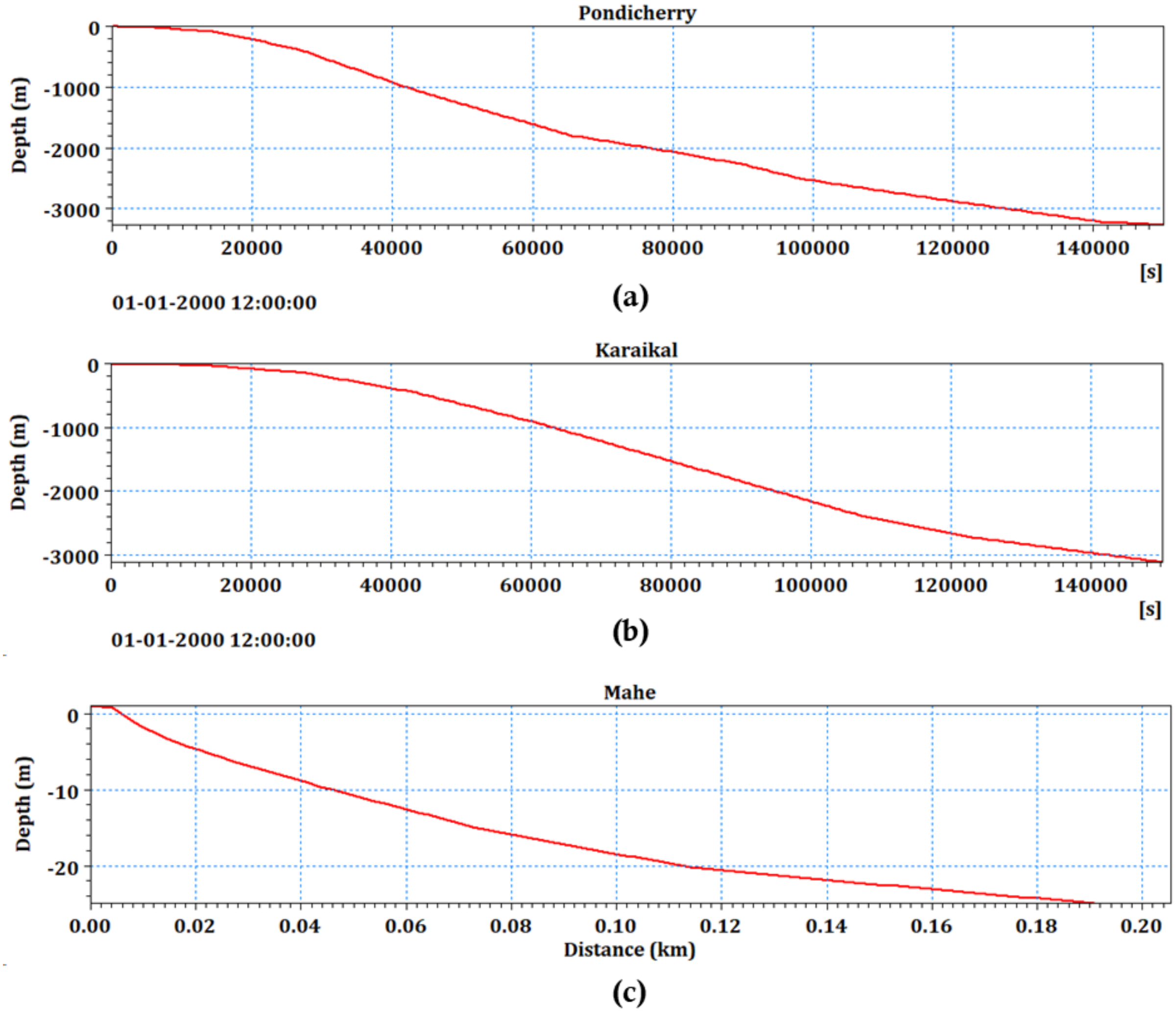


Figure 31 C-MAP bathymetry and cross-shore profile along Tamil Nadu Coast

The bathymetry profile extracted clearly shows almost similar profile for both Pondicherry and Karaikal. Distances of 20, 40, 60, 80 and 100 m contours are extracted as per Table 6. It is noted that 20 m water depth is arrived at about 6 km for Puducherry and 2.5 km for Karaikal. Near shore slope is steeper for Puducherry compared to Karaikal. From 20 to 40 m slope is moderate for both coast and 100 m water depth are at about 16 km far for Puducherry and 22.5 km far for Karaikal. In Mahé Coast, due to limited data availability, depths were plotted up to 32 m. 10 m water depth is at about 20 m distance from shore, and 20 m water depth is at about 190 m from coast (Figure 31 c).

4.7 Sea Level Rise

Sea level rise (SLR) is a phenomenon driven due to two major reasons: the melting of ice sheets and expansion of ocean water which are better explained by the rise in Earth's global temperature. The main source of temperature rise is the release of greenhouse gases along with solar radiation, atmospheric aerosols and land use changes. The ice sheets are also getting melted at an accelerated rate due to this rise in temperature and the oceans also absorbs a part of this heat resulting in the thermal expansion of sea water. SLR is an escalating process affecting the coastal areas where the major cities across the world are developed.

The Intergovernmental Panel on Climate Change (IPCC) provides scientific assessment on climate change scenarios using Representative Concentration Pathways (RCP) and general circulation models to predict the future risks of sea level rise. The rate of global sea level rise has increased up to 3.60 mm per year from 1.40 mm per year. As per the "Assessment of Climate Change over Indian region" report by the Government of India, the RCP 8.5 scenario projects the average temperature rise over India by 4.4^0 C towards the end of the century relative to recent past (1976-2005 average). The coastal erosion, land subsidence and increased high tide flooding are elevating which requires immediate actions to prevent the adverse effects that could possibly affect millions of people.

The Union Territory of Puducherry is spread in both East and West coast of India. Puducherry and Karaikal are encompassed with Tamil Nadu as borders in the East coast and Mahé in the West coast has borders with the state of Kerala. An estimate of SLR has been derived from the web-based application under RCP 4.5 and the results are plotted below (Figure 32). This gives a general idea of SLR at different locations along the UT of Puducherry coast.

The coastal stretch of Mahé has projected the highest rise of about 0.47 m for the year 2060 and +1.11 m for the year 2100. The lowest rise is projected for the coast at Puducherry of about +0.37 m and +0.94 m for the years 2060 and 2100 respectively. According to the projections, an overall increase in the range of about 0.94 m to 1.1 m is possible along the coast by the end of the century (Figure 32). This will have wide spread effects for the development and sustenance of commerce and tourism for all the stakeholders.

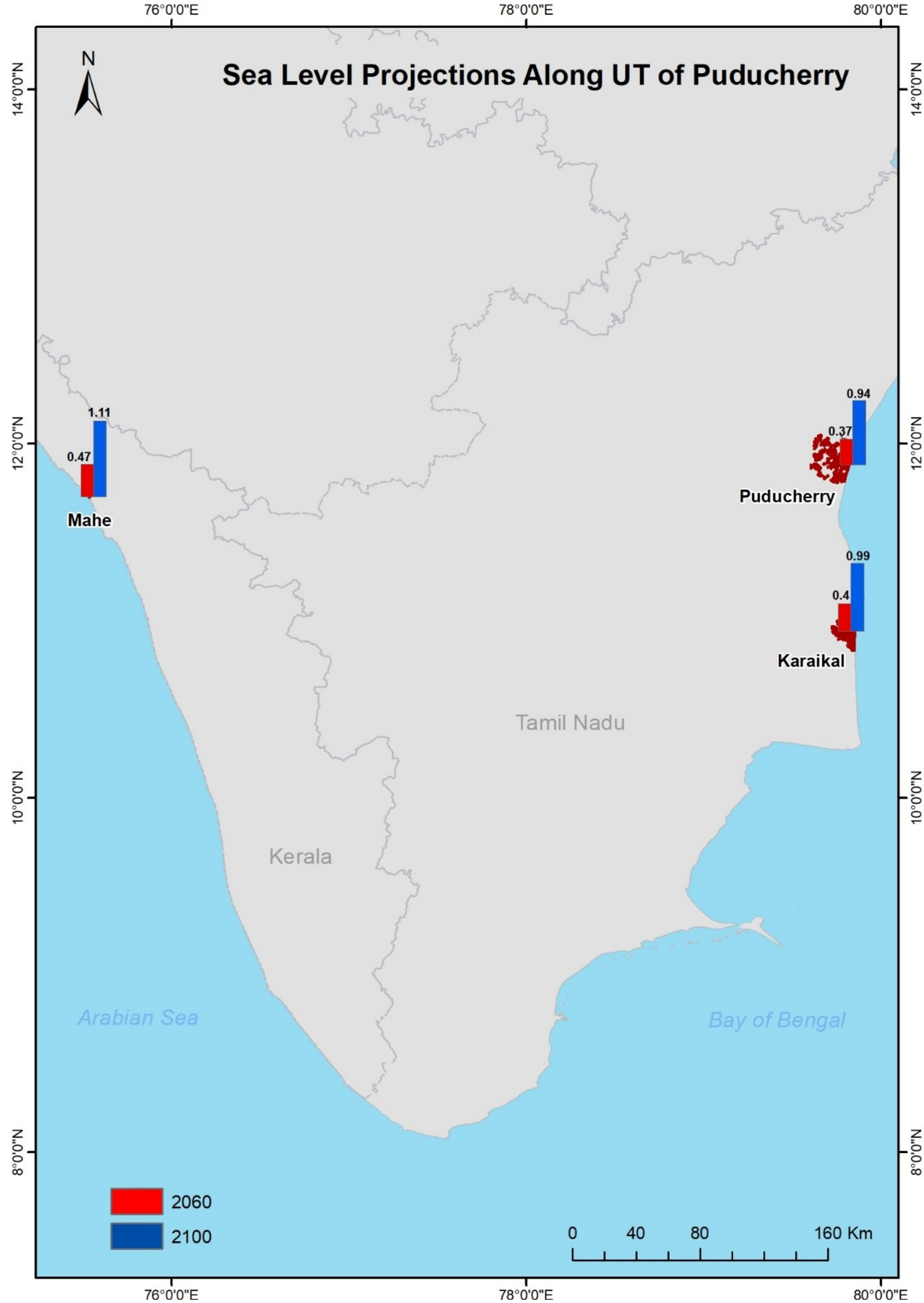
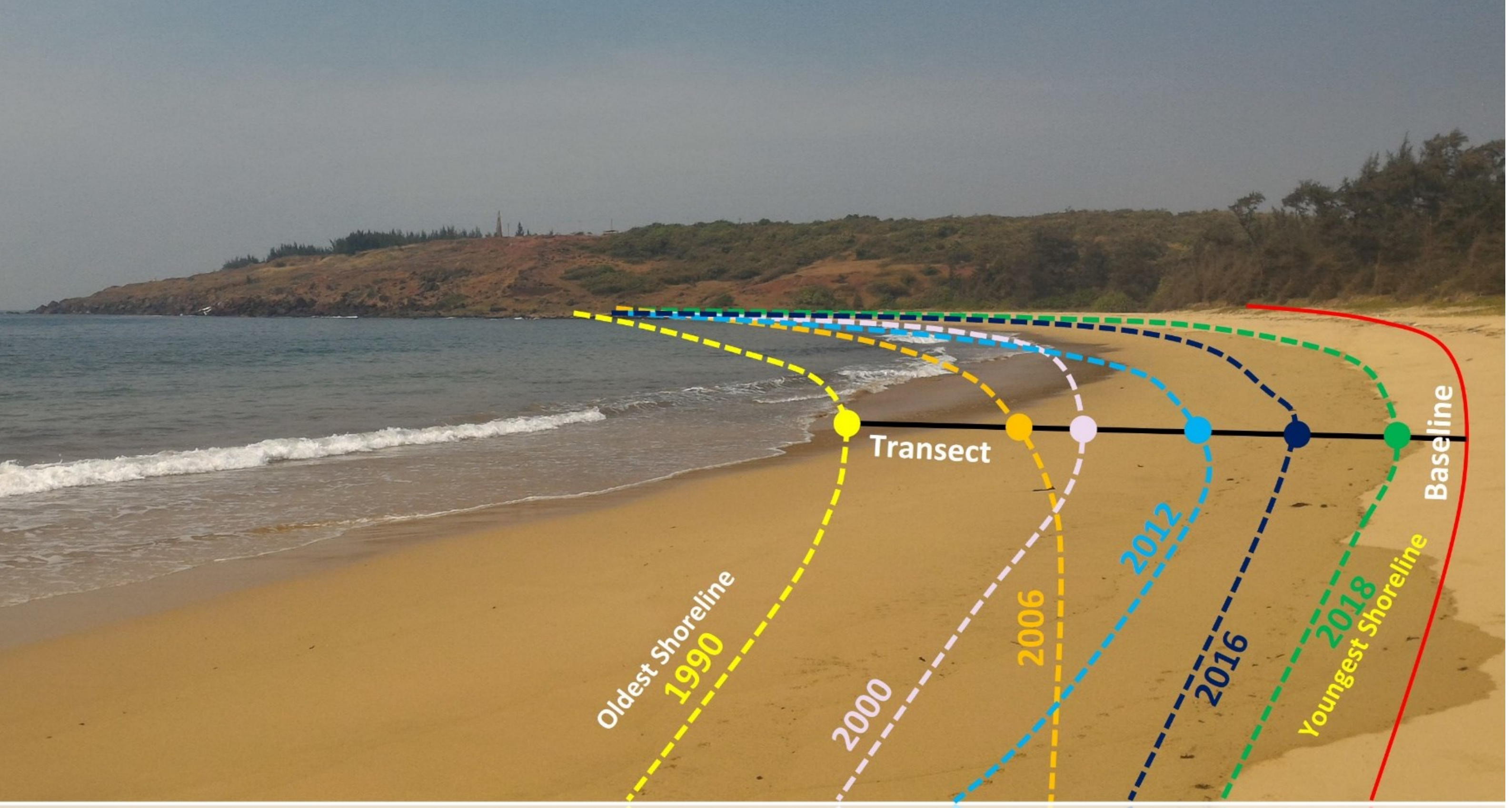


Figure 32 Sea level rise projections for UT of Puducherry coast under the RCP4.5 scenario using the Sea Level Rise and Vertical Land Movement app (http://slr.climsystems.com/)

Nearshore processes, including shoaling, refraction, breaking waves, and energy dissipation, shape coastal dynamics significantly. These processes are closely linked to variables like beach slope, angle of approach, and overall morphology, collectively dictating nearshore behavior. Wave breaking generates longshore currents that transport sediment along the coast, leading to continuous changes in bathymetry and affecting hydrodynamics and energy distribution. Climate dynamics, particularly in regions like Puducherry, with distinct SW and NE monsoon periods, bring varied rainfall patterns. Mahé, situated on the West coast, experiences notably higher rainfall compared to neighboring districts. Wind analysis reveals significant variations in speed and direction across coastal regions, influenced by monsoon patterns. Tidal analysis highlights variations in constituents, amplitudes, and frequencies, adding complexity to coastal dynamics. Seasonal changes in wave characteristics, such as significant wave height and direction, significantly influence coastal morphology. Coastal currents, influenced by tides, storm surge, and wave-generated forces, play a critical role in sediment transport and overall coastal processes. Bathymetric data provides insights into ocean floor topography, aiding navigation and coastal infrastructure planning. The looming threat of sea level rise, driven by factors like melting ice sheets, emphasizes the need for effective coastal management.

Oceanographic parameters play a key role in determining the appropriate coastal protection that a location can withstand. There is a net Northward flow, influencing the longshore sediment transport along the North direction for the coast during the monsoons. Cross-shore transport occurs during the extreme cyclonic events, in this coast. Consequently, oceanographic parameters play a crucial role in shaping the protection measures outlined in the SMP. This information is also instrumental in assessing the sediment budget.



5 SHORELINE CHANGE

Coastal evolution is the result of complex non-linear interaction between hydrodynamic, geomorphic, and anthropogenic processes at multiple time-scales. The day-to-day change in shoreline positions are considered as one of the major concerns for developmental activities such as ports, harbour, fishing jetties and embankment facilities. With the increasing trend of coastal population and rapid developmental activities along the shore, there is a need for prominent and precise information about the rate and trend of coastal erosion in the past and the present states. Therefore, a comprehensive analysis of shoreline change, which varies from one region to another, is necessary for the preparation of an appropriate management plan.

> **"Studying shoreline changes provides valuable insights into evolving landscapes and erosion-prone areas. This information is crucial for identifying priority areas and implementing sustainable management strategies, safeguarding and enhancing livelihoods of the coastal communities with minimal environmental impact**

Coastal erosion has emerged as a critical global concern in recent days due to climate change, with far-reaching environmental, social and economic implications. Its impact extends beyond specific sectors, significantly affecting economies on a broader scale. Consequences encompass the loss of land in short time, destruction of assets and diminished revenue potential, particularly coastal infrastructure.

India, in particular, faced a significant setback, losing about one-third of its coastline to erosion between 1990 and 2018 [1]. This alarming trend puts over 560 million people at risk in coastal areas. The economic toll is substantial, resulting in direct losses and damages to various properties, including coastal communities, fishing villages, beachfront residences and businesses. The rapid expansion of urban development along coastline escalates the risk, especially considering that 85% of the entire population resides in coastal states.

5.1 Shoreline Change and its Causes

The factor causing coastal erosion/accretion can be natural, artificial and combination of both.

(a) Natural causes

- **Action of Waves:** Waves are generated by offshore and near-shore winds, which blow over the sea surface and transfer their energy to water surface. As they move towards the shore, waves break and the turbulent energy released stirs up and moves the sediments deposited in seabed.
- **Winds:** Winds acts not just as a generator of waves but also as a factor of the landwards move of dunes (Aeolian erosion).
- **Tides:** Tides results in water elevation to the attraction of water masses by the moon and the sun. During high tides, the energy of the breaking waves is released higher on the foreshore.
- **Near-shore currents:** Sediments scoured from the seabed are transported away from their original location by currents. In turn the transport of (coarse) sediments defines the boundary of coastal sediment cells, i.e., relatively self-contained system within which (coarse) sediments stay. Currents are generated by the action of tides (ebb and flood currents), waves breaking at an oblique angle with the shore (long-shore currents), and the backwash of waves on the foreshore (rip currents). All these currents contribute to coastal erosion processes.
- **Storms:** Storms are formed by the raise in water levels (storm surge) and high energetic waves caused by extreme winds (Cyclones). Storm may result in catastrophic damages when it combines with high tides. These storms damage the coastal infrastructure. Due to the storm's waves, beaches and dunes get eroded to tenths of meters in a few hours.
- **Sea Level Rise:** In the past century, Sea level has risen about 40 cm and expected to rise another 60 cm in the next century (IPCC report 2007). Since from last ice age, sea level has risen nearly 110 meters. Due to global warming, an average rise of sea level is of the order of 1.5 to 10 mm per year. It has been observed that sea level rise of 1 mm per year could cause a recession of shoreline in the order of about 0.5 m per year.

(b) Anthropogenic causes

Human influence, particularly urbanization and economic activities, in the coastal zone has turned coastal erosion from a natural phenomenon into a problem of growing intensity. Anthropological effects that trigger beach erosion are: construction of artificial structures, mining of beach sand, offshore dredging, or building of dams or rivers. Human intervention can alter these natural processes through the following actions:

- dredging of tidal entrances
- construction of harbours in near shore
- construction of groynes and jetties
- river water regulation works
- hardening of shorelines with seawalls
- beach nourishment
- destruction of mangroves and other natural buffers
- mining or water extraction

5.2 Method of Shoreline Change Analysis

Historic shoreline position is considered as the major tool to understand the changes undertaken during different scenarios. Some of the methods for shoreline study includes the basic conventional field survey method, use of topographic maps, aerial photographs, and the latest remote sensing data. In the present scenario, remote sensing (satellite images) data has become more dependable dataset due to its availability (both present and past data), large spatial coverage, and availability of high spatial resolution images. Landsat, SPOT, Resourcesat-1 & 2, Cartosat-1, 2 and 3 (Panchromatic), IKONOS, Worldview and Quick Bird etc are some of the earth observation satellites available for change detection study.

For shoreline change analysis, multi-temporal satellite images of different periods were used as the primary dataset (Table 7). Satellite images of the years 1990 (Landsat-5 – thematic mapper I) and 2000 (Landsat-7 – Enhanced thematic mapper plus (ETM+)) are downloaded from the United States Geological Survey (USGS) web portal Earth Explorer (https://earthexplorer.usgs.gov). Similarly, satellite images for 2006 Cartosat-1 (PAN), 2008 (Resorucesat-1 – Linear Imagine Self Scanning Sensor (LISS-III)) and 2012–2024 (Resorucesat-2 – LISS-IV) were procured from the National Remote Sensing Centre (NRSC).

Table 7. Details of Satellite Data Used

List of Image	Pixel Size (m)	Date	Source
Landsat 5 TM	30.0	1989-1992	USGS
Landsat 7 ETM+	30.0	1999-2001	USGS
IRS P5 (Cartosat-1) PAN	2.5	2005-2006	NRSC
IRS P6 (Resourcesat-1) – (LISS-III)	23.5	2008	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2012	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2013	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2014	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2015	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2016	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2017	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2018	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2019	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2020	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2021	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2022	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2023	NRSC
Resourcesat 2 – (LISS-IV)	5.8	2024	NRSC

The satellite data should be cloud free and available probably during fair weather condition. Initially, all the satellite data should be projected to a common projection system. The satellite images used for the analysis were geo-rectified with Ground Control Points (GCP's) collected during field survey. Second-order polynomial transformation (Projection: UTM, Datum: WGS-84) was applied to all the satellite images. Different proxies such as wet-dry line, vegetative line, rocky coast edge, cliff edge, are used for shoreline extraction from all the satellite images.

Digital Shoreline Analysis System (DSAS) version 4.3 [13], which is an extension of ArcGIS software was used for shoreline calculation from different years. DSAS is a statistical tool, used for the time series dataset. For long-term shoreline change study, WLR (Weighted Linear Regression Rate) statistical method was adopted (Selvan et al, 2020). The results obtained from the analysis of shoreline changes are in the form of numbers i.e., ±m/yr., where + is for accretion, and – is for erosion. These quantitative results are plotted in Geographic Information System (GIS) environment and classified in to different classes considering the magnitude of changes. The shoreline changes rates are classified into seven classes (Table 8).

The analysed coastal length of Puducherry, which is a Union Territory, located along the Tamil Nadu coast is 43 km distributed along three (Puducherry, Karaikal and Mahé) coastal districts. Yanam is another district of Puducherry UT. However, this district does not share the coast and is located along the northern bank of Godavari River, Andhra Pradesh. The shoreline analysis suggests that 46% of coast is eroding, 11.1% is accreting and 42.8% is in stable state (Table 9). The district-wise shoreline change status are given in

Table 10 and Figure 33 to Figure 35 with seven different classes of erosion, accretion and stable in kilometres for Union Territory of Puducherry coast.

Table 8. Shoreline Classification Schemes Used in the Analysis

Classification	Rate (m/year)	Colour Schemes
High Erosion	< -5.0	
Moderate Erosion	-5.0 to -3	
Low Erosion	-3.0 to -0.5	
Stable Coast	-0.5 to 0.5	
Low Accretion	0.5 to 3.0	
Moderate Accretion	3.0 to 5.0	
High Accretion	> 5.0	

Table 9. Erosion and Accretion Percentage along UT of Puducherry

State 1990-2024	Status	(7 class) %	Length (in km)	(3 class) %	Length (in km)
Union Territory of Puducherry	High Erosion	0.0	0.00	46.0	19.7
	Moderate Erosion	0.1	0.06		
	Low Erosion	45.9	19.68		
	Stable	42.8	18.36	42.8	18.4
	Low Accretion	8.3	3.54	11.1	4.8
	Moderate Accretion	2.3	0.98		
	High Accretion	0.6	0.26		

Table 10. District-Wise Shoreline Status along UT of Puducherry

1990 - 2024 (Length in km)								
Region	**Coast Length**	**High Erosion**	**Moderate Erosion**	**Low Erosion**	**Stable**	**Low Accretion**	**Moderate Accretion**	**High Accretion**
Puducherry	23.50	0.00	0.00	4.3	16.56	2.1	0.54	0.00
Karaikal	18.16	0.02	0.06	15.0	1.66	0.84	0.4	0.2
Mahé	1.22	0	0	0.38	0.14	0.6	0.04	0.06
Total	**42.88**	**0.02**	**0.06**	**19.68**	**18.36**	**3.54**	**0.98**	**0.26**

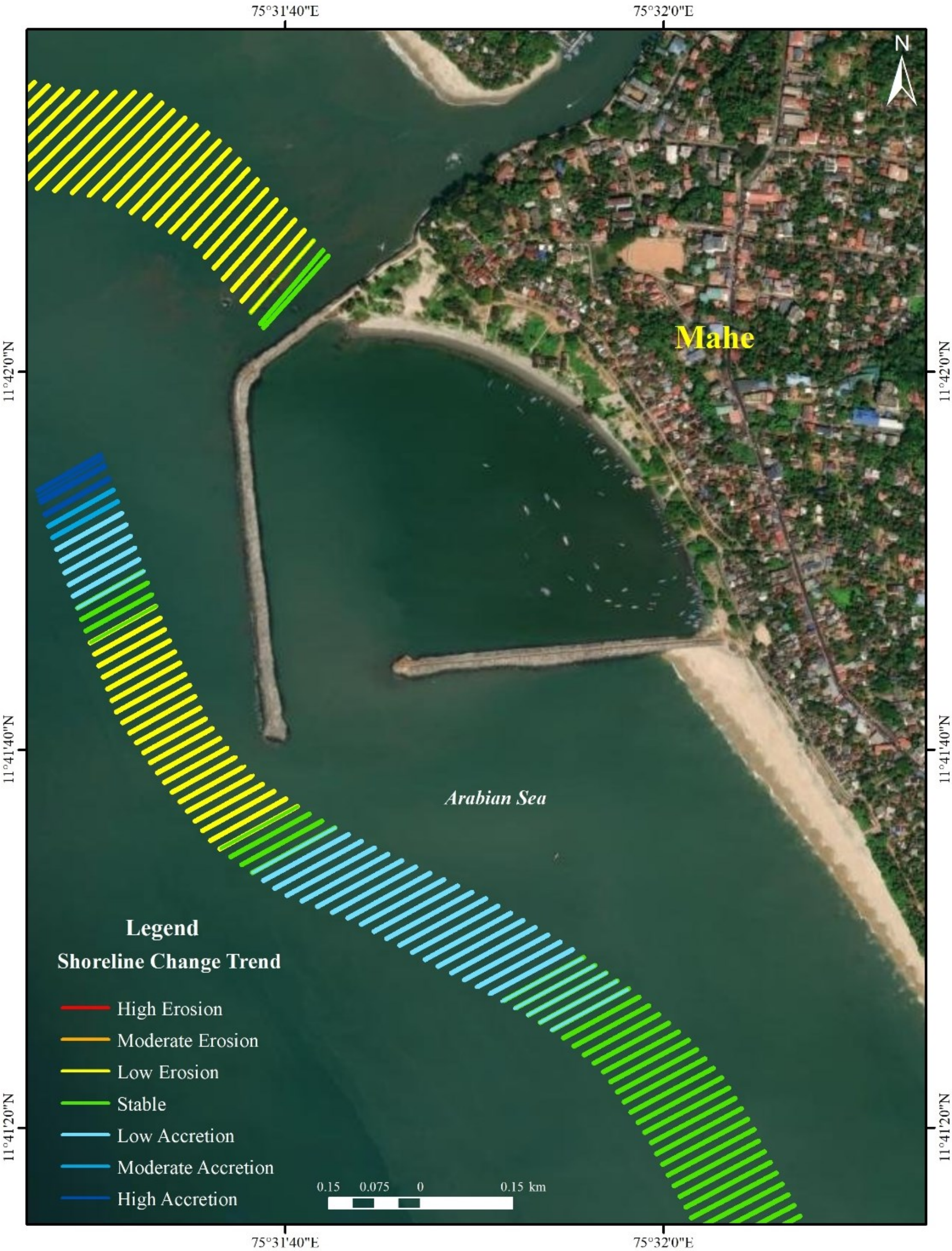


Figure 33. Shoreline Change Map of Mahé Coast (1990-2024)

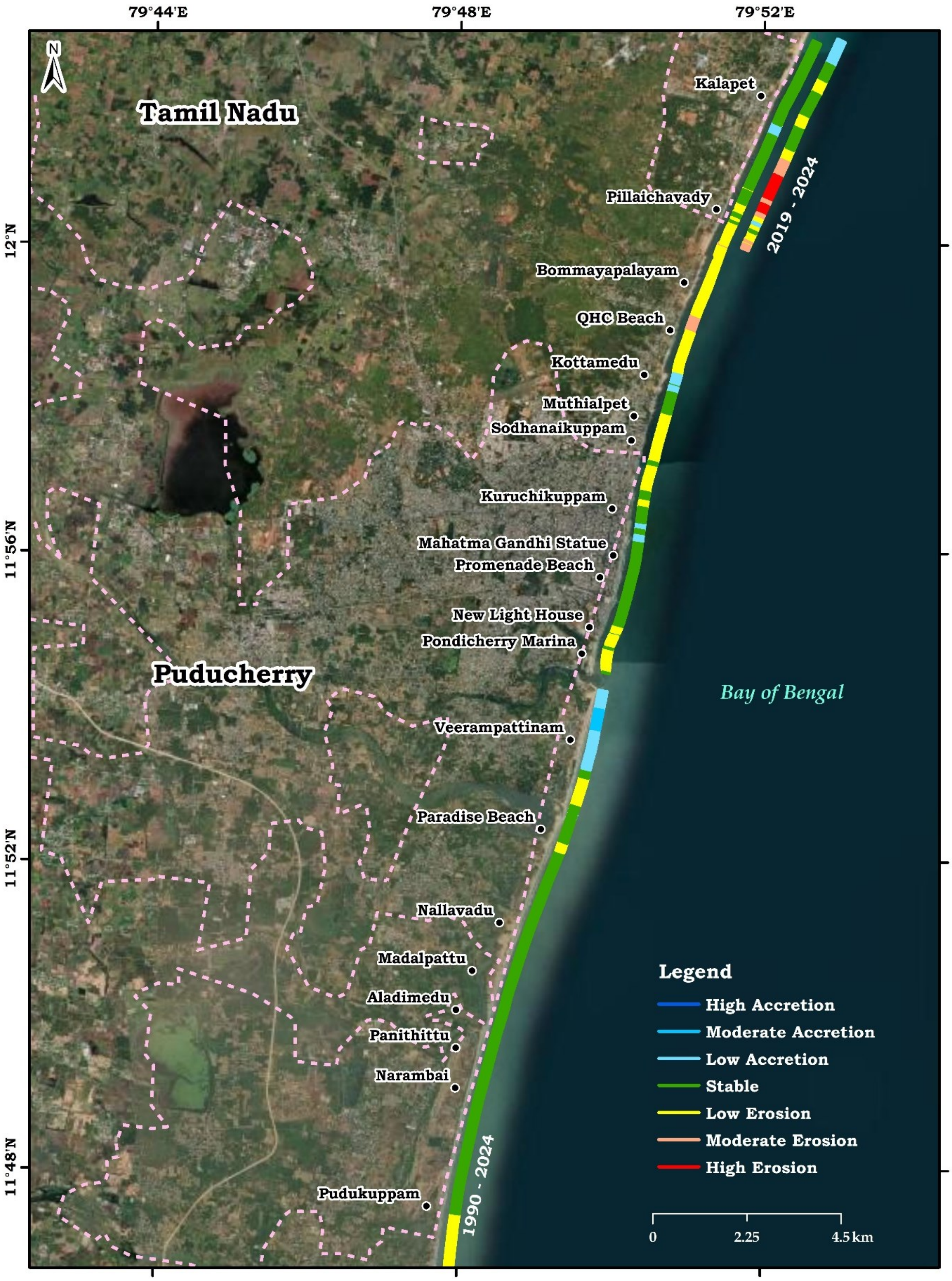


Figure 34. Shoreline Change Map of Puducherry Coast (1990-2024)

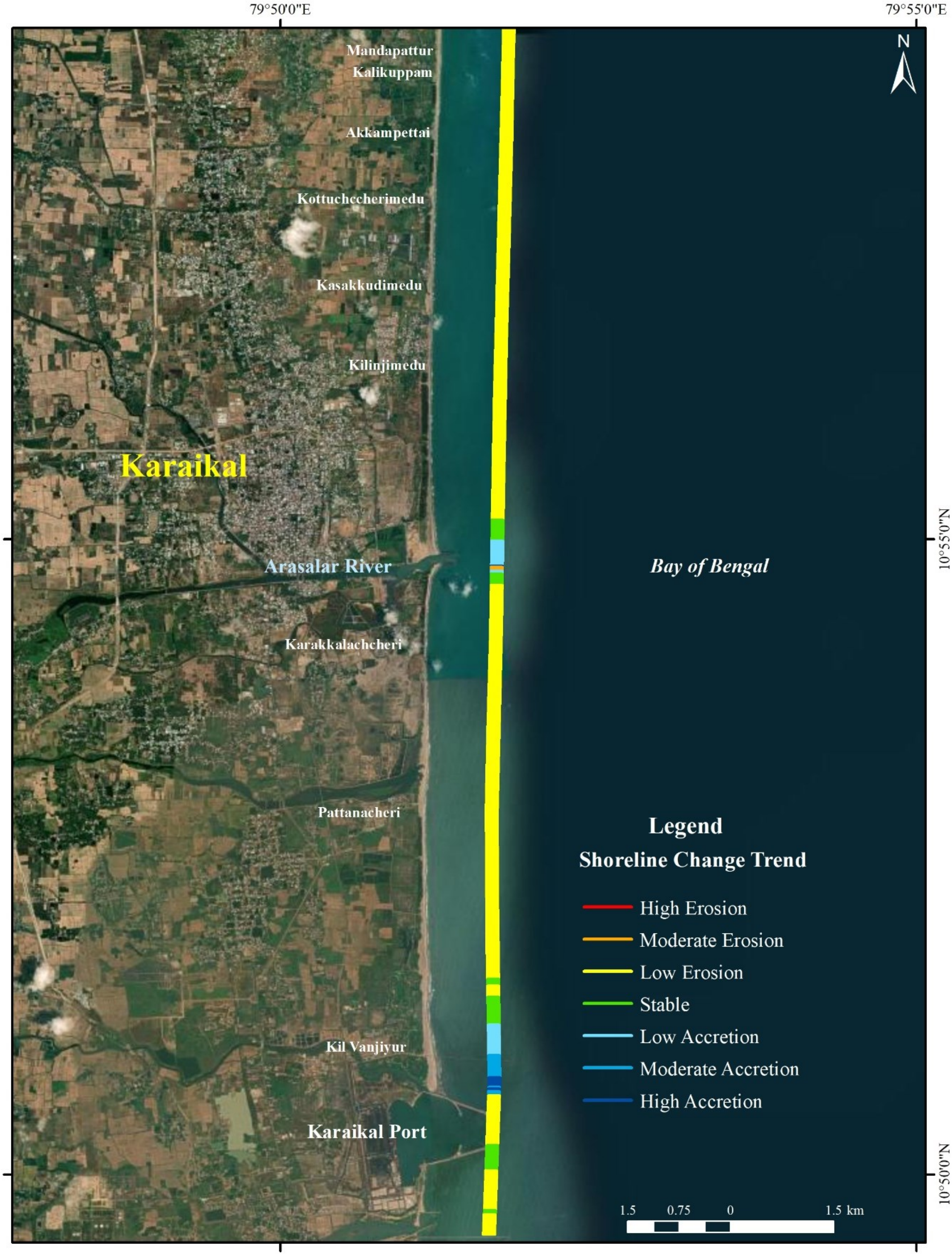


Figure 35. Shoreline Change Map of Karaikal Coast (1990-2024)

5.3 Erosion and Accretion Trends along the Coast

Erosion and accretion sites were depicted from the long-term shoreline change analysis for the period of 34 years (1990-2024) with about 43 km measured coastal length of Puducherry (UT). Satellite data were used to understand the spatial variation of the coast. Considering the magnitude of changes, the shoreline change rate is classified into 7 different classes (Table 8). This classification is categorised based on the rate of change results considering the shift in shoreline position.

The coastal environment needs to be managed and protected from shoreline erosion. The reason for erosion may vary from one regional setting to another. Hence, the coast is categorised into priority site, erosion monitoring site and accreting monitoring site based on the results obtained from long-term shoreline analysis.

From the long-term shoreline analysis, the coastal stretch with more than 1 km of continuous erosion was identified and categorised into different erosion classes. About 5 (2 – Tamil Nadu and 3 – UT of Puducherry) coastal stretches which constitute about 29 km were identified as erosion sites with different degrees of coastal erosion. The shoreline rate of more than -3m/yr is classified as a high erosion priority site that needs a suitable management plan. The field survey has been carried out in these priority locations to understand the present condition of the coast. Short-term shoreline analysis for a period of 5 years (2019-2024) was carried out for the Kalapet coastline based on the interaction with the local stakeholders. Based on the analysis, high erosion is observed for a length of about 3 km along the Kalapet coastline.

The range between -3.0 to -0.5 m/yr is categorised as monitoring erosion sites which need to be observed periodically. Annual field measurement needs to be undertaken for the monitoring erosion sites. However, if the monitoring erosion sites are located in highly developed zone, then the coastal stretch is reclassified as high priority erosion site and immediate action is required for better management. The priority sites as per shoreline change analysis is indicated in Table 11.

Table 11. Priority & Erosion Monitoring Sites along Puducherry & Adjoining Tamil Nadu Coast

Id	Coastal Stretch	District	Length (km)	Observation	Shoreline Change Status
1	Kalapet to Pillaichavadi	Pondicherry	3.0	High to Moderate erosion was noticed for about 1.6 km and Low erosion is observed in for 1.4 km in the short term shoreline analysis. This coast is mainly affected due to the impact of grions in Bommayapalayam, which is loacted south of Pillaichavadi.	High Erosion (short-term shoreline analysis)
2	Pillaichavadi to Serenity Beach	Villupuram, Tamil Nadu	4.5	Low erosion was noticed for about 4.5 km from Pillaichavadi to Serenity Beach. This region is located North of Puducherry. This is one of the tourism spots along the coastal stretch. Auroville beach and Serenity beach were located along this coastal stretch. Series of groins (6 nos) and seawall were noticed along the coastal stretch. Moderate erosion was observed along the Periya Muthalayar Chavadi coast. This coastal stretch is much significant due to the presence of coastal villages and tourism spots near to the coast.	Low Erosion
3	Kottakuppam to Kuruchikuppam	Villupuram (TN), and Puducherry	2.3	Low erosion was noticed for about 2.3 km from Kottakuppam to Kuruchikuppam coastal stretch. Apart from Kottakuppam, the entire	Low Erosion

				coast is protected with seawall. 4 numbers of groins were noticed along the stretch. This coastal stretch is much significant due to the presence of coastal villages near to the coast.	
4	Dubrayapet (Light House to Northern breakwater of Puducherry Port)	Puducherry	1.2	Low erosion was noticed for about 1.2 km from Light house to northern breakwater. Entire coastal stretch was cover with seawall. A small opening was noticed along the Pondi Marina.	Low Erosion
5	Paradise Beach	Puducherry	1.0	Low erosion was noticed for about 1.0 km on either side of Paradise beach. Chunnambar River is located exact south of the location.	Low Erosion
6	Mandapathur Beach to North of Karaikal Port	Karaikal	17	The entire coastal stretch of about 17 km was noticed with low erosion. This coastal stretch is much significant due to the presence of coastal villages near to the coast. Small stretch of sandy beach north of Karaikal port was noticed along coast.	Low Erosion

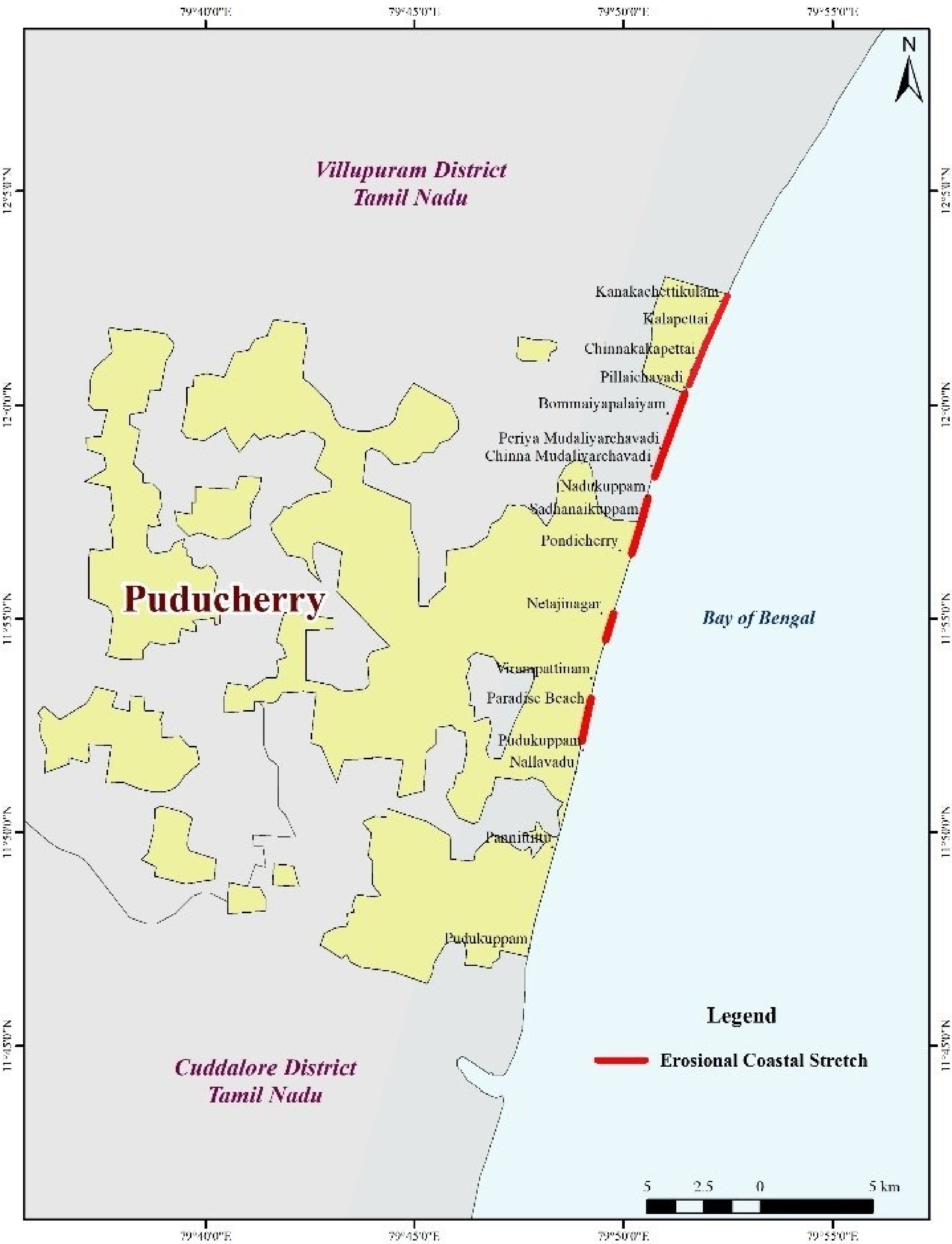


Figure 36 Erosion hotspots as per Shoreline Change Analysis of Puducherry

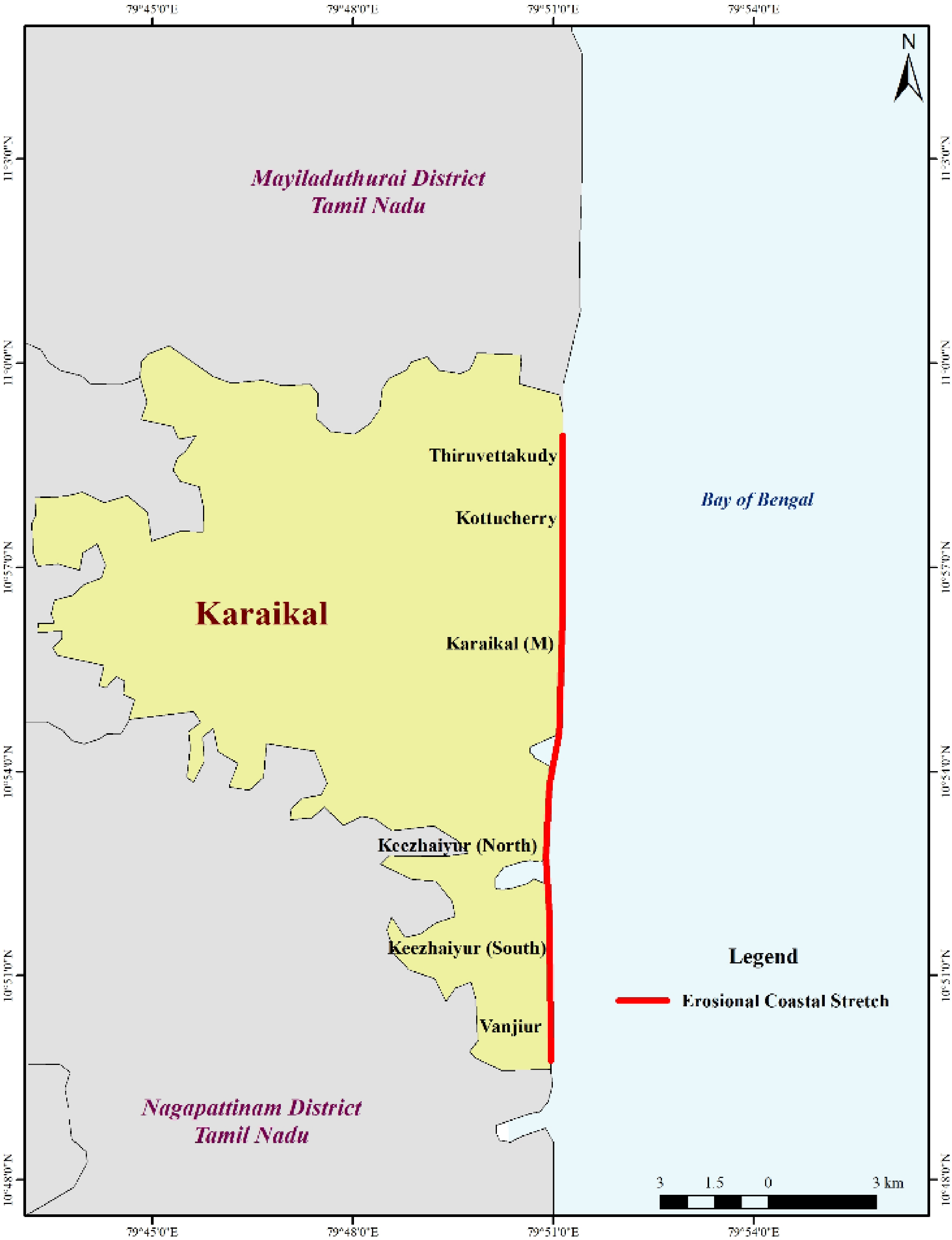


Figure 37 Erosion hotspots as per Shoreline Change Analysis of Karaikal

The extensive 34-year shoreline analysis of the 43 km coastal stretch of Puducherry (UT) and adjoining Tamil Nadu revealed critical findings. Utilizing satellite data, erosion and accretion sites were pinpointed, unveiling significant shifts in shoreline position. Classification into seven distinct shoreline change rate classes improved understanding of spatial variations, aiding targeted management strategies. Priority sites for erosion management were identified based on severity, underscoring coastal environmental protection's importance. Areas with continuous erosion exceeding 1 km were categorized, with high priority sites experiencing rates over -3m/yr, demanding urgent intervention. Monitoring erosion sites, with rates from -3.0 to -0.5 m/yr, required regular field measurements, with potential reclassification in highly developed zones. Detailed assessments of specific coastal stretches outlined erosion levels, protective structure presence, and geographical significance. Notably, areas with low erosion levels indicated stable conditions, attributed to protective structures and geographical features. Overall, the study highlights the crucial role of long-term shoreline analysis in understanding coastal dynamics and devising effective strategies for safeguarding coastal environments and communities.

Recognizing the gravity of this vulnerability and quantifying the erosion rates emerge as pivotal parameters in the strategic planning of a Shoreline Management Plan. By aligning protective measures with the specific needs of the most vulnerable areas, this detailed analysis forms the foundation for developing an effective and targeted plan to safeguard the coastline from the impacts of erosion.

6 SOCIO-ECONOMIC STATUS

The geographical area of Union Territory of Puducherry is about 490 sq. km. The U.T of Puducherry consists of two revenue districts viz., Puducherry District comprising of Puducherry, Mahé and Yanam regions and Karaikal District comprising of Karaikal region. Puducherry and Karaikal Districts are located on the East coast of Tamil Nadu, while Yanam is located along Andhra Pradesh. Whereas, Mahé District is located along the Kerala state. Puducherry and Karaikal regions are classified into both urban and rural areas, whereas entire Mahé and Yanam regions are classified as urban area. Puducherry is the 29th most populous and the third most densely populated State/UT in India. The U.T of Puducherry is categorised with 5 Municipalities, 10 Commune Panchayats, 8 Taluks and 3 Community Development Blocks. The per Capita income for the year 2020-21 and 2021-22 has been estimated to be Rs.2,15,583 and Rs.2,16,495 respectively. The literacy rate of the U.T. of Puducherry as per 2011 Census is 85.9 %. About 55.38 sq km of area of UT of Puducherry is covered under forest. This is about 9.14 % of its total geographical area of UT of Puducherry. The coastline of about Puducherry Union Territory (excluding Yanam) is 45 km as per Survey of India.

"Union Territory of Puducherry has 2 coastal districts. Population density-based prioritization of protective measures informs the Shoreline Management Plan to prioritize densely populated coastal regions

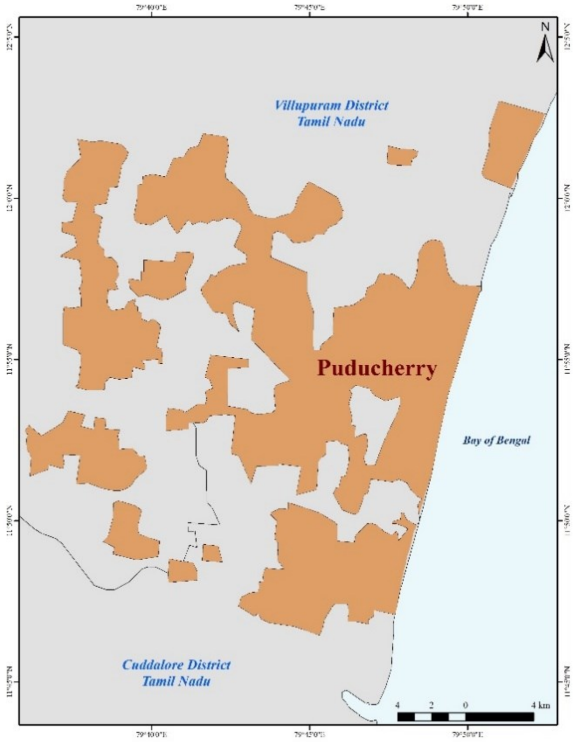
6.1 Demography

The Union Territory of Puducherry includes Puducherry, Karaikal, Mahé, and Yanam regions (Figure 38). As per 2011 Census, total population of the U.T is 12,47,953 (Puducherry – 9,50,289, Karaikal – 2,00,222, Mahé – 41,816 and Yanam – 55,626). There are 129 Revenue villages (Puducherry -81, Karaikal -37, Mahé -5 and Yanam -6). The total aerial coverage of Puducherry district is 294 sq kms. Karaikal District covers an area of 157 sq. km. Mahé which is on West coast covers an area of 9 sq km. Yanam district is located away from the coast along Andhra Pradesh, which bifurcates Coringa from Godavari River and it covers an area of 30 sq km. The population density was calculated using the 2011 census [14]. Puducherry district is the largest district in Puducherry UT. It covers an area of 294 sq.km. This is followed with Karaikal with 2,00,222. Yanam region which is located along the Godavari River Northern bank has the least population with 55,626 individuals.

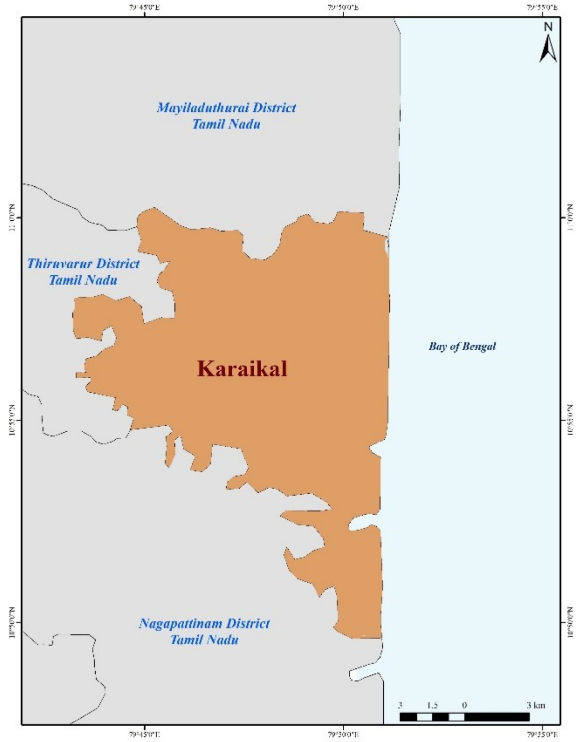
Table 12. Population Details for Union Territory of Puducherry

No.	Region	Population (Lakhs)	Area (sq.km)	Density (Per sq.km)
1	Puducherry	950289	294	3232
2	Karaikal	200222	157	1275
3	Mahé	41816	09	4646
4	Yanam	55626	30	1854

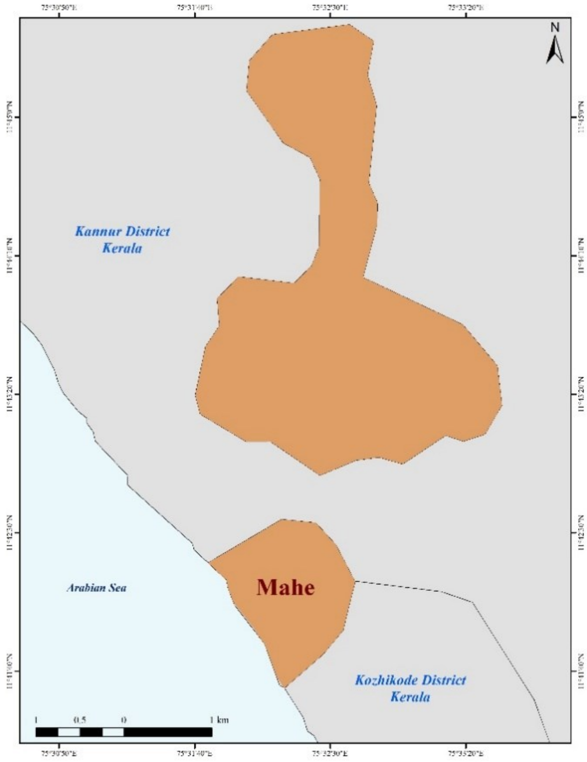
The total population density of Union Territory of Puducherry is 2547 per sq. km as per the census of 2011 [15]. The overall population of each coastal districts were shown in Table 12. Puducherry is the most populous district with 9,50,289 lakhs individuals. However, it covers large area with 294 sq.km. Mahé (09 sq.km.) and Yanam (30 sq.km.) has least aerial coverage. Mahé coastal district has the highest population density of 4,646 per sq.km. More population has occupied this coastal district where the aerial coverage is less and hence making the district has highly populous.



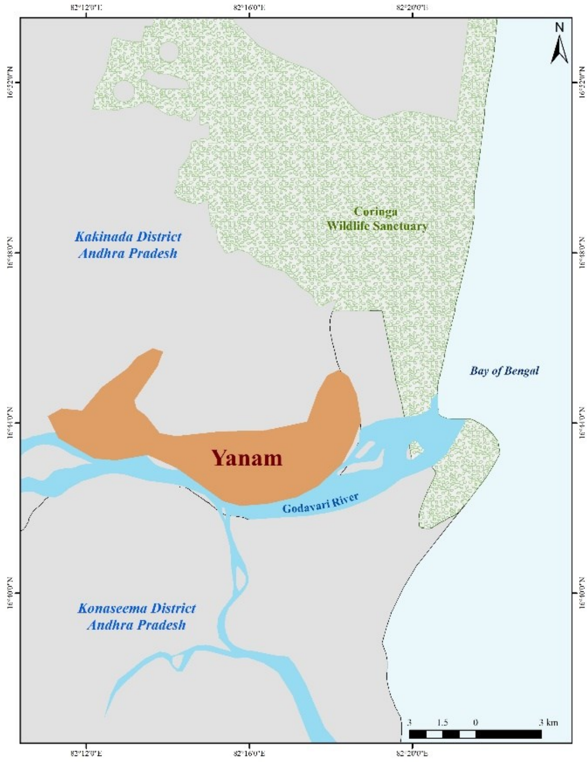
Puducherry Region



Karaikal Region



Mahé Region



Yanam Region

Figure 38. Regions Covering the Union Territory of Puducherry

6.2 Population Density

(a) Puducherry

Puducherry has 9 coastal revenue villages. The total population of all 9 coastal revenue villages is 6,28,762 individuals. The coast is covered with two municipalities namely Ozhukarai and Pondicherry. It also covered with two census town (CT) along the coast. The aerial coverage of Ozhukarai (M) is about 29.3 sq.km. which is higher than all other coastal revenue villages of Puducherry district. Ariyankuppam (CT) coastal villages has 3.3 sq.km. aerial coverage which is least among all coastal revenue villages. The total population for all Puducherry coastal villages is shown in Table 13.

Table 13. Details of Coastal Revenue Villages in Puducherry

Village Name	Total Population	Area (sq.km)	Population Density (Per sq.km)
Kilpudupatti	8372	4.5	1879
Ozhukarai (M)	300104	29.3	10228
Puducherry (M)	244377	19.3	12630
Ariyankuppam (CT)	29808	3.3	9069
Manaveli (CT)	15666	3.8	4090
Pooranankuppam	6766	3.4	1991
Kirumampakkam	10133	4.0	2553
Pillaiyarkuppam	5309	5.8	917
Manapet	8227	6.3	1297

Ozhukarai (M) has the highest individual populations of 3,00,104 followed by Pondicherry (M) with 2,44,377 individuals. Highest population density was recorded along Pondicherry (M) which is about 12,630 per sq.km. Higher numbers of population are concentrated in smaller area due to which the population density is higher along Pondicherry (M). This is followed by Ozhukarai (M) with 10,228 per sq.km. Pillaiyarkuppam coastal village has the least population density of 917 per sq.km. The population density of all coastal villages along Puducherry district is shown in Table 13 and Figure 39.

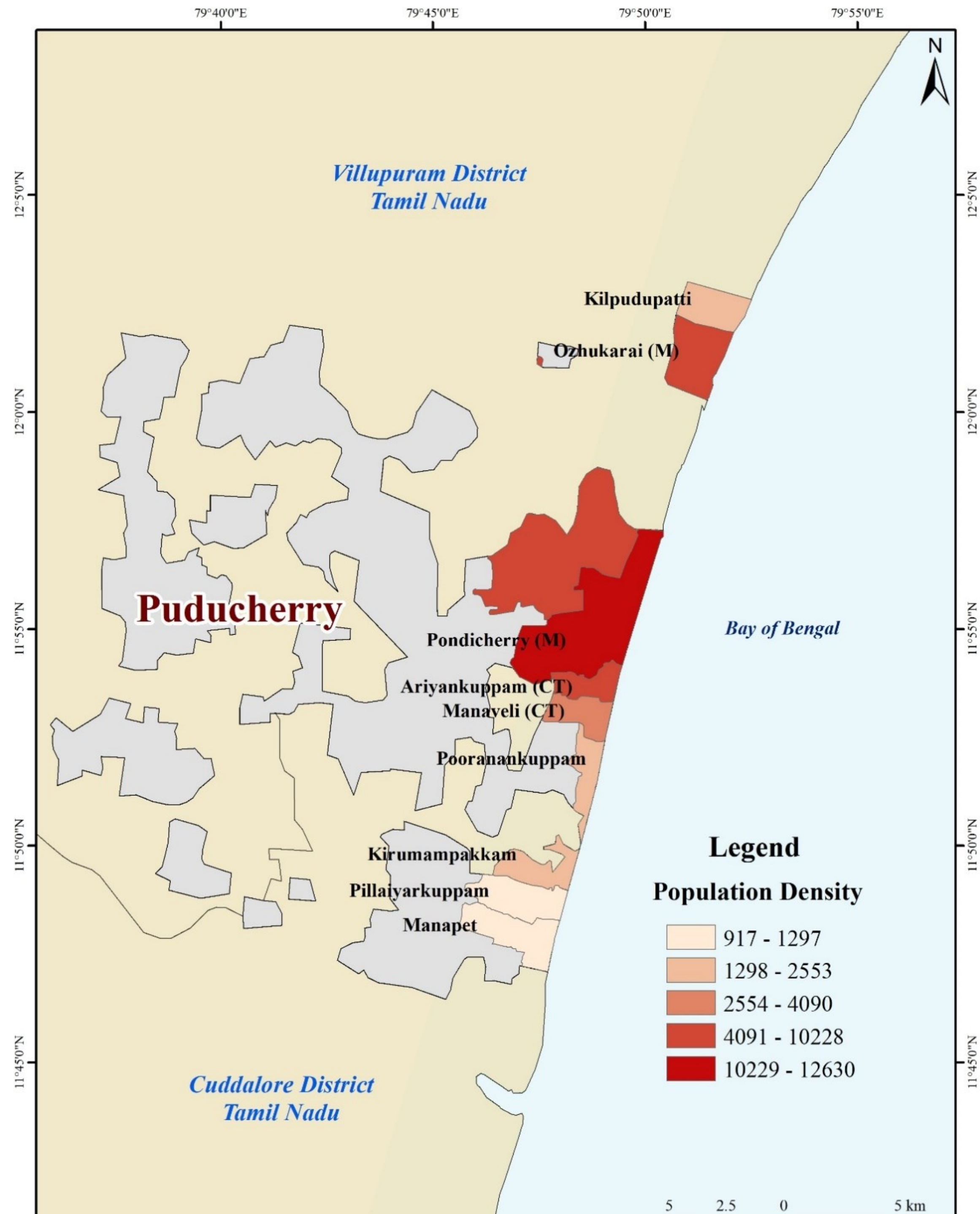


Figure 39. Population Density of Puducherry Coastal Revenue Village

(b) Karaikal

Karaikal has 6 coastal revenue villages. The total population of all 6 coastal revenue villages is 1,09,013 individuals. The coast is covered with one Municipality namely Karaikal (M). The aerial coverage of Karaikal (M) is about 33.6 sq.km which is higher than all other coastal revenue villages of Karaikal district. Keezhaiyur (South) coastal villages has 4.0 sq.km aerial coverage which is least among all coastal revenue villages. The total population for all Puducherry coastal villages is shown in Table 14.

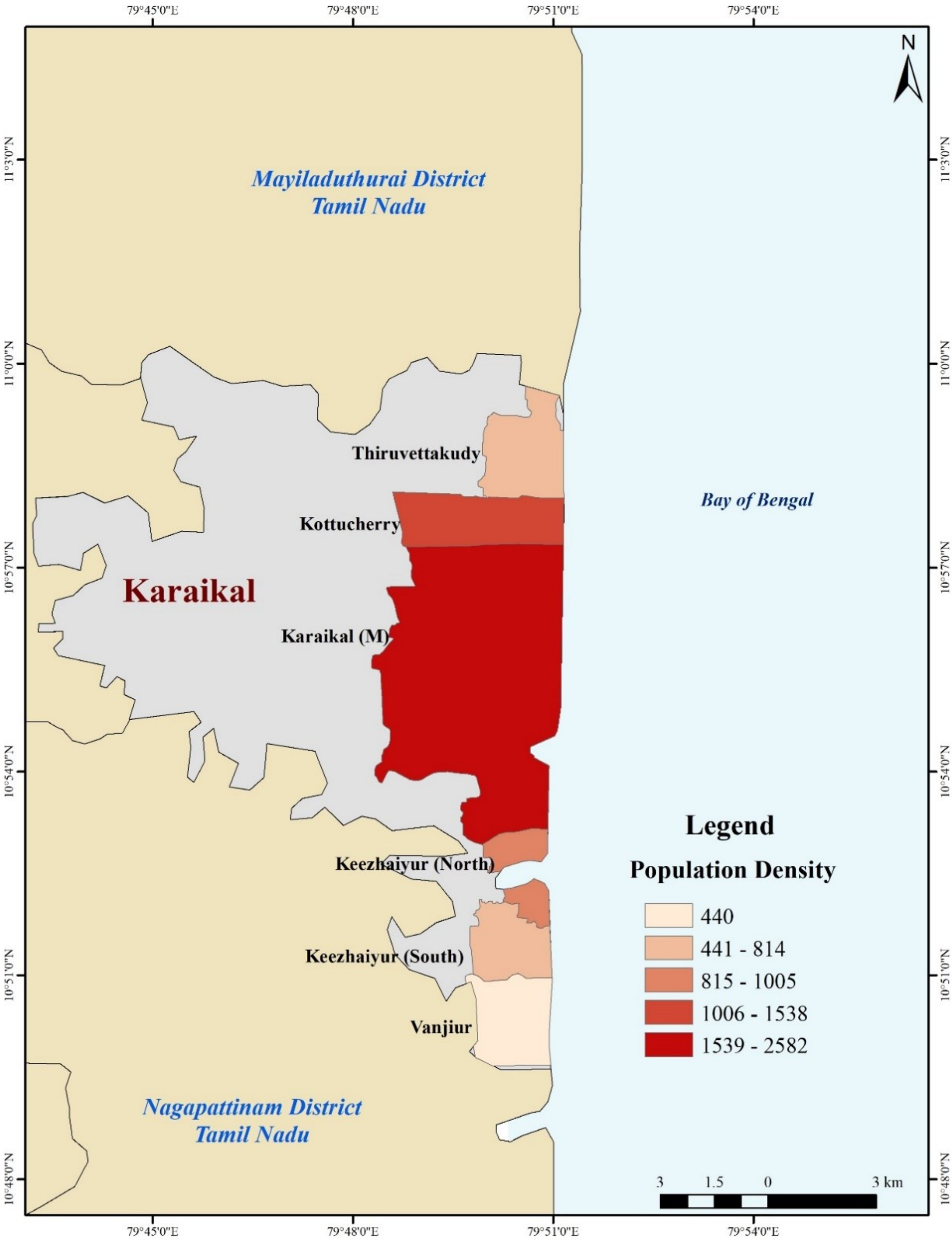


Figure 40. Population Density of Karaikal Coastal Revenue Village

Karaikal (M) has the highest individual populations of 86,838 followed by Kottucherry with 9,711 individuals. Highest population density was recorded along Karaikal (M) which is about 2,581 per sq.km. This is followed by Kottucherry with 1,538 per sq.km. Vanjiur coastal village has the least population density of 440 per sq.km. The population density of all coastal villages along Puducherry district is shown in Table 14 and Figure 40.

Table 14. Details of Coastal Revenue Villages in Karaikal

Village Name	Total Population	Area (sq.km)	Population Density (Per sq.km)
Thiruvettakudy	4281	5.5	771
Kottucherry	9711	6.3	1538
Karaikal (M)	86838	33.6	2581
Keezhaiyur (North)	2687	2.7	1005
Keezhaiyur (South)	3262	4.0	814
Vanjur	2234	5.1	440

(c) Mahé

Mahé is located on the Western coast of India, has 5 revenue villages. They are Mahé, Pandakkal, Chalakara, Palloor and Kallayi. Out of all 5 revenue villages, Mahé is the only revenue village which occupies the coast. The overall population of Mahé (M) as per 2011 census is 41,816 individuals and it covers an area of 9 sq.km. The population density of Mahé (M) is 4,646 per sq.km.

(d) Yanam

Yanam is located on the northern side of Godavari river bank in Andhra Pradesh, East coast of India. Yanam has 6 revenue villages. They are Yanam (M), Mettakur, Kanakalapeta, Francitippah, Adivipolam and Iskitippah. The overall population of Yanam (M) as per 2011 census is 55,626 individuals and it covers an area of 30 sq.km. The population density of Yanam (M) is 1,854 per sq.km.

The analysis of population data from the Union Territory of Puducherry reveals a nuanced picture of population distribution and density across its regions. Puducherry district emerges as the most populous, followed by Karaikal, Mahé, and Yanam. However, the disparity in population density becomes apparent when considering the area each district covers. Despite being the most populous, Puducherry district's larger area somewhat disperses its population density. In contrast, Mahé stands out with the highest population density among all regions, boasting 4,646 individuals per square kilometer despite its small aerial coverage of only 9 square kilometers. Coastal regions, such as Ozhukarai and Pondicherry in Puducherry district, and

Karaikal municipality in Karaikal district, exhibit significantly higher population densities compared to inland villages. This trend underscores the influence of coastal areas on population density. Furthermore, there's a noticeable inverse relationship between aerial coverage and population density, particularly evident in Mahé, where despite its limited size, it accommodates a substantial population, contributing to its high population density. These findings underscore the complex interplay between geographical factors, urbanization, and population distribution within the Union Territory of Puducherry, emphasizing the need for tailored development strategies to address the diverse needs of its regions.

Despite erosion being observed along extensive stretches of the coast, The choice of management strategy depends on the population density and infrastructure along the coast. Priority is accorded to regions with higher population density, as implementing protective measures in such areas would impact a larger portion of the population. This prioritization is considered in formulating the Shoreline Management Plan for the entire coastal area.

Pondy Marina

7 COASTAL INFRASTRUCTURE

Coastal areas are dynamic regions, that undergo continuous changes influenced by both natural and anthropogenic factors. The construction of coastal infrastructures and developmental activities leads to the alterations in the erosion and accretion patterns of the coast, and significantly impacting the local coastal communities. Assessing the current status of coastal structures is crucial for developing a sustainable shoreline management plan. Therefore, an extensive field survey of coastal structures along Puducherry has been undertaken to understand their existing structural and functional status. This data inventory is essential for the development of a comprehensive shoreline management plan, providing a scientific basis for decision-making by stakeholders and policymakers.

> **"Understanding impact of coastal infrastructures on coastal processes is crucial for mitigation and reduction of the efforts. Assessing the functional & structural performance of existing interventions will help in selection of sustainable management strategies as part of the Shoreline Management Plan**

The survey was specifically focused on validating and mapping the status of coastal protection structures and coastal infrastructure of Puducherry. The collected data contributes a deeper understanding of coastal processes and aided in developing effective measures to mitigate coastal erosion. The detailed geodatabase of coastal structures resulting from this survey was invaluable in identifying hotspots and guiding sustainable development and conservation efforts in the coastal zone.

The mapped coastal structures, encompassing protective elements such as seawalls and groins, as well as key infrastructure like ports and fishing harbours using the recent satellite images were validated during the field survey conducted from 5th July 2023 to 5th August 2023 by the team of NCCR, Chennai along with on-field support from Department of Science, Technology and Environment (DSTE), Puducherry.

Validation of the mapped coastal infrastructures was conducted in the field survey using handheld GPS (Garmin eTrex® 32X, Trimble Juno 3B, and Trimble Juno 3D) with accuracy of < ±5 meters to record the GPS locations of the structures. Additionally, various attributes, such as the dimensions (height and width) and condition of structures (whether intact or collapsed), were recorded using 'KOBO', a web-based application. These structures were further geo-tagged with field photographs to compile a comprehensive geodatabase. The information gathered from the field has been utilized to meticulously craft a comprehensive geodatabase for coastal structures using ArcGIS software. Additionally, the layout maps for individual districts have been generated by employing the service on the ArcGIS platform.

The overall measured coastal stretch in Puducherry spans about 43 km (including Puducherry, Karikal and Mahé), with 5 km covered by coastal protection structures and an additional 3 kilometres occupied by coastal infrastructure, primarily from the ports and fishing harbour. The details of the coastal length of Puducherry coast covered by artificial structures are shown in Table 15.

In Puducherry UT coast, groins, Jetties, artificial reef and Pier is observed in total of 5 locations. The details of artificial structures are tabulated in Table 16. Total of 3 ports, one in Puducherry and two in Karaikal and 3 fishing harbours are observed in each district of Puducherry, Karaikal and Mahé were operation. The details of ports and fishing harbour along the UTP are tabulated Table 17 and Table 18 respectively. Overall, in Puducherry UT, 5 km of the coast is covered by coastal protection structures and an additional 3 kilometres is occupied by coastal infrastructure, primarily from the ports and fishing harbour. 18% of Puducherry UT coastline is covered by coastal infrastructures (Figure 41).

Table 15. Coastal Length Covered with Artificial Structures along Puducherry Union Territory

No.	Region	Coastal Length (km)	Coastal length with Artificial Structures* (km)	Coastal length with Artificial Structures# (km)	Coastal length with artificial structures (%)
1	Puducherry	24	5	0.5	22
2	Karaikal	18	0.01	3.3	10
3	Mahé	1.2	0.3	1	100
Total		43	5	4.3	20

Table 16. Artificial Structures along Puducherry Union Territory

No.	Region	Coastal Length (km)	Number of structures*	Number of structures#
1	Puducherry	24	4	16
2	Karaikal	18	1	10
3	Mahé	1.2	-	1
	Total	43	5	27

** Seawall/Groyne/Jetty # Port/Fishing Harbour/FLP*

7.1 Ports and Fishing Harbours

In the UT of Puducherry, a total of 3 ports one in Puducherry and two in Karaikal, and a total of 3 fishing harbours Puducherry, Karaikal and Mahé are in operation. The details of ports and fishing harbour along the UTP are tabulated Table 17 and

Table 18 respectively.

Table 17. Major/Minor Ports along Puducherry Coast

No.	Region	Major/Minor Ports
1	Puducherry	Puducherry Port
2	Karaikal	Karaikal Port
3	Karaikal	Captive Marine Terminal Facility of M/s Chemplast Sanmar

Table 18. Fishing Harbours along Puducherry Coast

No.	Region	Fishing Harbours
1	Puducherry	Puducherry
2	Karaikal	Karaikal
3	Mahé	Mahé

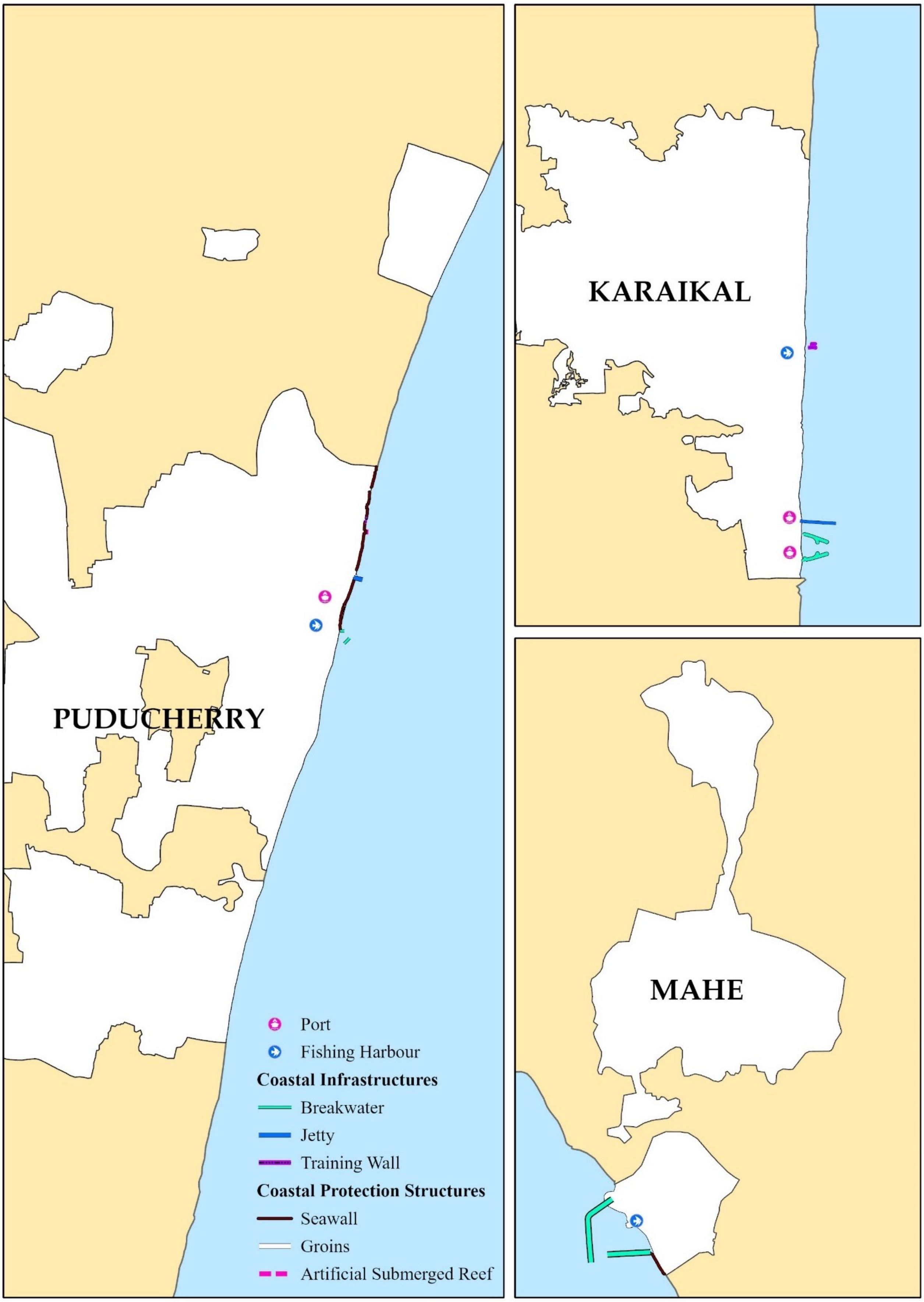


Figure 41. Coastal Structures along Puducherry Coast

7.2 Fish landing points

In the Union Territory of Puducherry, a total of 22 fish landing points (FLP) are available, out of which 14 are in Puducherry and 8 are in Karaikal. The details of fish landing points are tabulated in Table 19.

Table 19. Fish landing point along Puducherry Coast

No.	Region	Fish landing point
1	Puducherry	Chinna Kalapet
2		Periya Kalapet
3		Kanagachettikulam
4		Nallavadu
5		Narambai
6		Panithittu
7		Veerampattinam
8		Pillaichavady
9		Solai Nagar
10		Vaithikuppam
11		Moorthikuppam
12		Pudukuppam
13		Chinna Veeranpattinam
14		Kurusukuppam
15	Karaikal	Akkampettai
16		Kaalaikuppam
17		Karaikalmedu
18		Keela Kasakudamedu
19		Kilinjalmedu
20		Kottuacherrymedu
21		Mandapathur
22		Pattinancherry South

7.3 Impact of Port on Coast

A long-term satellite analysis of the Puducherry beach was conducted to assess the impact of a port on the shoreline. Puducherry once boasted pristine white beaches and was a major tourist hub, attracting visitors worldwide due to its heritage and cultural significance. However, shoreline erosion began after the construction of breakwaters for the Puducherry Port.

Initial efforts to mitigate downdrift erosion through sand bypassing were discontinued, exacerbating the erosion. To protect coastal infrastructure, the Puducherry government constructed a seawall along the coast.

This erosion then extended northward into the state of Tamil Nadu, affecting Kotakuppam beach, where seawalls were also implemented. This led to severe erosion Along Quiet Healing Centre which affected the village of Chinna Mudaliyar Chavadi were seawalls were constructred to protect the village. This, in turn, caused downdrift erosion affecting Bommayapalayam. To protect Bommayapalayam, a series of groynes were built, shifting the erosion problem to the northern village of Pillaichavady in Puducherry. These examples illustrate that short-term hard solutions protect the immediate coast but increase downdrift erosion in adjacent areas, as shown in Figure 42.

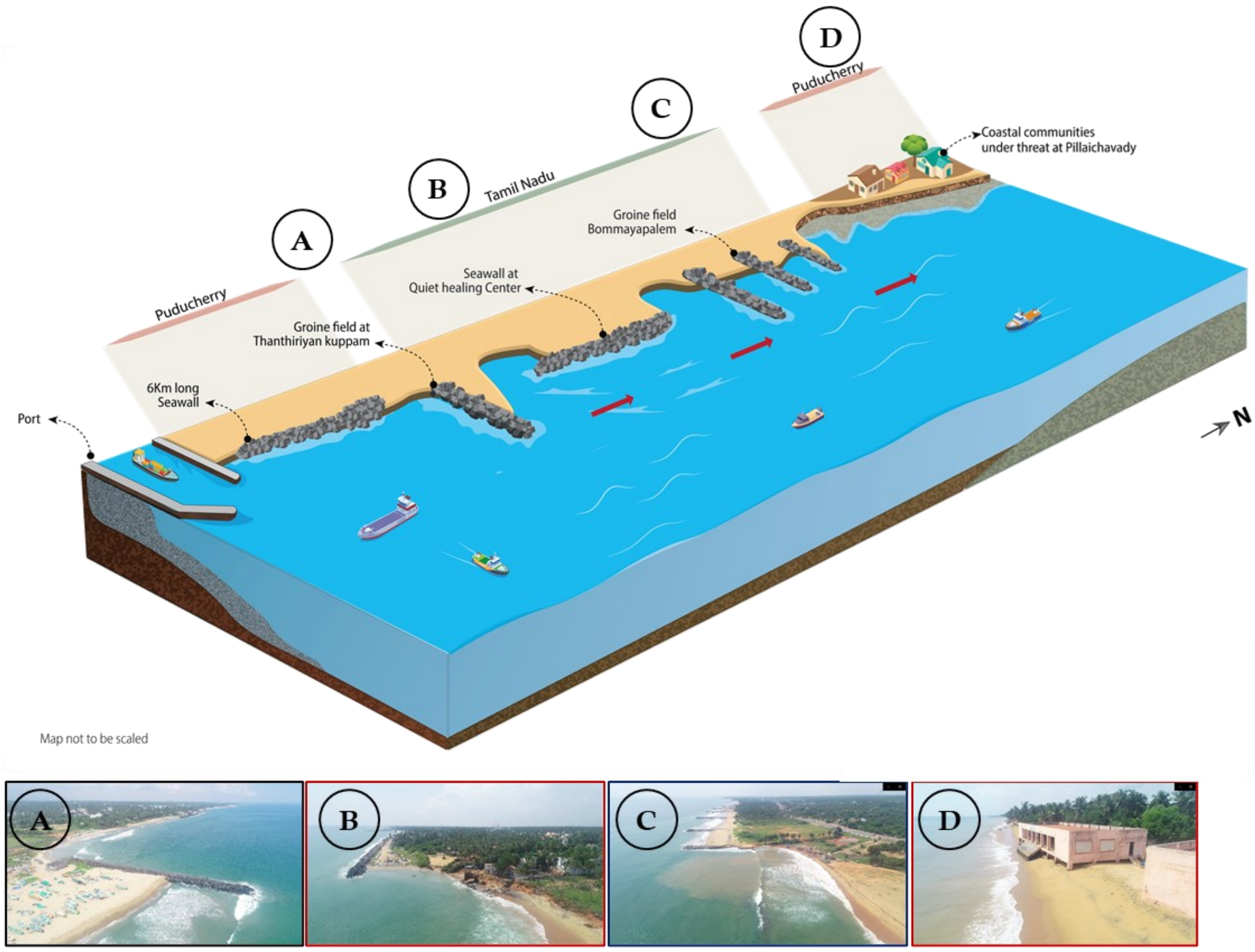


Figure 42 Schematic Representation of Impact and consequent protection measures

This not only created inter-state issues but also resulted in a loss of tourism revenue, with thousands of tourists visiting for recreation. With a detailed Shoreline Management Plan (SMP) for Puducherry, a hybrid solution involving beach nourishment and a northern wedge-shaped reef was implemented to restore the Promenade beach without affecting the existing coast. A significant portion of the coast has been restored, and the implementation of the southern reef will stabilize the beach and reduce the need for further nourishment. This demonstrates that suitable hybrid solutions can be planned with proper SMP and site-specific analysis to determine hydrodynamics, sediment transport, and coastal morphology.

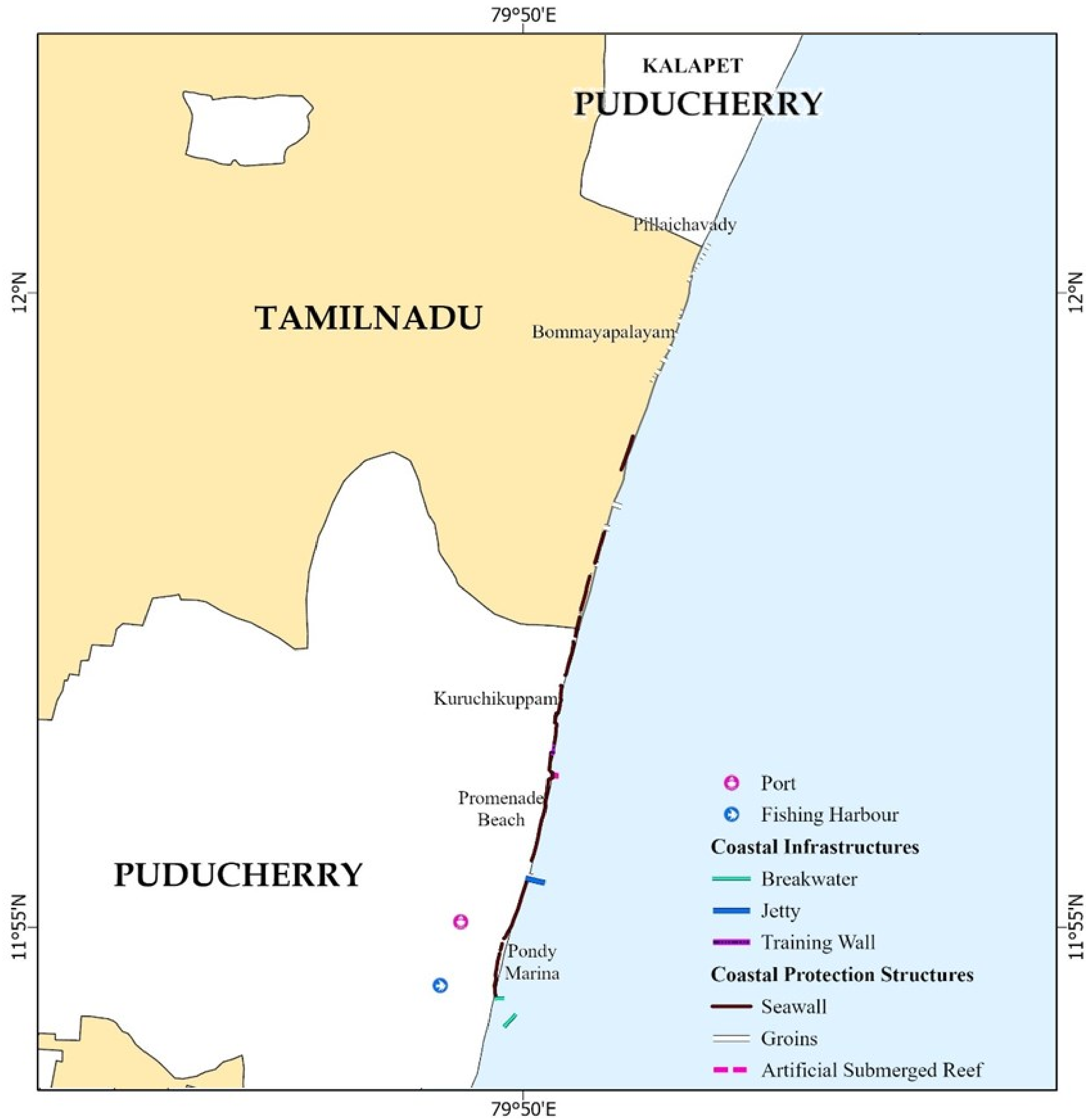


Figure 43 Map of coastal structures along Puducherry coast

7.4 Status of Infrastructure

a) Puducherry

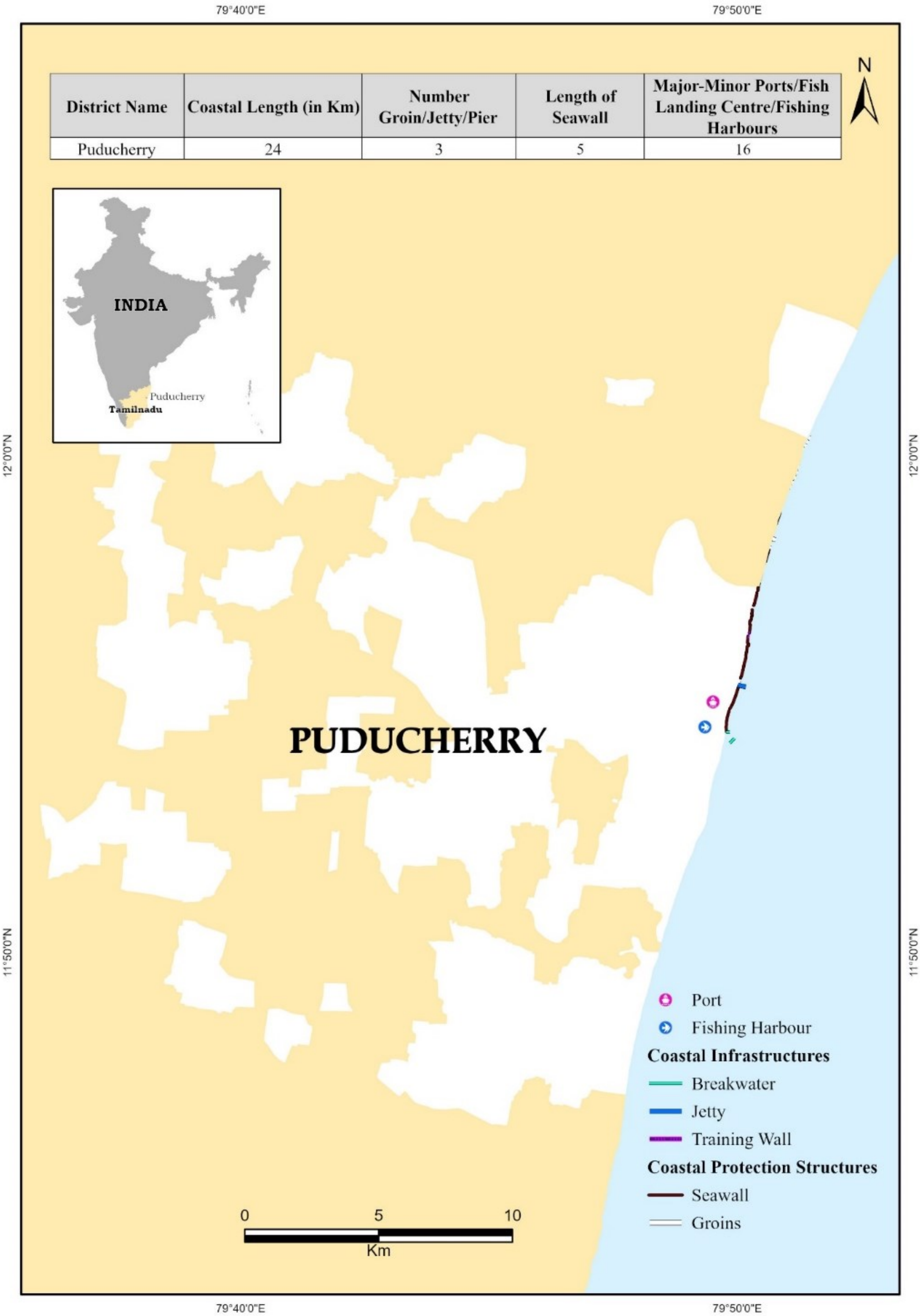
Puducherry district, enclaves by Tamil Nadu on its west and Bay of Bengal on eastern side. It consists of one operational port, a operational fishing harbour with breakwater on either side of the river mouth and 10 fish landing points which act as a major coastal infrastructure along Puducherry coastline. A 900-ton wedge shaped artificial submerged reef was constructed in 2018 before the Puducherry Secretraite, which act as a major coastal protection structure of Puducherry coastline.Additionally, RMS Seawall of 4.8 km stretch has been observed north of Puducherry and two groins at Pondy Sunrise beach and south of Rock beach serve as coastal protection structures along this coastline. Seawall strettch from Kottakuppam to Kurichikuppam and Pondy Marina are under partially disintegrated condition. Further, one training wall at north of Puducherry beach and old pier at Rock beach is observed as a coastal infrastructure facilities in Puducherry. The overall coastal stretch in Puducherry spans 24 kilometres, with 5 kilometre covered by coastal protection structures and an additional 0.5 kilometres occupied by coastal infrastructure of Puducherry (Figure 44).

b) Karaikal

Karaikal, is one of the districts of Puducherry UT, enclaved by Tamil Nadu. This district includes three coastal infrastructures along the coastal stretch. It includes operational port at Vanjoor Village, an operational fishing harbour at Oduthurai village and 8 fish landing point, which acts as a major coastal infrastructure of Karaikal district. Additionally, a jetty was observed in Vanjoor village utilized as port for Captive Marine Terminal Facility of M/s Chemplast Sanmar. Aside from this, no other coastal structures were identified along the 18 km coastal stretch of Karaikal district (Figure 45).

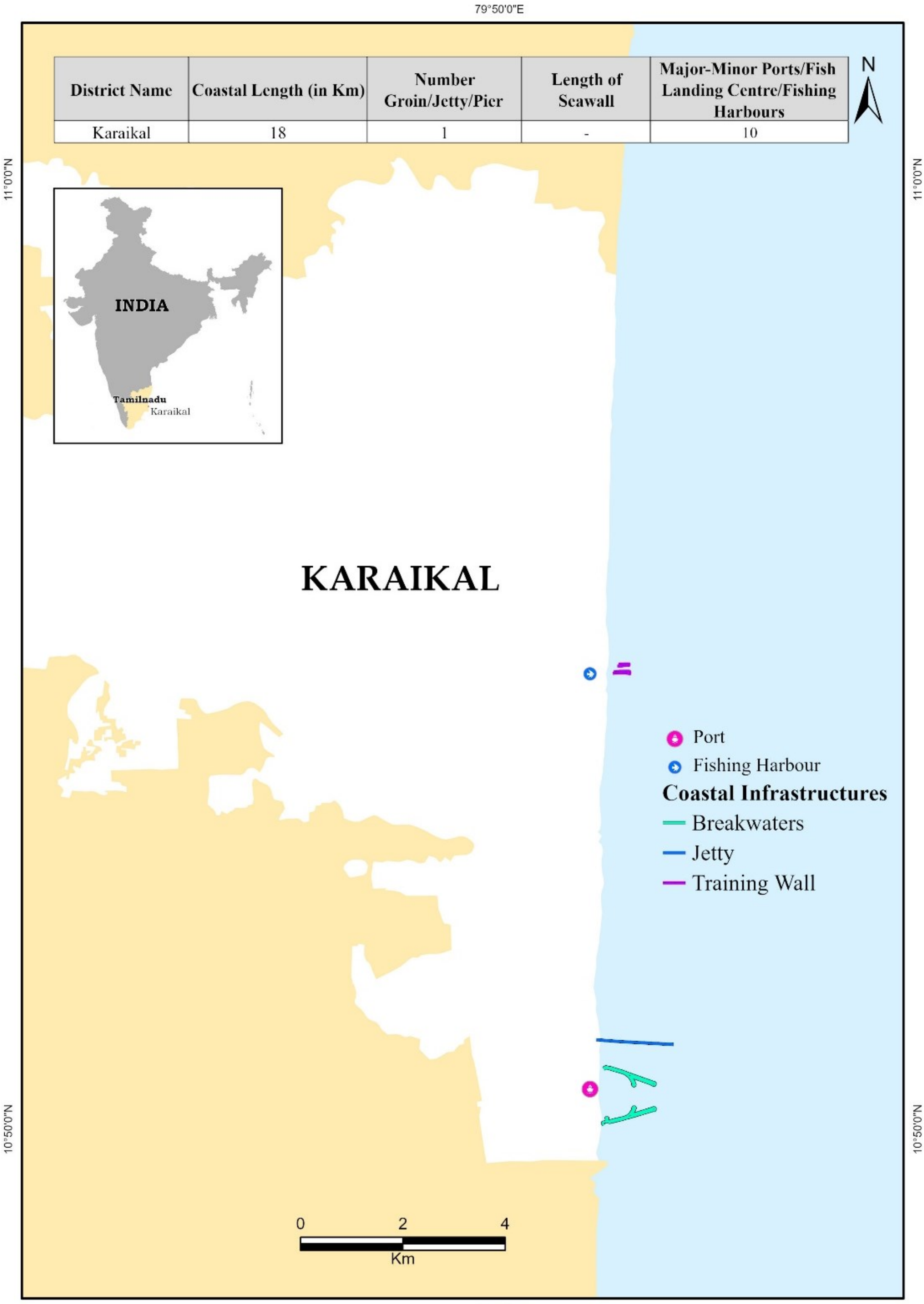
c) Mahé

Mahé, is one of the four districts of the Union Territory of Puducherry, enclaved by Kerala. It is also the smallest district of India, in terms of land area. Coastal area of Mahé is fully covered by coastal infrastructures. It includes operational fishing harbour at Mahé with breakwater and a seawall of 330m north of fishing harbour, which is in partially disintegrated condition. The overall coastal stretch in Mahé spans 1.2 kilometres, with 0.3 kilometre covered by coastal protection structures and an additional 0.9 kilometres occupied by coastal infrastructure of Mahé (Figure 46).



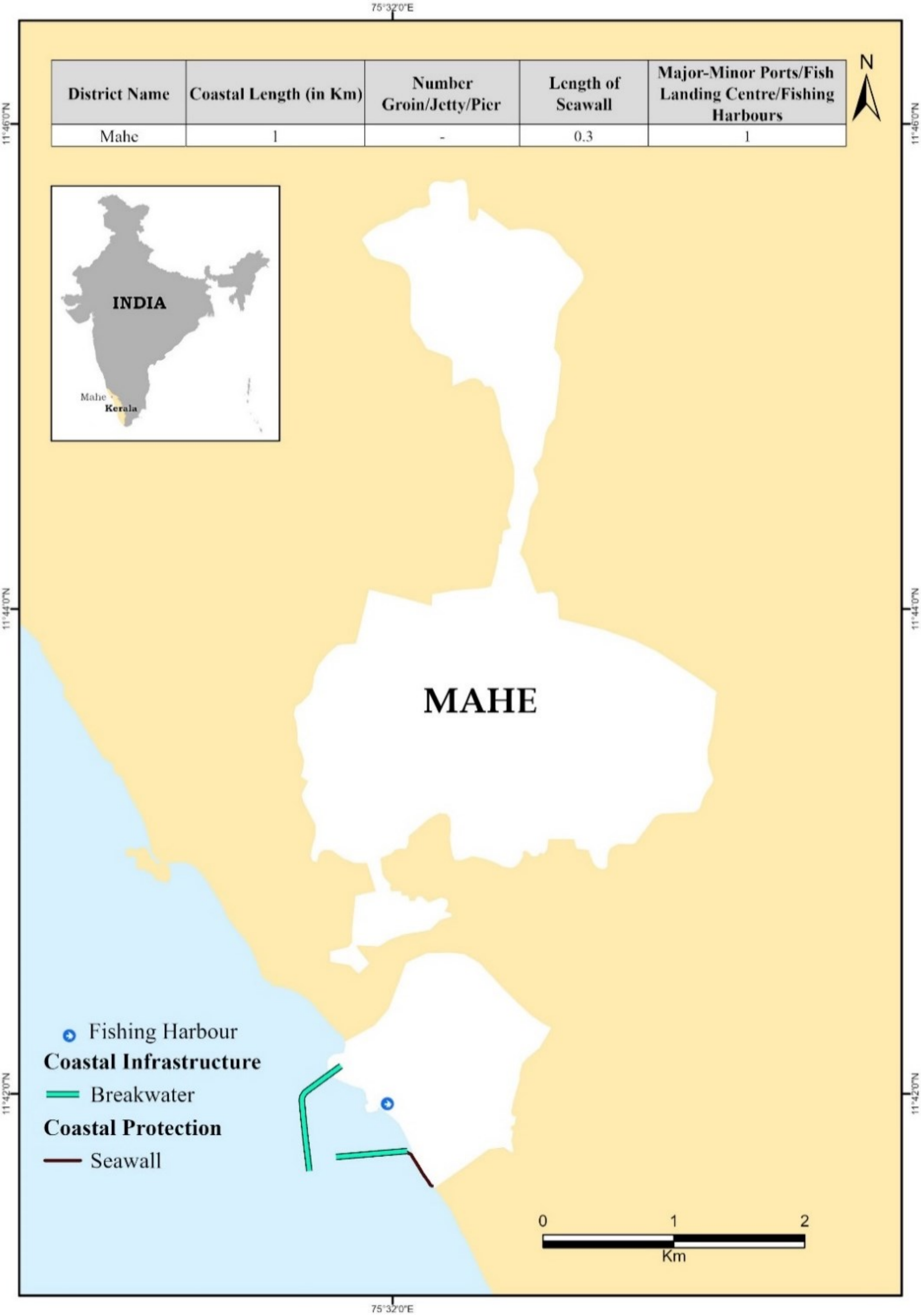
District Name	Coastal Length (in Km)	Number Groin/Jetty/Pier	Length of Seawall	Major-Minor Ports/Fish Landing Centre/Fishing Harbours
Puducherry	24	3	5	16

Figure 44. Coastal Structures along Puducherry Coast



District Name	Coastal Length (in Km)	Number Groin/Jetty/Pier	Length of Seawall	Major-Minor Ports/Fish Landing Centre/Fishing Harbours
Karaikal	18	1	-	10

Figure 45. Coastal Structures along Karaikal Coast



District Name	Coastal Length (in Km)	Number Groin/Jetty/Pier	Length of Seawall	Major-Minor Ports/Fish Landing Centre/Fishing Harbours
Mahe	1	-	0.3	1

Figure 46. Coastal Structures along Mahé Coast

7.5 Priority Sites from Structures

The identification and mapping of coastal structures play a pivot role in comprehensively assessing their influence on the coastline [16]. The analysis reveals that a significant portion of Puducherry's coastline remains undisturbed, emphasizing the need for closer examination of the existing infrastructure.

Understanding the structural and functional status of the coastal structures over a spatial distribution becomes crucial in evaluating their potential impact on the coast environment. About 2 sites along the Puducherry UT coastline were identified based on the functional and structural design of these coastal infrastructures which are partially damaged due to the dynamics of the coast (Figure 47 and Table 20). The Southern Reef which is a part of the integrated hybrid solution to restore the beach at Promenade is also considered a priority for its implementation to stabilise the formed beach and restore Promenade to its former glory. These priority sites play a crucial role in shaping the region's socio-economic landscape, and strategic importance requires a detailed Shoreline Management plan to safeguard coastal ecosystems and livelihoods.

Table 20. Structural Priority Sites along UT Puducherry coast

No.	Region	Coastal Stretch	Structure Details	Status of Structure
1	Puducherry	Kottakuppam to Kurichikuppam	Seawall	Partially damaged seawall
2		Pondy Marina	Seawall	Partially damaged seawall
3		Promenade Beach	South Reef	Need to be implemented

Analysis of coastal protection structures highlights the need for evaluating their status, especially in erosion-prone areas, with identified priority sites indicating the necessity for effective shoreline management. This survey provides essential insights for coastal management and resilience planning, serving as a foundation for further research on coastal dynamics and human impacts on ecosystems. The identification of intervention priority sites emphasizes the interdisciplinary approach required for effective coastal zone management, integrating engineering, environmental science, and socio-economic considerations.

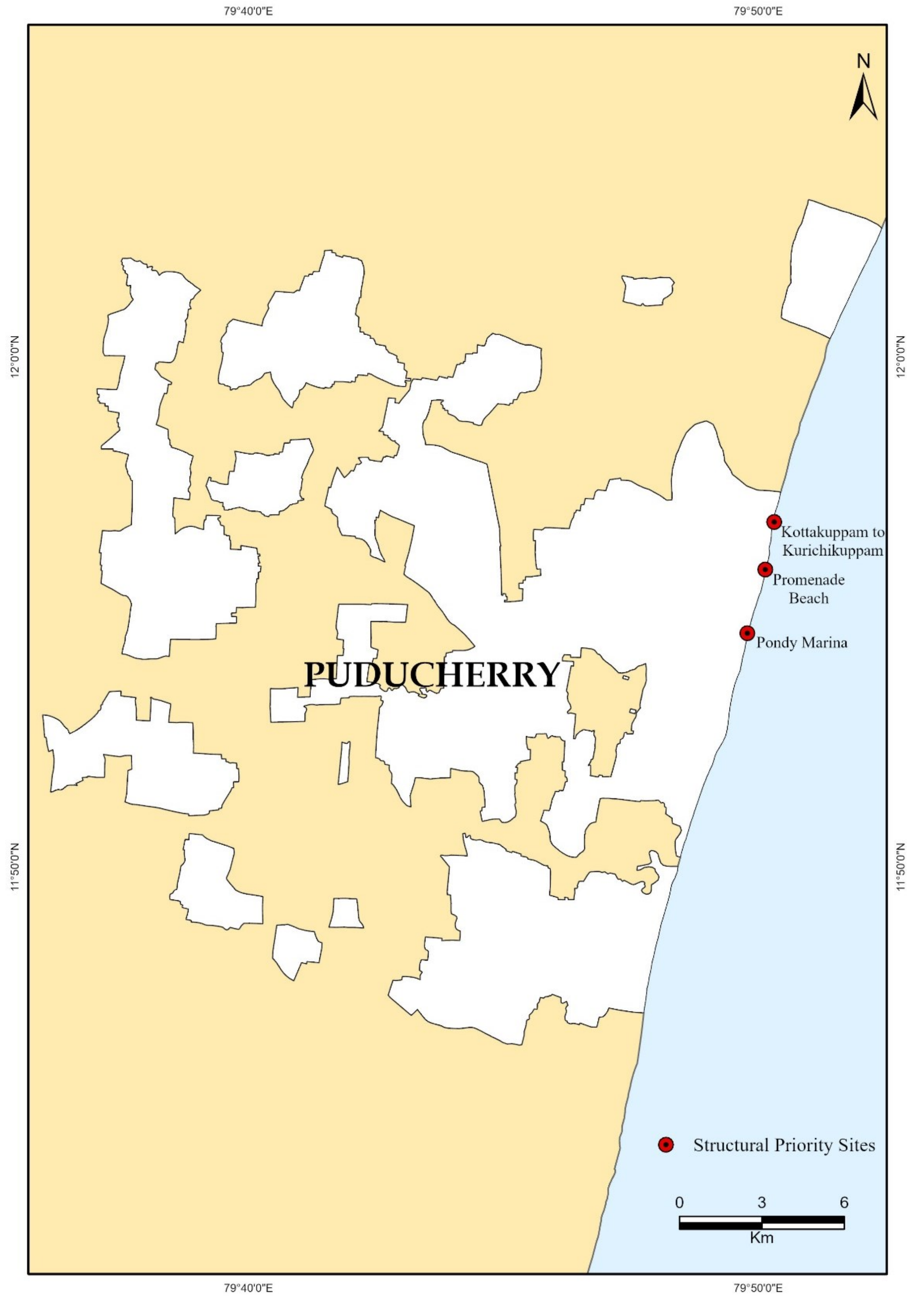


Figure 47. Structural Priority Sites along Puducherry UT Coastline

By conducting a detailed inventory of coastal infrastructures, valuable insights are gained into the potential stressors on the coastal ecosystem. The functional and structural performance of existing structures will provided key indicators in choosing suitable coastal protection statagies for futute. This information proves instrumental in formulating targeted and effective strategies within the Shoreline Management Plan to mitigate any adverse effects on the environment while ensuring the sustainable development of coastal areas in the union territory of Puducherry.

8 STAKEHOLDER INTERACTION

Stakeholders play a pivotal role in the formation, development and execution of Shoreline Management Plans (SMPs). The delicate balance between safeguarding coastal ecosystems, promoting economic activities and ensuring the well-being of communities is multifaceted challenge. In this context, stakeholders, representing diverse interests, are essential contributors to crafting effective and sustainable solutions. Their involvement brings together a wealth of knowledge, perspectives and resources that are critical for informed decision-making, conflict resolution and the long-term success of shoreline management initiatives.

> **"Stakeholder involvement is essential in SMP as it integrates diverse perspectives and resources, enabling informed decision-making and fostering community support. This inclusive approach not only enhances the effectiveness of coastal management but also increases the likelihood of long-term sustainability for both ecosystems and communities.**

Stakeholders in SMPs encompass a broad spectrum of individuals, groups and organizations with vested interests in coastal areas. These include local residents, community associations, Government agencies at various levels (local, regional, and national), tourism, commercial enterprises, fisheries, conservationists, academic institutions, and indigenous or traditional communities. Each stakeholder brings a unique perspective and set of priorities to the table, reflecting their respective roles and concerns related to the shoreline. From conservationists advocating for habitat preservation to businesses seeking economic opportunities and from local governments concerned with infrastructure to recreational users valuing public access, the diversity of stakeholders ensures that SMPs are comprehensive, inclusive and able to address the complex challenges faced by coastal communities and environments.

Involving stakeholders and consideration of their positive interests in shoreline management planning is a crucial step in creating well-informed, inclusive and sustainable approach to managing coastal areas. Their participation leads to better decisions, greater community support and increased chances of successful plan implementation.

To prepare a comprehensive SMP for the Union Territory of Puducherry, scientists from National Centre for Coastal Research (NCCR) engaged with local communities within fishing villages across Puducherry and Karaikal, focusing on areas with existing infrastructure facilities, such as fish landing points. In Puducherry, of the 15 fishing villages, 14 are equipped with fish landing points, where interactions were conducted, Similarly, in Karikal, out of 10 villages, 8 have fish landing points and were also included in engagement efforts. The details of fishing villages indicating the presence or absence of fish landing points is shown in Table 21. This inclusive approach ensures that the perspectives and needs of the local fishing communities are integral part in the development of the SMP, promoting sustainable and informed shoreline management strategies.

In Puducherry (Figure 48), the northern fishing villages of Kanaga Chettikulam, Periyakalapet, Chinnakalapet, and Pillaichavady have reported significant concerns regarding shoreline erosion, emphasizing the urgent need for shore protection measures to preserve their infrastructure, sustain fishing activities, and protect their livelihoods. Similarly, communities in Solai Nagar, Vaithikuppam, and Kurusukuppam have highlighted the challenges posed by erosion at the fishing gaps between the seawalls, which adversely affects their fishing operations. Additionally, residents of the southern villages of Moorthykuppam and Narambai have informed their difficulties due to erosion, underscoring a widespread concern across both the northern and southern sectors of Puducherry. Despite these critical issues, the remaining areas have mostly intact structures, with reports of limited erosion, indicating a varied impact of coastal erosion across different parts of the territory. A similar stakeholder interaction was also carried out for Karaikal (Figure 49). The diversity of experiences underscores the importance of a tailored, comprehensive approach in the Shoreline Management Plan to address the specific needs and challenges of each community effectively.

Table 21. Fish landing point Information of Puducherry and Karaikal Fishing Villages

Region	Fishing Village	Fishing Landing Centre
Puducherry	Kanagachettikulam	Present
	Periyakalapet	Present
	Chinnakalapet	Present
	Pillaichavady	Present
	Solai Nagar	Present
	Vaithikuppam	Present
	Kurusukuppam	Present
	Vamakeerapalayam	Absent
	Veerampattinam	Present
	Chinnaveerampattinam	Present
	Pudukuppam	Present
	Nallavadu	Present
	Panithittu	Present
	Narambai	Present
	Moorthykuppam	Present
Karaikal	Mandapathur	Present
	Kalikuppam	Present
	Akkampettai	Present
	Kottucherrymedu	Present
	Keezhakasakudimedu	Present
	Kilinjalmedu	Present
	Karaikalmedu	Present
	Pattinacherry	Present
	Karukkalacherry	Absent
	North Vanjore	Absent

Kanaga Chettikulam

Kanaga Chettikulam

Veeram Pattinam

Veeram Pattinam

Nallavadu

Nallavadu

Panithittu

Periyakalapet

Solai Nagar

Chinnakalapet

Figure 48. Fish landing point Field Pictures of Puducherry Fishing Villages

Akkampettai

Kaalikuppam

Karaikalmedu

Keezhakasakudimedu

Kilinjalmedu

Kottucherrymedu

Mandapathur

Pattinacherry

Figure 49. Fish landing point Field Pictures of Karaikal Fishing Villages

Stakeholder engagement is pivotal in creating effective Shoreline Management Plans (SMPs), drawing on diverse perspectives from local residents, government agencies, businesses, conservationists, and indigenous communities. The local community involvement in the development of SMP acknowledges the unique challenges faced by these communities, such as shoreline erosion impacting infrastructure and livelihoods. Through field interactions in Puducherry and Karikal, significant concerns regarding erosion were identified in northern villages like Kanagachettikulam and Periyakalapet, as well as in southern areas like Moorthykuppam and Narambai. Tailoring SMP strategies to address these localized challenges is essential for fostering sustainable coastal management and safeguarding the well-being of coastal communities.

Stakeholder interaction in shoreline management plans ensures diverse viewpoints are considered, fostering community engagement and enhancing the plan's effectiveness and sustainability. It also promotes transparency and accountability in decision-making process, leading to greater stakeholder buy-in and support.

Pillaichavady to Kalapet Coast

9 SEDIMENT CELLS AND BUDGET

The coastline of Union Territory of Puducherry is interspersed with open beaches sand dunes. Located on the southeastern coastal stretch of India, the movement of sediments holds particular significance influencing coastal erosion and accretion patterns impacting coastal communities and ecosystems. The integrity of these coastal areas is intricately linked to sediment transport and beach dynamics, highlighting the crucial role these processes play in sustaining the ecological balance and resilience of coastal ecosystems.

> **"Sediment transport is a dynamic process that is wave and wind-driven which redistributes the sediment and plays a crucial role in re-shaping the morphology of the coastline and other geological features.**

Wave parameters along the coast majorly contribute to sediment movement in the form of "littoral drifts". Littoral drift is defined as the movement of sediments along the coastline due to the wave induced longshore currents. The sediment gets churned and transported by the erosive forces of longshore current and settle at a place where the sediment resistance exceeds these erosive forces. These sediments can be quantitatively assessed based on the sources and sinks.

Coastal orientation significantly influences sediment transport along the coast. The stretch from Kalapet to Pudhukuppam exhibits a coastal orientation close to 250, while the section from Tarangambadi south to Nagore of Karaikal is nearly North oriented. Mahé in the west coast has a coastal orientation close to 150 degree [17]. Although sandy beaches are present along the coast, sand dunes are a prominent feature of the extensive coastline, especially at locations like Nallavadu and Pudhukuppam. Beyond the sediment sources from the rivers, eroding sand dunes also contribute as a significant source of sediments for littoral drifts.

9.1 Littoral Drift and Role of Sediment Cells

The transport of sediments due to nearshore processes is demarked within conceptual boundaries known as sediment cells. The formation of these cells is influenced by a combination of factors including the geology and geomorphology of the coast, shoreline orientation, wave climate, and the presence of major coastal infrastructures. Sediments typically circulate within these cells, which can extend over considerable distances along the coast. They are however, subject to interruption by coastal structures or geomorphological features that hinder sediment bypassing.

While local bypassing of sediments is particularly pronounced during the monsoon season across minor rivers, a sub-classification of primary cells has been introduced. This results in the formation of secondary cells, addressing the sediment bypassing from sources other than the major river systems or significant ports and harbors along the coast. The delineated sediment cell locations along the Indian coastline, including notable cells at Coleroon River and Point Calimere close to the UT of Puducherry [18].

The secondary cells specific to the Puducherry coast are outlined in Table 22 and Figure 50. There are no primary cells specific to Union Territory of Puducherry, whist being surrounded by Tamil Nadu. The primary sediment boundaries encompassing Puducherry coasts are Palar river in the north, Caleroon river and Point Calimere in the South. Secondary sediment cells are further defined by coastal infrastructures and rivers that contribute substantial sediments to the coast but may allow sediment transfer during different seasons. Puducherry harbour and Karaikal port are classified as secondary sediment cells owing to their extensive breakwaters altering the course of sediment movements.

The classification of sediment cells is instrumental in understanding sediment movement patterns and effectively compartmentalizes the sources contributing to sediment transport. Along the coast of Union Territory of Puducherry, two secondary sediment cells are identified. Owing to the small coastal stretches with open beaches and nearly Northward orientation of the coast, the sediment transport is minimal compared to other locations along east coast of India. Sediment cells, therefore, establish a natural demarcation that aids in the comprehension and management of sediment movements along the coastline. This concept is invaluable for long-term strategic planning and provides a structural framework for coastal engineering interventions and developmental undertakings.

Table 22. Primary And Secondary Sediment Cells along Tamil Nadu

Primary Sediment Cells	Secondary Sediment Cells
Palar River to Caleroon Estuary (Tamil Nadu)	Puducherry Harbour
Caleroon Estuary to Point Calimere (Tamil Nadu)	Karaikal Port

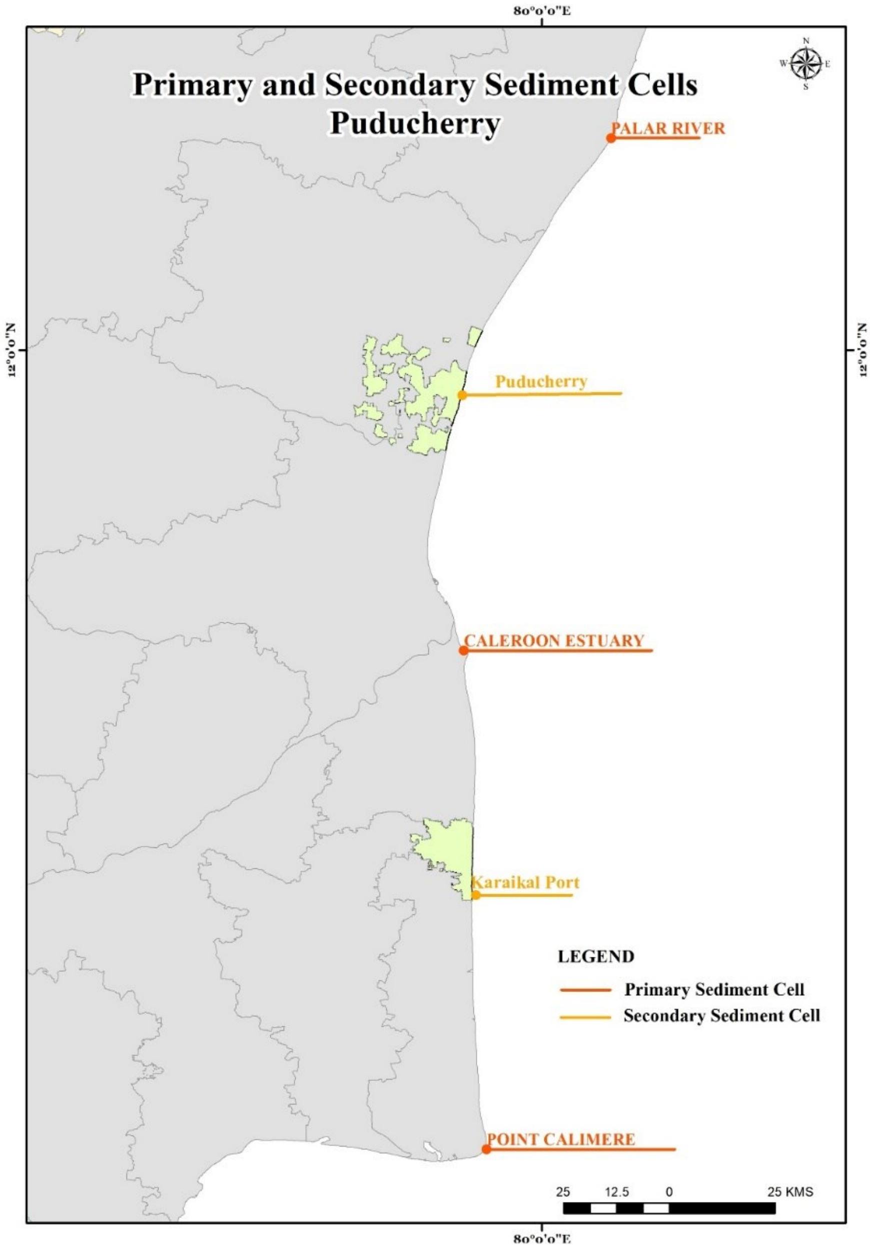


Figure 50. Primary and Secondary Cells

9.2 Littoral Drift and Onshore-Offshore Transport

Understanding the littoral drift rates and their directional patterns along the coast is crucial for understanding sediment transport mechanisms. These insights into the sources and sinks of sediment assist policymakers in identifying and implementing coastal management strategies. Sediments move northwards and southwards depending on the season.

Onshore-Offshore transport, characterized by seaward sediment movement, is negligible on the east coast of India but becomes prominent during extreme events such as cyclones and storm surges. In these events, sediments are transported offshore and are deposited in the nearshore regions, forming sand bars. As the natural cycle returns, the eroded materials will be deposited back into the coastal area. However, with the increasing frequency of extreme events, this natural cycle is disrupted, leading to a net loss of sediment. Although, quantifying onshore-offshore sediment transport is challenging, continuous profiling can yield accurate predictions of these transport regimes. The dynamics of offshore sand movement and its reclamation are depicted in Figure 51.

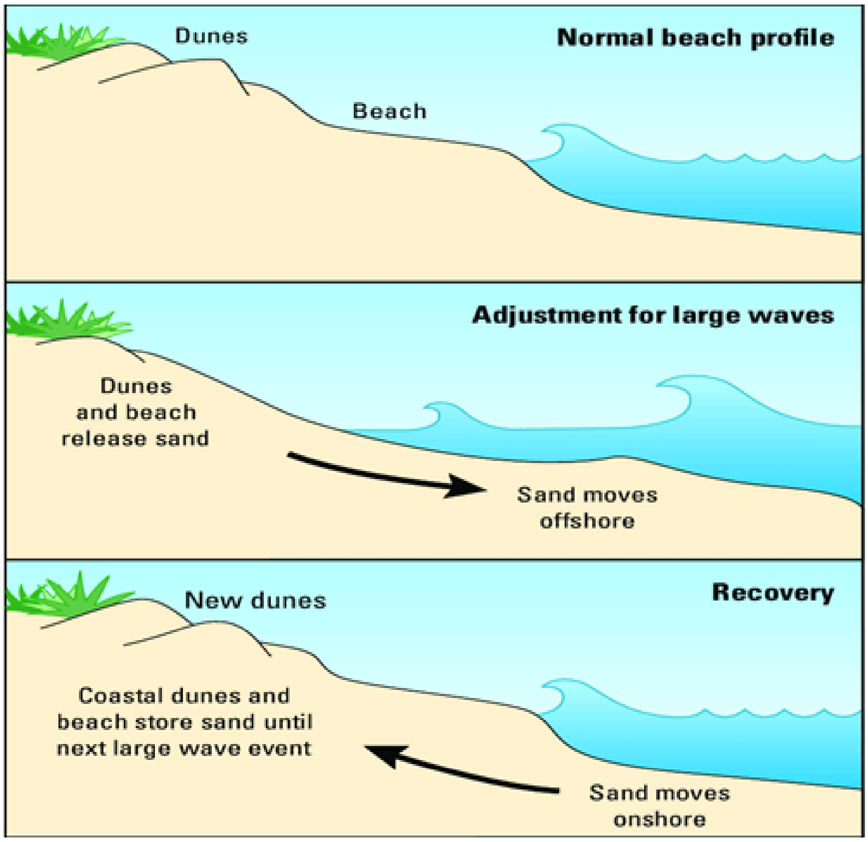


Figure 51. Beach Profiles during different Events

The Puducherry and Karaikal coastal stretch exhibits net northerly drift in the range of 50,000 to 1,00,000 m^3/year [19][20]. Mahé experience net northerly drift of less than 50,000

m^3/year. Coastal orientation plays a significant role in sediment transport dynamics along the coastlines of Puducherry, Karaikal, and Mahé, with distinct orientations influencing sediment movement patterns. The presence of sandy beaches and prominent sand dunes, particularly at locations like Nallavadu and Pudhukuppam, highlights the significance of sediment sources, including river inputs and eroding dunes, in littoral drift processes.

Littoral drift, governed by sediment cells, delineates the transport of sediments within conceptual boundaries influenced by coastal morphology, wave climate, and human interventions. Secondary sediment cells, such as those identified along the Puducherry coast, illustrate how coastal structures like harbors and ports can alter sediment transport patterns. The classification of sediment cells aids in understanding sediment movement patterns and guides coastal management strategies.

Net sediment transport rates along the Puducherry coast vary, with predominantly Northern transport. Onshore-offshore sediment transport, though typically minimal on the east coast, becomes pronounced during extreme events like cyclones, impacting coastal morphology and sediment budgets. Continuous monitoring and profiling are essential for accurately predicting sediment transport regimes and informing coastal management decisions.

About two secondary sediment cells were identified along the coast. These sediment cells serve as natural boundaries, aiding in understanding and managing coastal sediment movements. This information is crucial for long-term strategic planning, guiding coastal engineering interventions, and determining suitable sources for beach nourishment based on grain size analysis.

Promenade Beach

10 LESSONS LEARNED

India has a diverse coastline spanning about 7500 km, making it one of the longest coastlines in the world. The coastline is characterized by its diversity in geology, ecology and culture. The evolution of the coastline is mainly driven by coastal processes due to monsoons, cyclones, riverine sediment deposition, wave energy, sea level rise and tides. Some coasts experience extreme precipitation during monsoons while some are influenced by cyclones. Together these factors result in a dynamic and varied coastal environment that governs the impact on the coast. Therefore, coastal management and sustainable development are quintessential and require site-specific interventions for addressing issues.

> **"Adoption of green and hybrid coastal protection schemes are increasingly gaining traction in addressing climate change and promoting sustainability. Evaluating the success of these implemented strategies along the Indian coast can provide valuable insights for future interventions**

The coastal protection strategies are arrived at based on analysis of satellite data, process-based field measurements and numerical model studies. The design of coastal protection structures should consider local hydrodynamics, seabed characteristics, site conditions, vulnerability of the coast and cost of the project. The National Centre for Coastal Research (NCCR), formerly Integrated Coastal and Marine Area Management Project Directorate (ICMAM-PD), has undertaken several research initiatives in the areas of shoreline management since 1998. The two decades of expertise of the organisation with its shoreline management projects implemented along the coastal areas are detailed in the form of case studies.

The case studies in this section have been discussed to provide a broad perspective on the site-specific management strategies that can be implemented on the coast depending on the functional requirement and coastal processes. These coastal strategies have been designed based on globally acclaimed best practices and received widespread appreciation from the public and the stakeholders.

10.1 Hybrid Solution at Chellanam

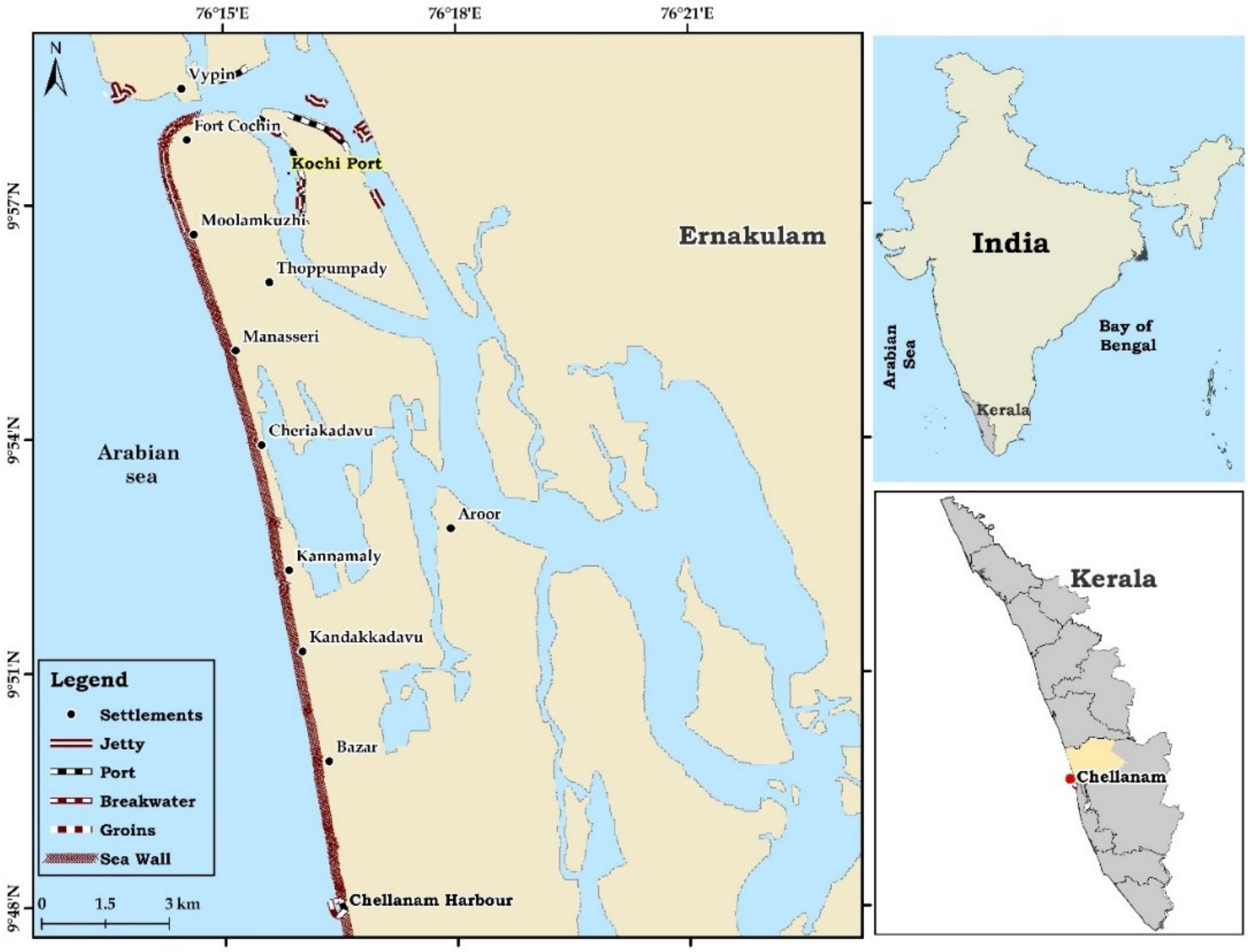


Figure 52. Chellanam Coast in Kerala and its Environments

Chellanam, a narrow strip of coastal village, situated 16 km South of Kochi port, is a low-lying area in Ernakulam district of Kerala (Figure 52). The village lies between the Kochi Port in the North and the Chellanam Fishing Harbour in the South. This densely populated fishing village is wedged between the Arabian Sea to the West and Kerala's backwaters to the East, rendering it highly vulnerable to severe sea erosion, flooding and inundation, particularly during the monsoon seasons (Figure 53). The region experiences annual flooding and inundation due to a substantial increase in wave energy over the years and a rise in the frequency of cyclonic events in the Arabian Sea. The damage to this village during the monsoon months, including the loss of property, was devastating leaving many fishing families as a refuge in relief camps after their houses were destroyed. The Government of Kerala through the irrigation department approached NCCR to design a technically sound solution to prevent flooding and erosion at Chellanam.

Figure 53. Wave Activity, Flooding and Inundation at Chellanam Coast

As the proposed site is a barrier island with the open sea on one side and backwater on the other, long-term analysis of shoreline changes and nearshore processes were analyzed to understand the environmental forcing (Figure 54). Based on the beach profile data, numerical model studies were conducted to design the coastal protection strategy. The effect of climate change by the inclusion of the Sea Level Rise and storm surge has been considered in evaluating the overtopping discharge to finalize the crest of the seawall. The sizing and type of the armour unit have been arrived at by considering the anticipated scour depth at the toe of the seawall in addition to extreme events and sea level rise.

While analyzing coastal stretches at the other locations, Bazar and Kannamaly, a hybrid solution with groynes and beach nourishment has been designed to restore the beach in addition to coastal protection from historical wave activity and cyclones (Figure 55). The beach nourishment for the locations has been derived based on the sediment budget in the area arrived at through model studies. Considering dominant cross-shore transport at the site T-groynes have been suggested to minimise the loss of sand during monsoon season.

On these highly eroding stretches, a combination of hard and soft solutions was attempted to protect the coast from the fury of the waves during the monsoon and cyclonic activities. While designing the solution, an attempt has been made to restore the beach based on the sediment budget estimated for the long-term shoreline data. The project has already been implemented along the Chellanam coast with the technical support of NCCR (Figure 56). The Kerala Government is also regularly monitoring the coast and the seawall at Chellanam has proven effective in mitigating the impact of sea erosion and shielding the coastal community from flooding. Notably, Chellanam experienced no flooding during the last two monsoons following the seawall's construction – a significant accomplishment. The success of the initial phase has garnered substantial support from the local community and the Government, prompting calls for the swift implementation of the second phase. The successful implementation of the Chellanam seawall has also inspired the Government to contemplate similar site-specific coastal protection measures in other areas of Kerala, as part of their ongoing commitment to safeguard coastal communities in the region.

Similar solutions are designed at locations with highly dense coastal communities and well-developed infrastructure near the coast where the coast is subjected to severe erosion and flooding at regular intervals. The Government of Kerala and NCCR are working together in the design and implementation of environmentally sustainable solutions along the Kerala coast.

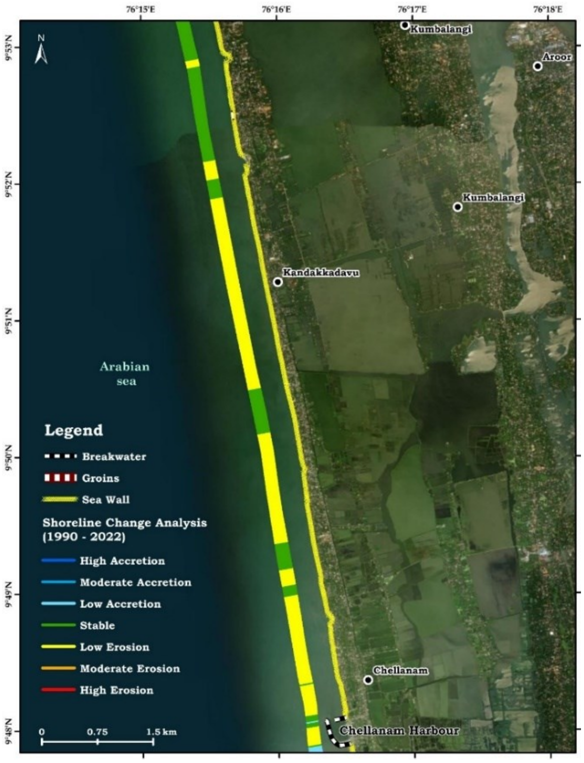


Figure 54. Shoreline Change at Chellanam

Figure 55. Management Strategy for Chellanam

Figure 56. Seawall Constructed at Chellanam

10.2 Hybrid Solution at Puducherry

Puducherry (Formerly Pondicherry), a French colonial settlement in India until 1954, is a Union Territory town bounded by Tamil Nadu State. Its French legacy is preserved in its French quarters with a seaside promenade that runs along the Bay of Bengal which once housed the wooden jetty constructed in the past. The promenade housed a beach that was once the pride of the region.

Puducherry's coastline has been severely impacted by coastal erosion, resulting in the absence of a sandy beach. The once beautiful historical beachfront has vanished, leaving only a rock wall that hindered access to the seaside, conflicting with the city's tourism aspirations. The construction of the Puducherry port just South of the Promenade had altered the sediment transport along the coast resulting in severe erosion along the city coast. The construction of various coastal protection strategies had helped to protect the coastal infrastructure but shifted the erosion further North (Figure 57). The government of Puducherry has requested MoES to restore the lost beach along the city to improve resilience and meet the tourism aspiration of the State. A comprehensive shoreline management plan was prepared for the entire Puducherry coast, considering the impact of all the existing coastal protection structures implemented along the coast.

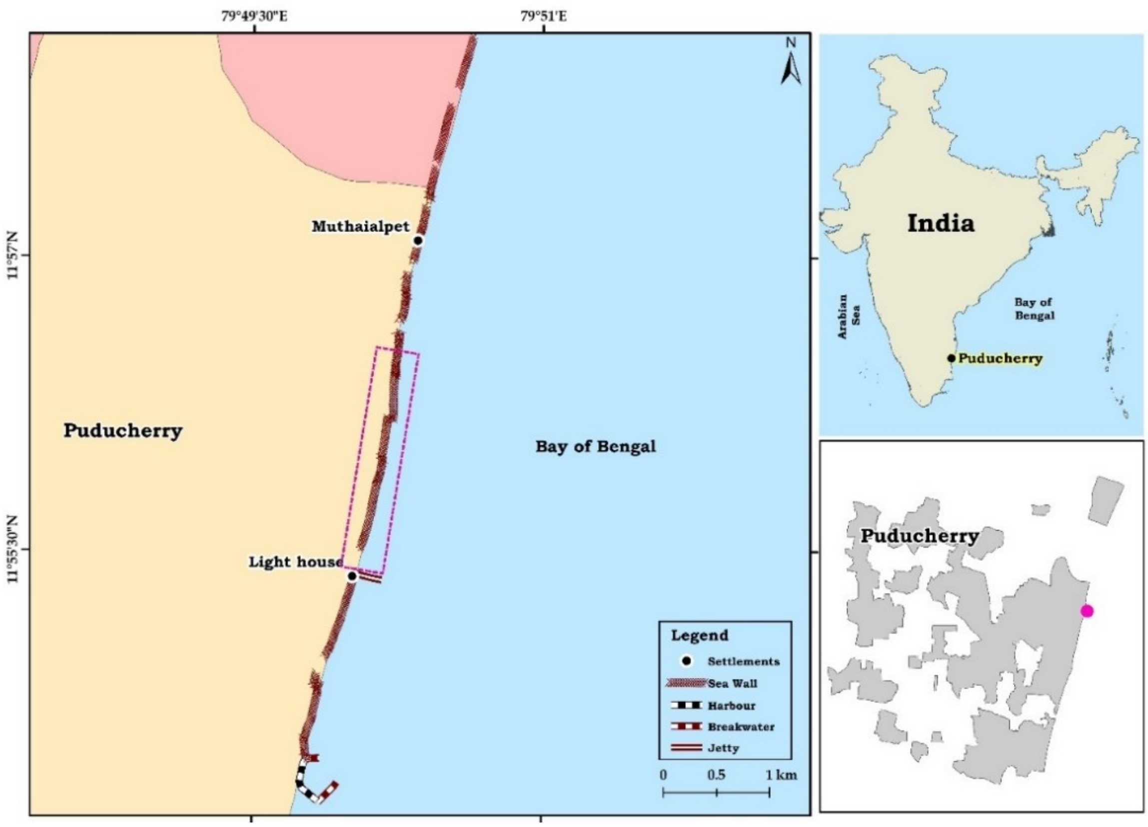


Figure 57. Puducherry Coast and its Environments

A hybrid solution was proposed based on process-based measurements and numerical model studies which include a submerged wedge-shaped north reef and an offshore detached breakwater along with beach nourishment (Figure 58). The concept of the proposed solution was developed in similar lines of headland and bay system which creates a calmer environment due to the divergence of the waves between the headlands. However, in this case, the North Reef is designed as a submerged structure for partially bypassing the sand during high tide to reduce downdrift erosion. The south reef is designed to be an emerged reef with discrete units and slightly reoriented to prevent reflection of waves and effectively dissipate wave-induced currents. This reef will stop the movement of nourished sand back to port thereby significantly reducing the dredging issues at port.

Beach nourishment utilizing rainbow nourishment and pipeline nourishment was carried out using dredged sand from the port mouth to create a stable beach profile. The nourishment was continuously monitored through field studies at regular intervals for mid-course corrections in the nourishment scheme.

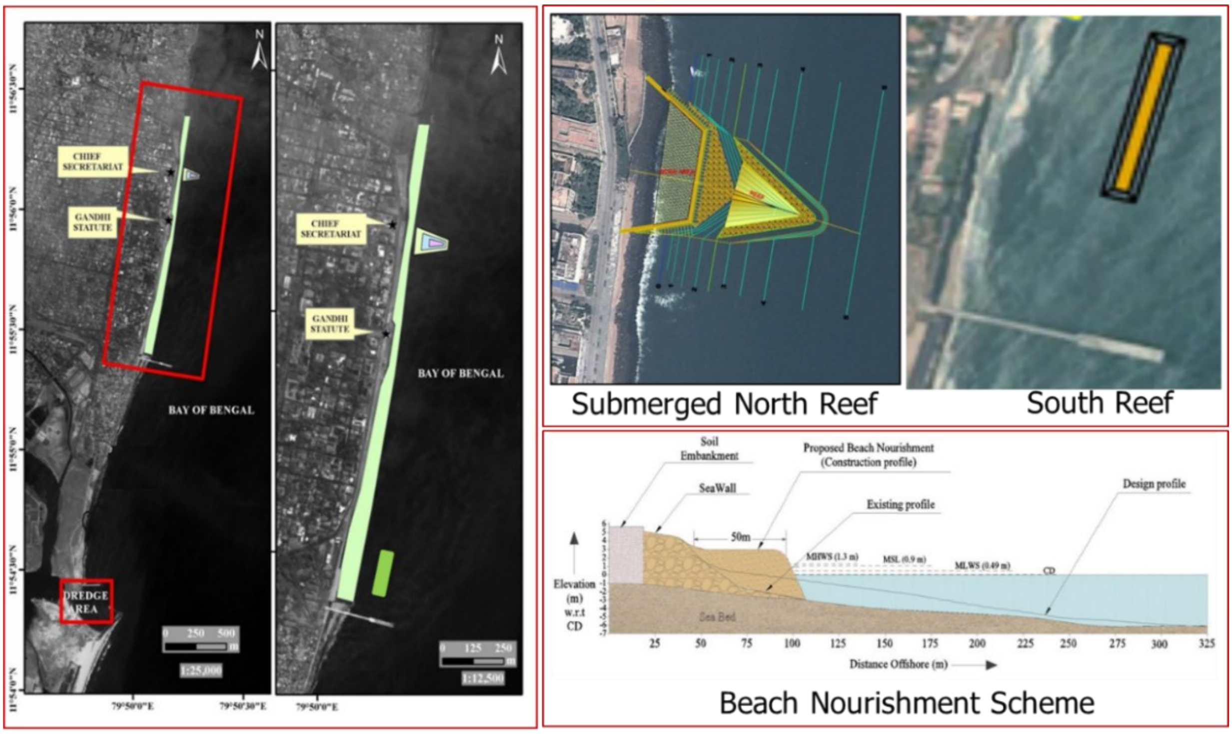


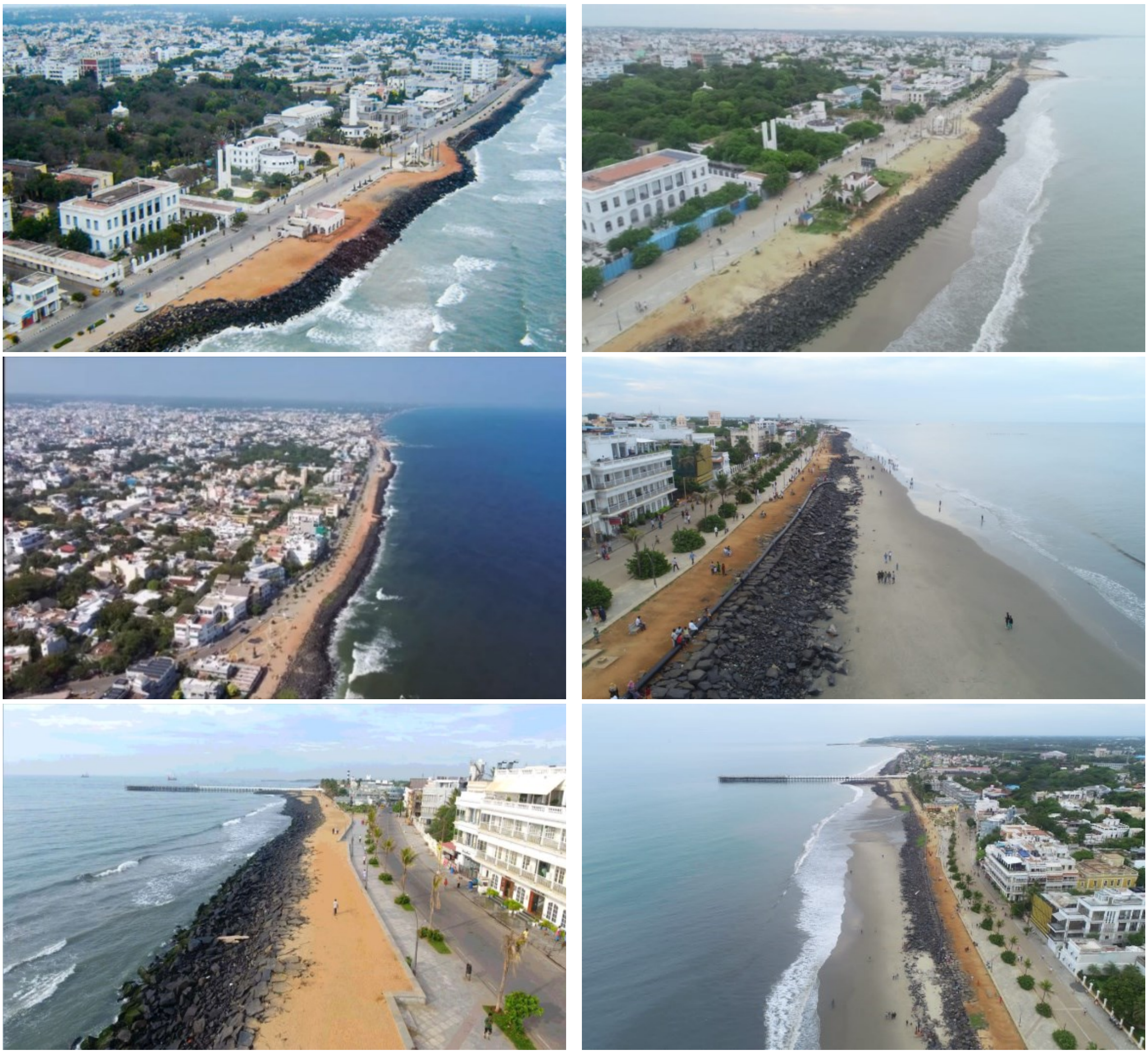
Figure 58. Beach Restoration Scheme for Puducherry Coast

The project was implemented in 2018 as a demonstration with funding from the Ministry of Earth Sciences, showcasing its success through the formation of a wide beach. Following the supplementary nourishment efforts by the Puducherry Government, the length of the beach has further expanded, reaching approximately 1.5 km up to the new pier. (Figure 59 and Figure 60).

A decade-long sand deficit beach is now being flooded with thousands of tourists and residents every day. With the implementation of the South Reef, the entire stretch of the Promenade shall once more be restored to its former glory. Beyond its direct contribution to the Puducherry Government, this initiative holds significance for the economy, environment, tourism and the well-being of the local community. The multifaceted benefits underscore the project's positive impact, not only in coastal protection but also in enhancing the overall quality of life for the residents and visitors. The shoreline is being continuously monitored by NCCR through field surveys and installation of Autonomous Beach Monitoring System (ABMS) to monitor the shoreline change, based on the coastal processes observed, in co-operation with the Government of Puducherry.

In coastal communities, a comparable solution can be formulated, wherein the restoration of beaches plays a pivotal role in enhancing coastal resilience and concurrently fostering tourism and fisheries activities. However, to craft such solutions, it is imperative to identify sediment sources, such as a nearby port, river mouths or offshore.

Figure 59. Implementation of Hybrid Solution in Puducherry



Before After

Figure 60. Puducherry Coast Before and After the Implementation of Hybrid Solution

10.3 Beach Nourishment

Generally, construction of breakwaters for a port traps longshore sediment leading to downdrift erosion. The dredging activity along the navigation channel exacerbates this problem by acting as a sediment sink, further reducing sediment supply. It is crucial to engage in proper planning and management of the port to address erosion issues adjacent to the port. One effective mitigation strategy involves nourishing the sand using either capital or annually dredged sediment from the channels and inner harbour. A similar approach has been successfully implemented in the coastal stretches of Ennore and Visakhapatnam, demonstrating the positive impact of sediment nourishment in reducing erosion problems.

(a) Visakhapatnam

Visakhapatnam (formerly known as Vizagapatam), is the largest and most populous metropolitan city in Andhra Pradesh. It is between the Eastern Ghats and the coast of the Bay of Bengal. This is an ancient port city that was utilized for trading with the Middle East and Rome. This port is established at about 880 km from Kolkata Port and 780 km from Chennai Port, almost midway between two major established ports. The construction of the inner harbour commenced in 1927 mainly to export manganese from central provinces. With the Second World War, the military significance of the port increased establishing itself as a major port in 1964. The outer harbour provides tranquillity to additionally about 200 hectares through three breakwaters on the Eastern, Southern and Northern sides (Figure 61).

The coast of Visakhapatnam is a rocky headland in the South with a narrow beach on the North of the Port. The Dolphin's Nose Hill to the North of the entrance channel protects the harbour from cyclones that strike the East coast while the coastal river Narava Gedda joins the sea through a narrow creek in the port. Visakhapatnam experiences a strong littoral drift of sand northwards from March to September. The littoral drift of the order 0.56 Mm^3 from south to north during the South-West monsoon and the order of 0.10 Mm^3 from north to south during the North-East monsoon, resulting in a net northerly drift of the order of 0.50 Mm^3.

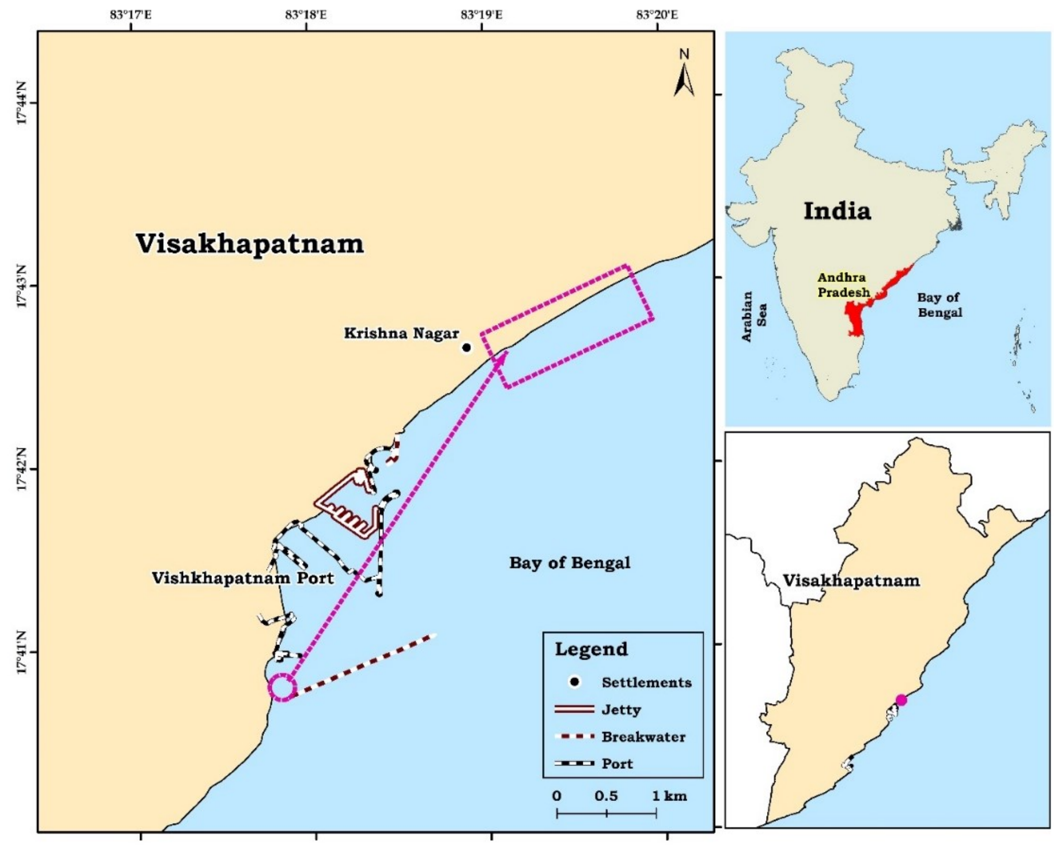


Figure 61. Visakhapatnam Coast in Andhra Pradesh and its Environments

Figure 62. Pipeline Nourishment in Vishakhapatnam Coast

When the sediment is stopped due to the construction of breakwaters, the sediment causes accretion on the south of the structure. This causes a sediment reduction that is carried to the north of the port. This deficit sediment is compensated by erosion of the coast. Considering this issue, a sand trap is incorporated into the layout of the outer harbour on the lee side of the south breakwater to facilitate the collection of the sand drift. This sand captured in the sand trap is regularly dredged using a dredger. The dredger is then floated in the sea towards RK beach and sediment is then pumped to the coast utilizing a floating pipeline directly onto the beach. An annual nourishment of about 0.4 Mm^3 is being carried out by the Port for replenishing the beach (Figure 62). In Figure 63, the accretion is evident to the south of the port breakwater, creating a mostly stable coast to the north, due to the nourishment efforts by the port. The sand trap serves a dual purpose by not only preventing siltation in the navigation channel but also acting as a sediment source for nourishing the northern beach. This dual functionality ensures the protection of both the navigation channel and inner harbour from siltation, while simultaneously safeguarding the beach from erosion.

This strategy has been quite successful in mitigating erosion in the North of hard structures as can be seen from (Figure 64). A similar approach should be pursued for all existing Ports along the East coast of India, to successfully negate the effects of erosion.

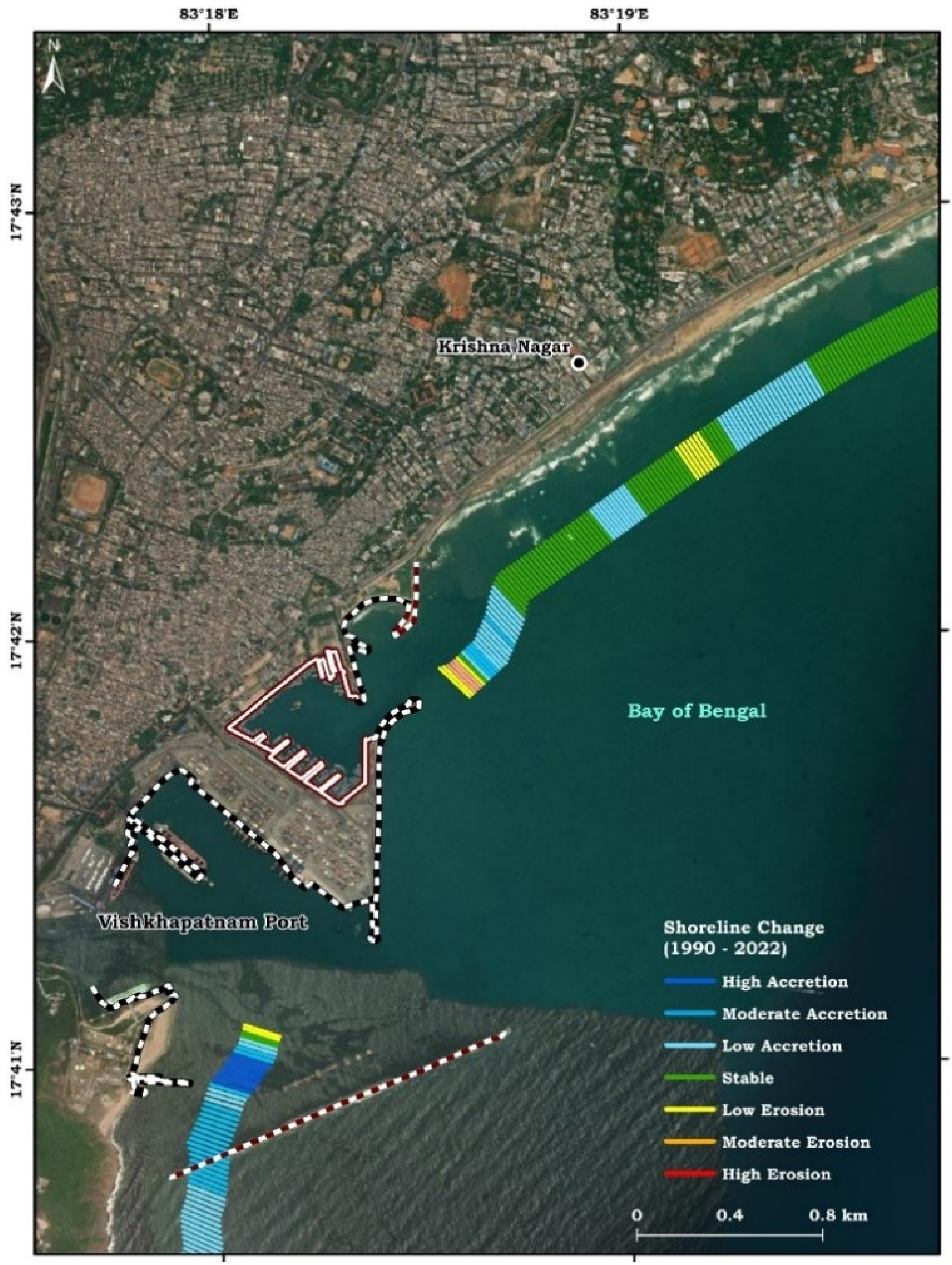


Figure 63. Shoreline Changes along Visakhapatnam Port

Figure 64. Beach Formed and Stabilized Post-Nourishment in RK Beach

(b) Ennore

Kamarajar Port, formerly known as Ennore Port, was constructed as a satellite port to supplement to the existing Chennai Port, primarily to handle the supply of coal to the thermal coal requirement of Tamil Nadu Electricity Board, in 2000. This Port lies on the North-Eastern corner of the Chennai City of Tamil Nadu on a flat coastal plain known as the Eastern Coastal Plains. It is located on the east coast of the Indian peninsula known as the Coromandel coast in the Bay of Bengal and is situated 2.6 km north of the Ennore Creek (Figure 65).

The Chennai Port is one of the largest ports in Bay of Bengal. The official port operation had begun in 1881, while maritime trading in this location dates as back as 1639. It has therefore turned into one of the major maritime trading points, even historically. After the construction of the Chennai Port, it is estimated that about 400 ha of land has been lost just North of the port between 1900 and 2001. A 5.5 km long seawall was implemented in 1979 to prevent further erosion, North of the Chennai Port. This shifted the erosion further north, affecting about a 16 km stretch of the coast that was home to a large fishermen population. It was estimated that about 300,000 coastal communities were affected due to this. Based on the effects of the Chennai

Port, it was envisaged that the construction of the Kamarajar Port would also cause similar erosion Northward. The construction of the port was also envisaged to increase the wave concentrations just North of the Port, leading to the degradation of the existing shoals and berms in the Kattupalli region. This will threaten the Northern coast, which also includes the sensitive Pulicat Lake ecosystem.

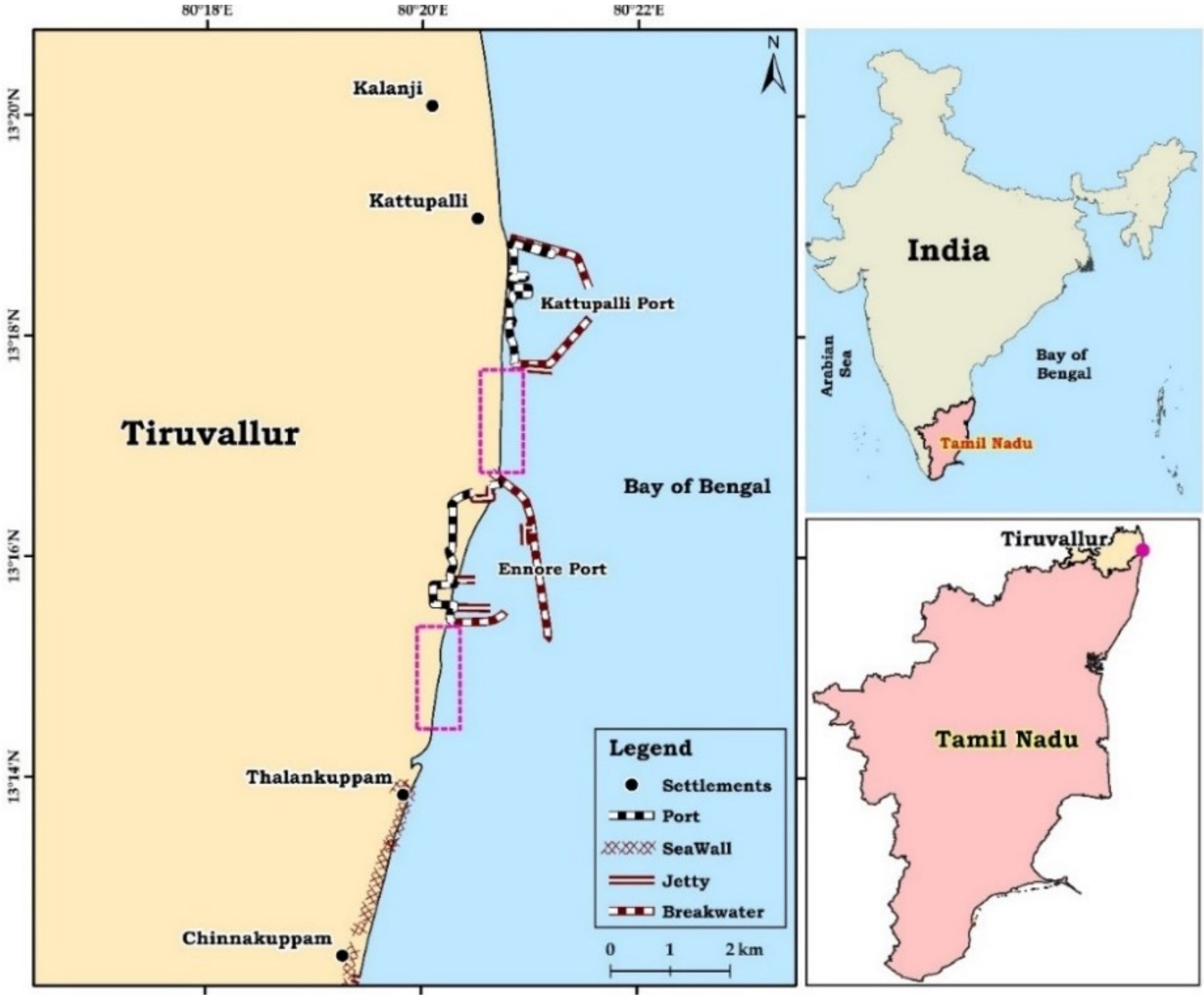


Figure 65. Ennore Port in Tamil Nadu Coast and its Environments

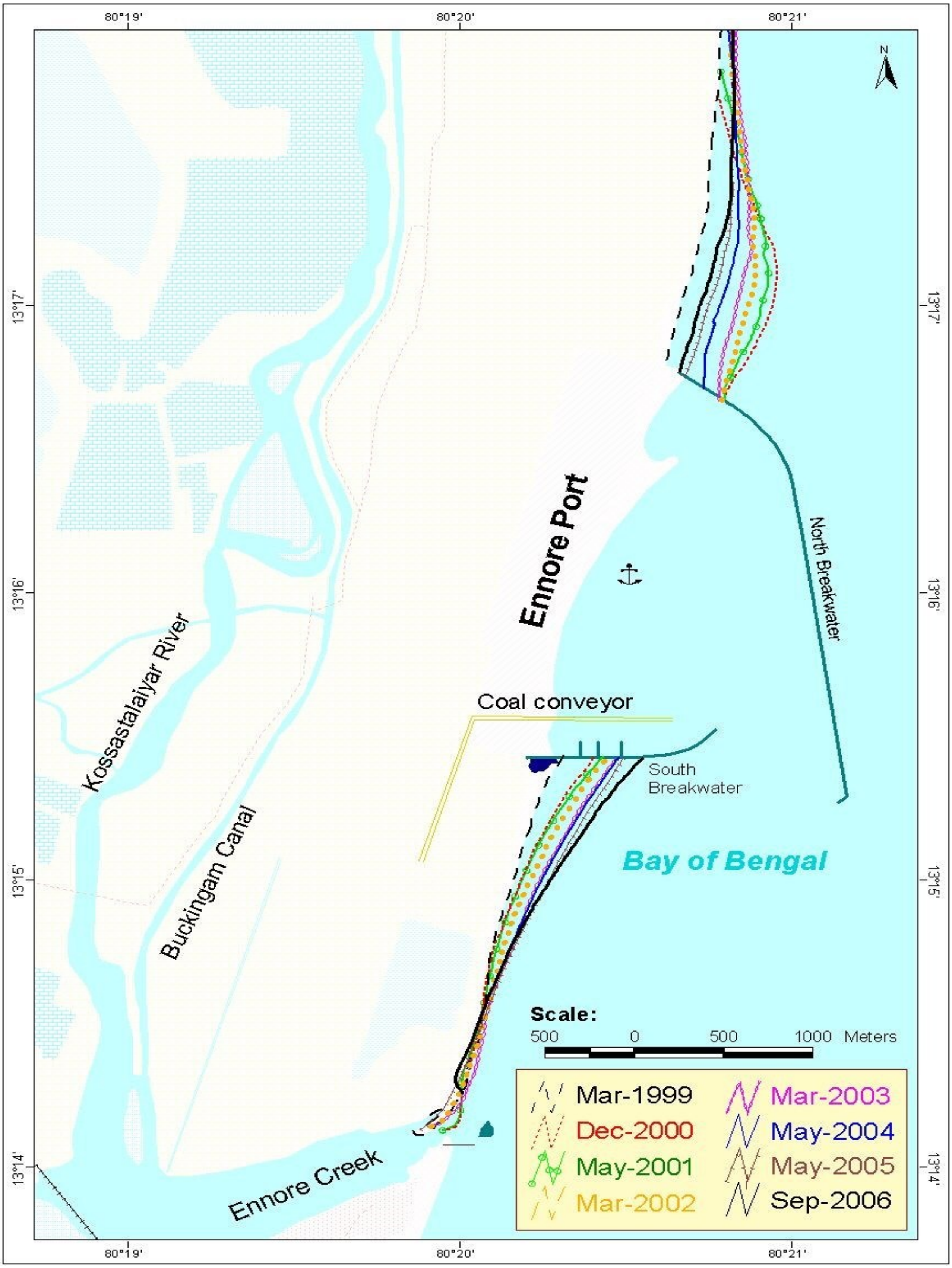


Figure 66. Shoreline Change Trend along Ennore Port

10.4 Inlet Management at Ramayapatnam

Ramayapatnam located on the north of Bahuda River in Ganjam district of Odisha is a fishing village, which hugely depends on the beach for various fishing activities like drying of nets and beaching of small fishing crafts (Figure 67). The river has a dynamic shore-parallel spit formation that changes seasonally as well as annually as seen in (Figure 68).

Generally, in the East Coast of India, the shifting of the river mouth is influenced by strong longshore transport and river discharges. When the discharges from the river are high during monsoon the mouth opens. The opening slowly migrates north due to littoral drift when the river discharges are weak. Once the river discharges are very low, the mouth closes and during the next season when discharges are high, the mouth opens once again on the southern side, this phenomenon is often cyclic. Similarly, in this location, the spit grows in the northerly direction for about 1000 m during the southwest monsoon before closing.

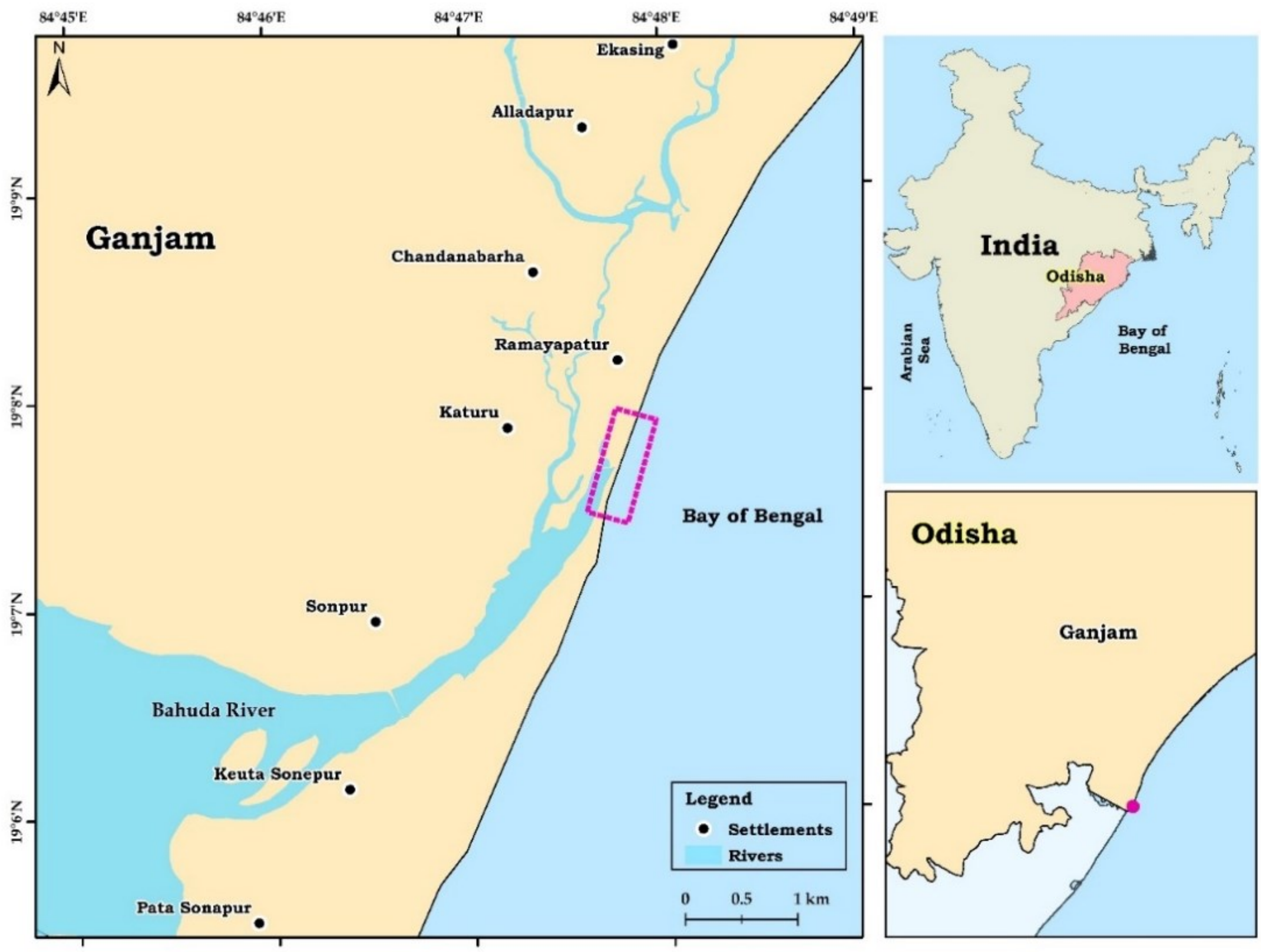


Figure 67. Ramayapatnam Coast in Odisha and its Environments

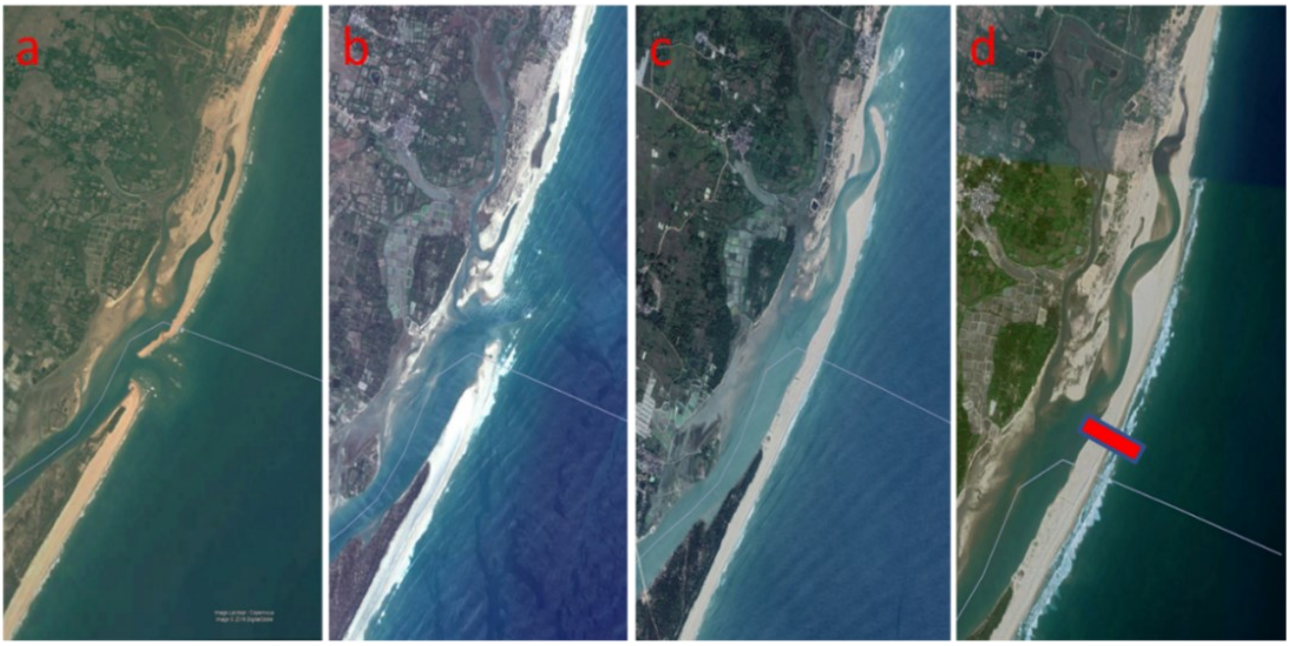


Figure 68. Seasonal Variation of the River Mouth and the Shoreline Erosion

The dynamic nature of this inlet poses a significant challenge, particularly for the village of Ramayapatnam located adjacent to the mouth, which experiences severe erosion. The beach is lost by the end of the southwest monsoon and given the frequent occurrence of extreme cyclonic events along the Odisha coast in the subsequent season, the village faces further erosion and inundation. Tidal ingress, coupled with extreme events, results in steep cliffs and substantial property loss in the affected area. The coastal village in the region bears the brunt of these challenges, losing access and livelihood. Nearly 400 fishing families are impacted almost annually.

Numerical analysis was carried out to understand the dynamics of the coast. From the analysis, it was understood that as the discharge of the river reduces, the spit from the South of the river mouth grows Northward, diverting the discharge towards the village. This diverted water erodes the coast. From the numerical analysis and satellite-based studies, it was observed that opening of the mouth, not only stops the erosion but also supplies sediment that re-creates the beach for the village.

Accordingly, the mouth of the river was artificially opened, which immediately recreated the beach, (Figure 69) thereby saving the village during extreme cyclonic events. In this scenario, the erosion issue is seasonal and can be addressed by opening the river mouth. Similar solutions can be applied to inlets with substantial upstream discharges. However, when upstream discharges are low, it becomes crucial to implement training walls to enhance the tidal prism, thereby ensuring the stability of the inlet.

Figure 69. Beach Before and After Implementation of the Proposed Solution

10.5 No Intervention at Eden Beach

Eden Beach is located in Chinna Veerampattinam, south of Puducherry harbour. This beach is situated just North of the famous Paradise beach of Puducherry. Eden Beach was developed as the first blue-flag beach, in the Union Territory of Puducherry. The blue flag beach is to promote eco-tourism for a sustainable tourism. With this in mind, infrastructure for the beach had been developed for the beach (Figure 70). However, in 2022, there was a sudden erosion of the beach, leading to damage of the infrastructure, developed for blue flag beach.

NCCR was approached to determine the cause of the erosion and to suggest suitable protection measures. A Shoreline change analysis carried out using satellite data from 1990 to 2022 indicated the beach to be in a low erosion to stable transmission region (Figure 71). Detailed analysis of the bi-annual trend based on satellite data indicated that a similar erosion was also observed in 2017 (Figure 72) and the beach recovered in the following seasons.

Detailed analysis carried out of the Chunnambar River mouth dynamics indicates the opening of the inlet for most of the year during 2022 when compared to previous years. This constant discharge from the river has obstructed the sediment transport, thereby causing erosion on the north of the inlet, acting as an obstruction to the littoral drift. As this is a very rare event, the option of wait and watch with continuous monitoring was recommended, expecting the same recovery as the 2017 erosion. As predicted, during the following season, the beach regained its former width (Figure 73).

A proper understanding of the coast and its influencing factors is necessary before developing coastal infrastructure. Generally, the construction of coastal infrastructure for tourism and other activities is to be avoided in erosion stretches. However, if the development must be carried out in that specific location, a proper estimation of the long and short-term erosion rate is to be considered. Based on the rate, allowance of the additional beach width, raising on stilts, or effective coastal protection measures should be provided for any permanent infrastructure.

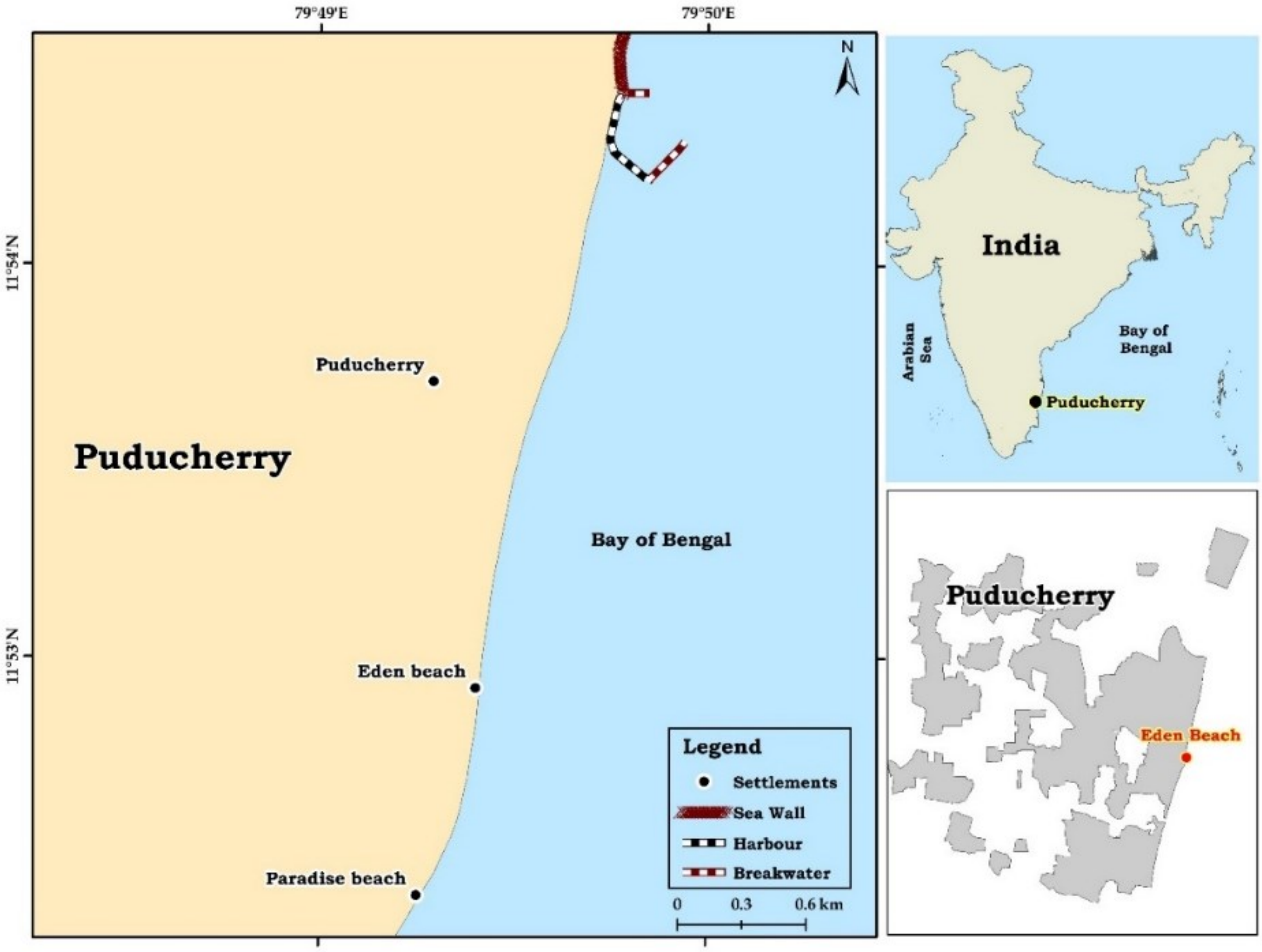


Figure 70. Eden Beach in Puducherry and its Environments

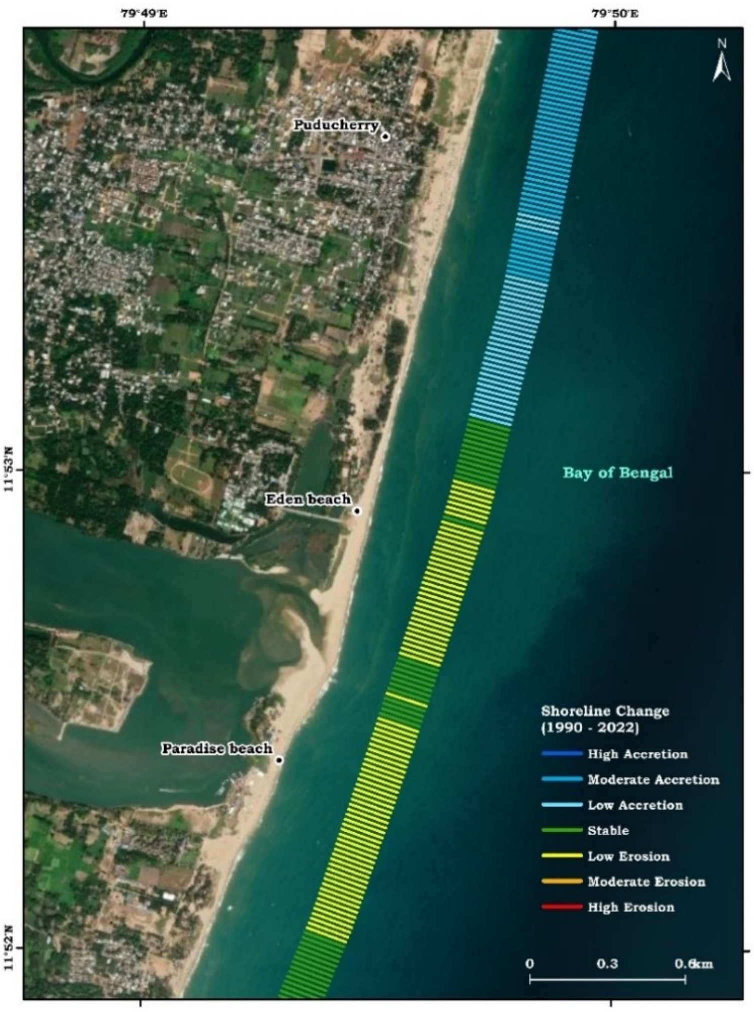


Figure 71. Long-Term Shoreline Changes in Eden Beach

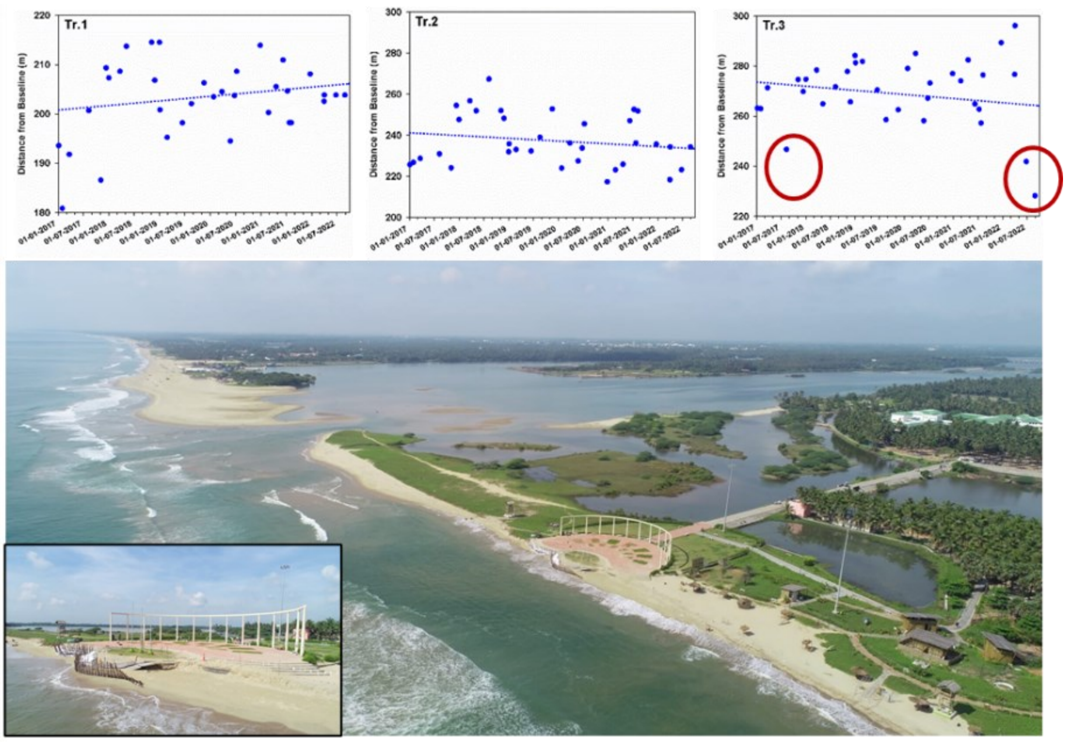


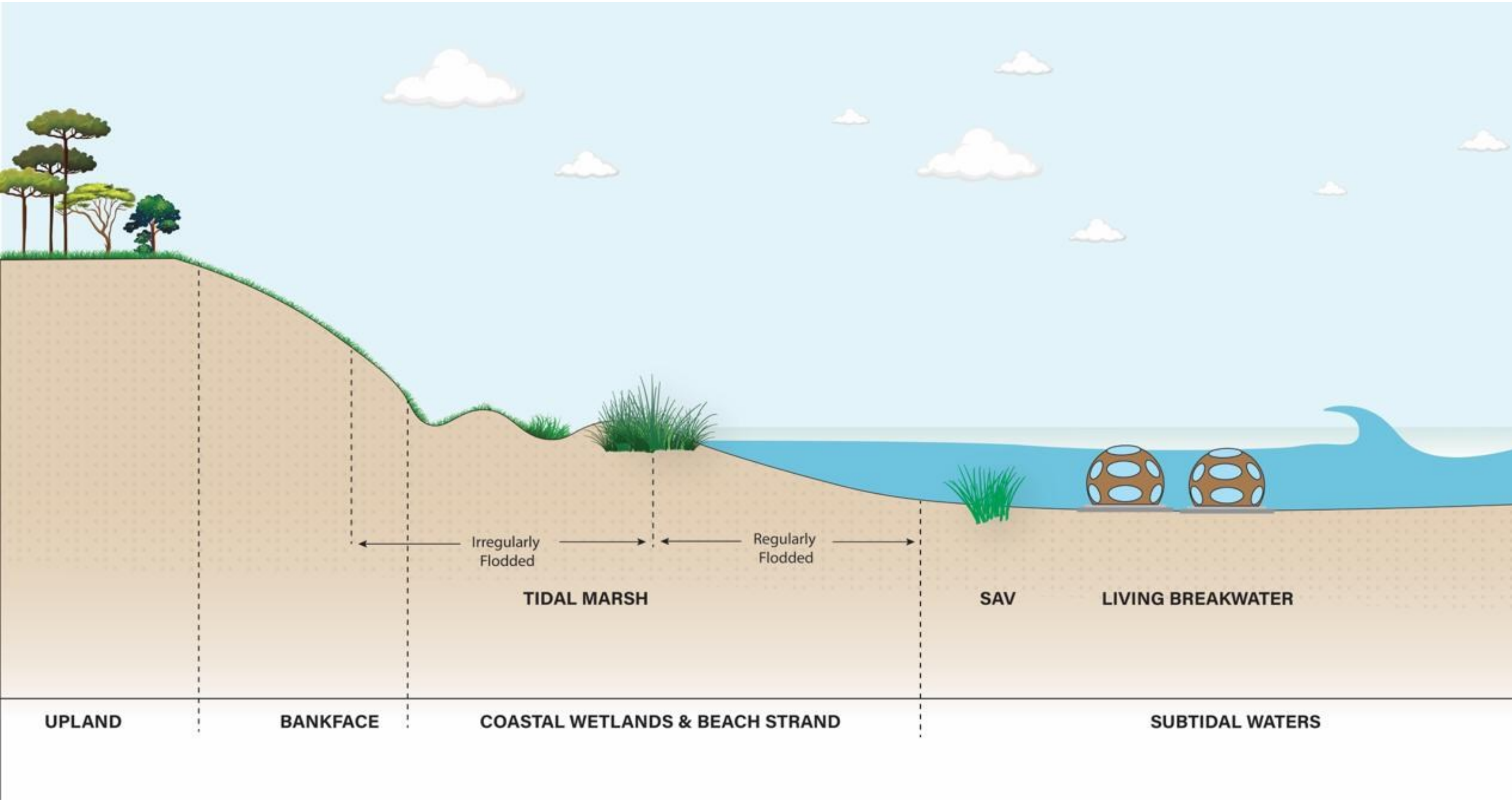
Figure 72. Shoreline Change Trends in Eden Beach

Figure 73. Eden Beach Restored without Intervention

The preceding case studies provide a succinct summary of diverse protection measures applicable to coastal areas. They showcase successful projects undertaken along the Indian coastline, ranging from hybrid to green solutions, and occasionally, scenarios with no intervention. Each case study was scientifically studied and proper monitoring has also been taken up to monitor their performance.

These projects act as guidelines and emphasize the importance of conducting a thorough analysis of the specific area in question. This detailed examination is crucial for devising sustainable protection measures without inadvertently causing negative implications in the targeted area or adjacent regions. The studies underscore that a one-size-fits-all approach is inadequate, highlighting the need for tailored solutions based on the unique characteristics and challenges of each coastal zone.

Similar projects can be implemented along the Indian coast to not only protect the coast but also in an adaptable and sustainable way.



11 SHORELINE MANAGEMENT PLAN

> **"It provides comprehensive and integrated framework for managing the coastal areas, addressing the challenges posed by natural processes, human activities, and climate change**

A Shoreline Management Plan (SMP) serves as a comprehensive and strategic framework guiding the management and utilization of coastal regions over a designated horizon, typically spanning 10 to 15 years. This plan is meticulously crafted to align the multifaceted interests of a wide array of stakeholders including residents, businesses, recreational enthusiasts, and environmental organizations within the context of the coastal zone's inherent dynamism and associated risk factors. Its overarching aim is to foster a balanced coexistence between human activity and the natural environment, thereby ensuring the resilience and well-being of coastal communities. Furthermore, the SMP is instrumental in preserving the integrity of natural ecosystems, addressing the challenges posed by climate change and protecting the area's rich cultural and historical legacies. Through a judicious blend of planning, regulation, and community engagement, the SMP embodies a forward-looking vision for sustainable coastal management, underpinning efforts to enhance environmental stewardship, economic vitality and social welfare along the shoreline.

11.1 Key Components for SMP

The interface between land and sea represents a dynamic zone of continuous transformation, governed by the complex interplay of ocean processes and geological forces. A profound understanding of these interactions is crucial for devising robust Shoreline Management Plans (SMPs). Such plans are designed to navigate the array of challenges confronting coastal communities, ranging from erosion and flood risk to ecological degradation. By merging scientific insights with active stakeholder involvement and principles of adaptive management, SMPs aim to harmonize the preservation of natural ecosystems and the safeguarding of coastal infrastructures, all while fostering sustainable development practices. The core components critical for informed policymaking and the formulation of an effective management strategy include:

(a) **Understanding of Nearshore Processes:** A thorough examination of nearshore phenomena encompassing wave action, tidal movement, currents, and sediment dynamics is fundamental. This analysis aids in understanding the forces sculpting the coastal landscape, informing both protective measures and conservation efforts.

(b) **Shoreline Change Analysis**: Evaluating historical shoreline shifts is pivotal for pinpointing regions subjected to significant erosion or accretion. This empirical evidence serves as a basis for identifying vulnerable hotspots, directing targeted intervention to mitigate potential risks.

(c) **Stakeholder Engagement**: Engaging a wide array of stakeholders, from Government bodies to local communities, is essential for gathering a broad spectrum of insights on coastal challenges, especially in the context of extreme weather events and climate change impacts. This inclusive approach ensures the SMP reflects the collective needs and preferences of all stakeholders involved.

(d) **Data Collection**: Comprehensive data collection on beach characteristics, geomorphological attributes and the current state of coastal protection structures underpins the development of the SMP. This entails detailed field surveys to delineate natural defences warranting preservation and areas necessitating engineered protections, thereby informing a strategy that is both effective and ecologically sensitive.

(e) **Monitoring**: The implementation of SMP requires continuous monitoring to evaluate its efficacy and adaptability. This involves the regular assessment of policies and interventions to guarantee they remain responsive to evolving coastal conditions and emerging challenges.

Incorporating these fundamental components, the SMP becomes a living document, capable of guiding the sustainable management of coastal zones through informed decision-making and proactive stewardship.

11.2 Strategies of SMP

The strategies delineated within a Shoreline Management Plan (SMP) are fundamental in navigating the complex challenges posed by dynamic coastal environments and underscore the critical need for sustainable coastal management. SMPs offer a spectrum of strategies that tailored to the unique characteristics and needs of each coastal region. The primary strategies include:

(a) Nature based solution: This approach leverages the inherent capacity of natural ecosystems to mitigate coastal hazards and bolster resilience. By preserving the coastline in its natural state as much as possible, this strategy employs techniques such as beach nourishment, dune replenishment, the establishments of plantations and the creation of living shorelines to enhance coastal defence in an environmentally sustainable manner.

(b) Hard solution: Involving the deployment of engineered structures to protect the coast, hard solutions are designed for immediate impact in areas where alternative approaches are impractical. Common methods include the construction of seawall, groins, breakwaters, training walls, which, while effective in the short term, may require significant maintenance and can impact adjacent areas.

(c) Hybrid solution: A blend of nature-based and hard solutions, hybrid strategies aim for a balanced approach to coastal management. This methodology capitalizes on the benefits of both strategies, aiming to offset their limitations by integrating engineered structures with natural processes to achieve sustainable coastal protection.

(d) Monitoring site: Identified as areas for vigilant observation, monitoring sites adopt a 'wait and observe' approach. These locations, currently not experiencing severe erosion, are recognized as potentially vulnerable and monitored for signs that may necessitate future intervention.

(e) No Action: This strategy represents a conscious choice to refrain from intervention, typically employed when the issue at hand is considered negligible (stable or accreting coast) or when the cost or risk associated with action outweighs potential benefits. It underscores the importance of judicious decision-making in shoreline management.

In conclusion, SMPs provide a multifaceted toolkit for coastal risk mitigation, incorporating nature-based, hard, hybrid, and adaptive management strategies, alongside monitoring and selective non-intervention. Careful selection and implementation of these strategies, informed by an in-depth analysis of environmental, social and economic factors, are crucial for the long-term success of coastal management efforts. By fostering collaboration and employing a comprehensive and adaptive approach, SMPs play a crucial role in protecting coastal communities and ecosystems, enhancing resilience, and preparing for future challenges.

11.3 Policy Units and SMP

Building upon the foundational analyses and insights garnered throughout this document, this section serves as a pivotal junction in Shoreline Management Plan. It draws upon key findings from shoreline change analysis, field surveys, stakeholder interactions, and infrastructure assessments across the Union Territory of Puducherry. The recognition of erosion and structural priority areas, alongside understanding stakeholder needs, has been crucial in crafting tailored strategies for each policy unit. This aggregation of data and insights not only reinforces the strategic underpinnings of our management approach but also emphasizes the importance of a collaborative, evidence-based framework that is responsive to both environmental dynamics and community needs. As we delve into each policy unit, the convergence of shoreline analysis, stakeholder input and infrastructural assessment forms a critical backdrop, informing a nuanced approach to shoreline management that is aligned to the unique characteristics and challenges of Puducherry coast.

This section presents an in-depth exploration of the four delineated policy units extending from Ganapathychettikulam to Puducherry Harbour and from Puducherry harbour to Pudhukuppam in Puducherry, from Mandapathur to Vanjur in Karaikal, and Mahé bordering Kerala, forming the intricate coastal tapestry of the Union Territory of Puducherry. It methodically unpacks the strategic vision tailored to each unit, emphasizing the harmonization of environmental sustainability with community welfare and infrastructure resilience. This segment is meticulously curated with discussions, tables, and maps, offering a comprehensive understanding of the localized challenges, opportunities, and planned interventions. They are not merely segments of the coastline but are recognized as dynamic stretches formed by thoughtful division based on geomorphology, coastal infrastructures and sediment drift patterns. It stands as a testament to the overarching aim of the SMP: to foster a resilient, vibrant coastline that supports the livelihoods of its communities while ensuring the protection and rejuvenation of its natural habitats. Below are the details of each of the four stretches.

Stretch 1 – Ganapathichettikulam to Puducherry Harbour

This coastal stretch of the Union Territory of Puducherry is a vibrant amalgamation of major tourist destinations and fishing villages. This stretch has prominent tourist attractions such as Auroville, White Town, Promenade, Pondy Marina, alongside key fishing hubs including Kalapet, Pillaichavady and Puducherry harbour. The Thengaithittu estuary and Ariyankuppam river, discharging into the Bay of Bengal at Puducherry harbour, enhance the area's ecological diversity with their mangrove populations, conserved by Government efforts. The coastal protection measures in this stretch are predominantly composed of seawalls and groins placed from Muthialpet to Puducherry harbour to safeguard the shoreline. An innovative approach through the use of an artificial reef along Rock beach demonstrates the potential for beach development and protection within the Union Territory. This one of its kind protection structure facilitates year-round beach presence. Additionally, groin fields along Pillaichavady and Serenity beach are instrumental in shore protection and facilitates boat landing along the coast.

The shoreline exhibits stability across Muthialpet and White Town with erosion at Auroville and Serenity beaches. However, the heightened protection of coast south of Kalapet has exacerbated the erosion along the Kalapet stretch necessitating the protection of coast for promoting beach growth and sustainable fishing activities. The regulatory zone transitions from CRZ III in Ganapathichettikulam to Pallaichavady, to CRZ II from White Town to Pondy Marina. High population densities in the fishing villages contrast with the sparser tourists' spots of Rock beach and Promenade beach, making these prime locations for tourism development. For coastal protection, the introduction of transition groins at with nourishment Kalapet, Auroville beach, and Serenity beach is proposed, alongside seawall reformations at Pondy Marina to maintain expansive beaches. Reconfiguration of the Puducherry harbour breakwaters facilitates the free exchange of water, reduces siltation, effectively bypasses the sand and permits safe manoeuvring of fishing vessels. This blend of soft and hard protective measures is tailored to address the unique characteristics of this stretch, ensuring a balanced approach to shoreline management that supports both ecological preservation and the thriving local economy.

Table 23. Management Stretch from Ganapathichettikulam to Puducherry Harbour

Ref	Proposed Infrastructure / Coastal Protection	Observations / Recommendations	Environmental safeguard
A	Protection of coast at Kalapet, Pillaichavady and Ganapathy Chettikulam	Hybrid solution with transitional groins is recommended with sand filling in groin compartments. Sediments can be sourced from offshore if there is non availability of sediments from nearby sources.	-
B	Protection of coast at Auroville beach	Hybrid solution with transitional groins is recommended with sand filling in groin compartments. Sediments can be sourced from offshore if there is non availability of sediments from nearby sources.	-
C	Protection of coast at Serenity beach	Hybrid solution with transitional groins is recommended with sand filling in groin compartments. Sediments can be sourced from offshore if there is non availability of sediments from nearby sources. Additionally the possibility of T-groins may also be considered after detailed modelling studies.	-
D	Protection of coast along Kottakuppam to Kuruchikuppam	Reformation of the seawall is recommended.	-
E	Protection of Vaithikuppam	Nature-based solution comprising of beach nourishment recommended	
F	Beach development along Promenade beach	Construction of South Reef is recommended for beach stabilization.	Dredged sand from Puducherry harbour shall be continued as beach nourishment along the South of existing reef
G	Protection of coast along Pondy Marina	Reformation of the seawall is recommended.	-

H	Puducherry harbour breakwaters	The reconfiguration of breakwater to improve sediment bypassing and reducing harbour siltation is recommended after detailed numerical modelling studies.	Dredged sand from Puducherry harbour can be used as a sediment source to protect adjacent coast.

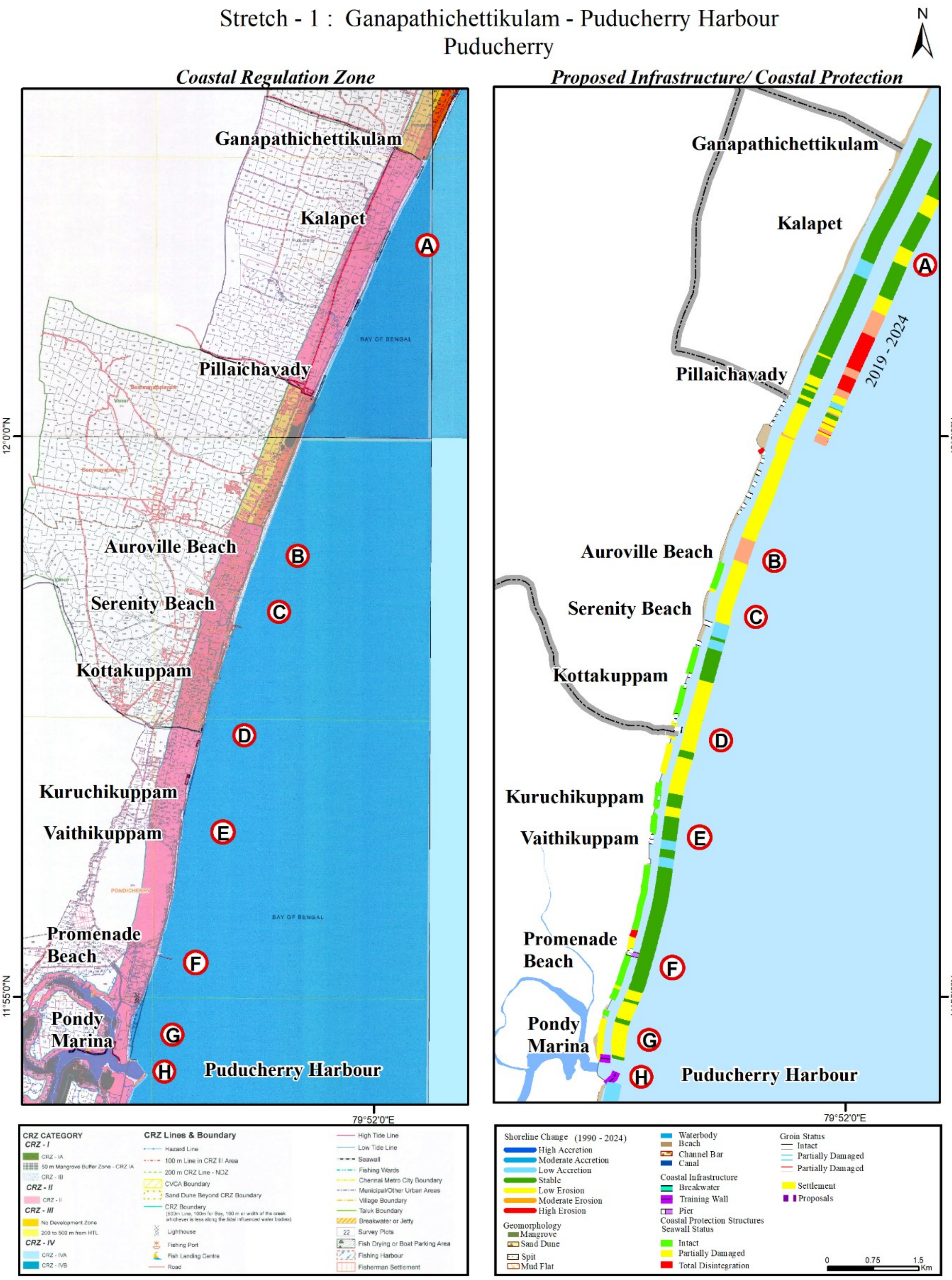


Figure 74. Management Stretch from Ganapathichettikulam to Puducherry Harbour

Stretch 2 – Puducherry Harbour to Pudhukuppam

The coastal area encompassing this stretch of Union Territory of Puducherry reinforces its shoreline with naturally broad beaches and sand dunes, serving as a buffer against ocean waves. The Chunnambar river and the Nallavadu inlet constitute significant sources of sediment transport from land to sea. The area from Veerampattinam to Eden beach shows signs of accretion, with seasonal fluctuations anticipated around the Chunnambar river mouth. Eden Beach, a Blue Flag beach in Puducherry, is situated adjacent to the mouth of the Chunnambar river and stands as a prominent tourist attraction. Following it is Paradise Beach, offering a wide range of beach sports and activities, thus contributing to the tourism development of the Union Territory. Characterized by a coast that is accreting and stable, conservation efforts are kept to a minimum level. The naturally sheltered coast, with sparse population, is best preserved in its pristine state. The Coastal Regulation Zone (CRZ) designation transitions from CRZ II at Puducherry Harbour to Eden Beach, with the remaining stretch up to Nallavadu falling under CRZ III. The optimal management strategy for this stretch is dictated by nature itself, suggesting that enhancement of dunes preserves the natural balance of the ecology and ecosystem along Nallavadu and Pudhukuppam. Further management for free exchange of water through Thenpennai river mouth can be achieved through construction of training walls and placement of dredged sediments on the downdrift side to mitigate erosion.

Table 24. Management Stretch from Puducherry Harbour to Pudhukuppam

Ref	Proposed Infrastructure / Coastal Protection	Observations / Recommendations	Environmental safeguard
A	Dune replenishment along Nallavadu to Pudhukuppam	The stretch is under stable zone and bio shied strengthening measures through plantation is suggested to strengthen the sand dunes for coastal resilience.	-
B	Protection of Moorthykuppam coast	This stretch is under low erosion and beach nourishment is recommended using dredged sand from Thenpennai river mouth. Additionally, the possibility of groins may also be considered after detailed modelling studies if erosion persists after nourishment.	-
C	Construction of training wall for Thenpennai River mouth	Construction of training wall at Thenpennai river mouth can be considered after detailed numerical modelling studies.	Dredged sand from Thenpennai river mouth can be used at suitable locations to prevent down drift erosion.

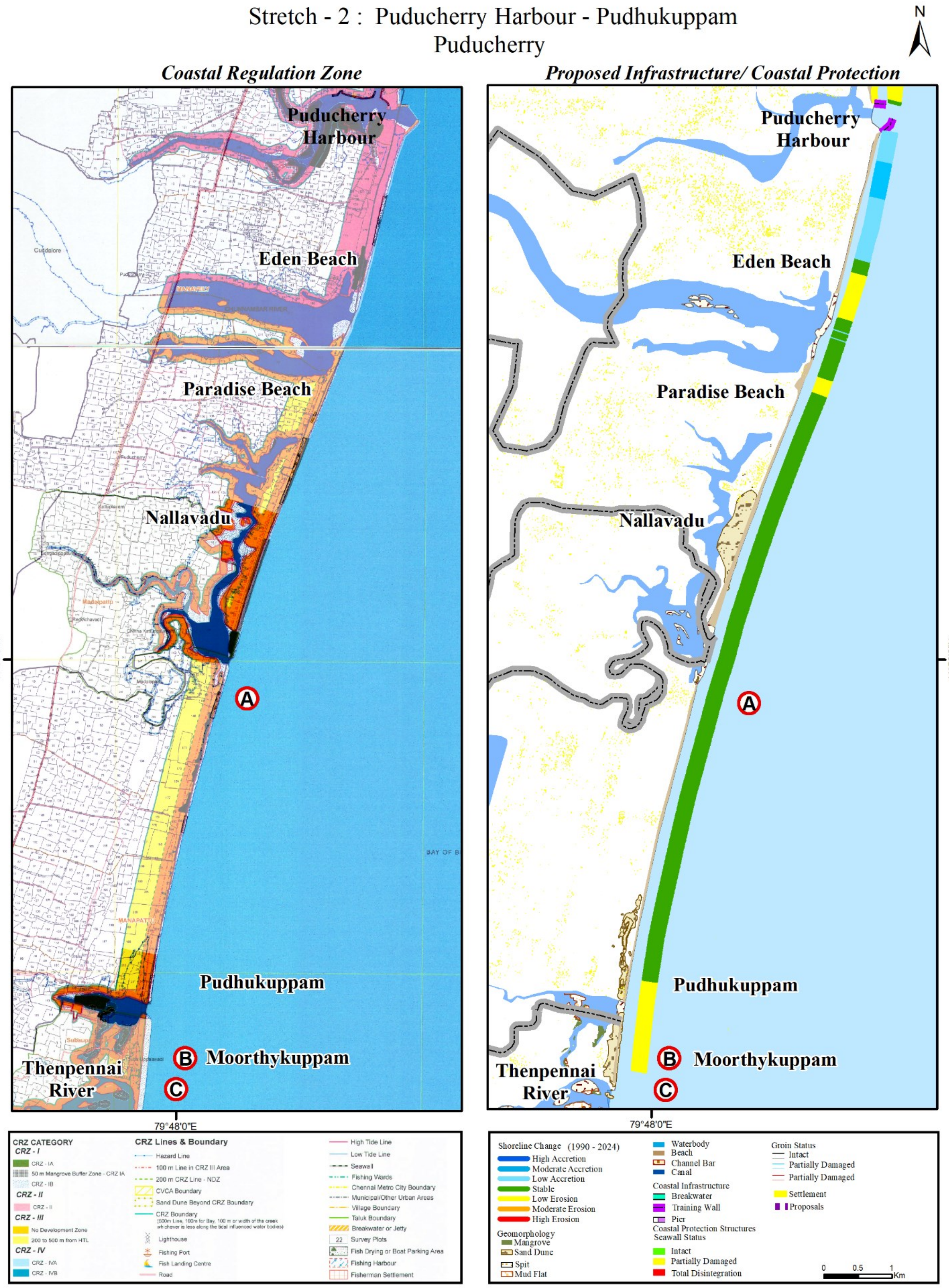


Figure 75. Management Stretch from Puducherry Harbour to Pudhukuppam

Stretch 3 -Mandapathur to Vanjur

The coastal stretch from Mandapathur to Vanjur, within the Karaikal district of the Union Territory of Puducherry, is endowed with sandy beaches, inlets, river mouths, sand dunes, seawalls, training walls, and a commercial harbour, facing challenges of sea erosion across its expanse. To mitigate this, enhancing sand dunes through strategic plantations at locations from Mandapathur to Kazakudimedu is proposed to control erosion. Additionally, the maintenance dredging of inlets at Kalikuppam, Kottucherry and Kazakudi could serve dual purposes: replenishing the dunes and aiding in coastal protection.

For the area stretching from south of Kazakudimedu to Kilinjalmedu, where settlements and coastal infrastructure are in close proximity to the shoreline, the installation of short groins is recommended to minimize erosion, coupled with beach nourishment to maintain coastal stability. The Karaikal regions hosts a river-based fishing port, with the Arasalar river mouth being stabilized by two training walls. This segment, characterized by its ecological sensitivity due to the presence of numerous sand dunes, would benefit from the reinforcement of these natural barriers through suitable vegetation to reduce erosion impact.

This comprehensive management plan across the diverse CRZ zones – from CRZ III in Kalikuppam to Kazhkudi medu (3 Km), CRZ II from Kazakudi medu to Tirumalairayan Pattinam (7 Km), and back to CRZ III towards Vadakku Vanjur (7 Km), aims to integrate hard and soft protective measures. By prioritizing bio-shield measures and beach nourishment, the strategy seeks to not only safeguard the coastline from erosion but also preserve the ecological integrity of this vital stretch, enhancing the livelihoods of the local fishing communities. This balanced approach underscores the importance of maintaining the natural landscape while addressing the pressing challenges posed by sea erosion, ensuring the sustainability and resilience of the Karaikal district's coastal regions.

Table 25. Management Stretch from Mandapathur to Vanjur

Ref	Proposed Infrastructure / Coastal Protection	Observations / Recommendations	Environmental Safeguard
A	Protection of coast along Mandapathur to Kazakudimedu stretch	Bio shield measures through plantations is recommended to strengthen the sand dune	-
B	Protection of coast along Kazakudimedu to Kilinjalmedu stretch	Construction of short groins with beach nourishment at Kilinjalmedu is plausible after detailed numerical modelling studies. Bio shield measures through plantations is recommended to strengthen the sand dune on either side.	Suitable sand source maybe identified for nourishment
C	Protection of coast along Kilinjalmedu to Karaikal stretch	Bio shield measures through dune replenishment and plantations is recommended to strengthen the coastline	-
D	Protection of coast along Karaikal to Thirumalairayan (TR) Pattinam stretch	Bio shield measures through dune replenishment and plantations is recommended to strengthen the coastline	-
E	Protection of coast along Thirumalairayan Pattinam to Vadakku Vanjur stretch	Nature based solution comprising of beach nourishment using dredged sand from Karaikal private port is recommended to strengthen the coastline. Additionally, bio shield measures through dune replenishment and plantations are recommended to strengthen the sand dunes.	-
F	Protection of coast from south of Karaikal private port to Vettar river.	Nature based solution comprising of beach nourishment using dredged sand from Vettar river is recommended to strengthen the coastline.	-

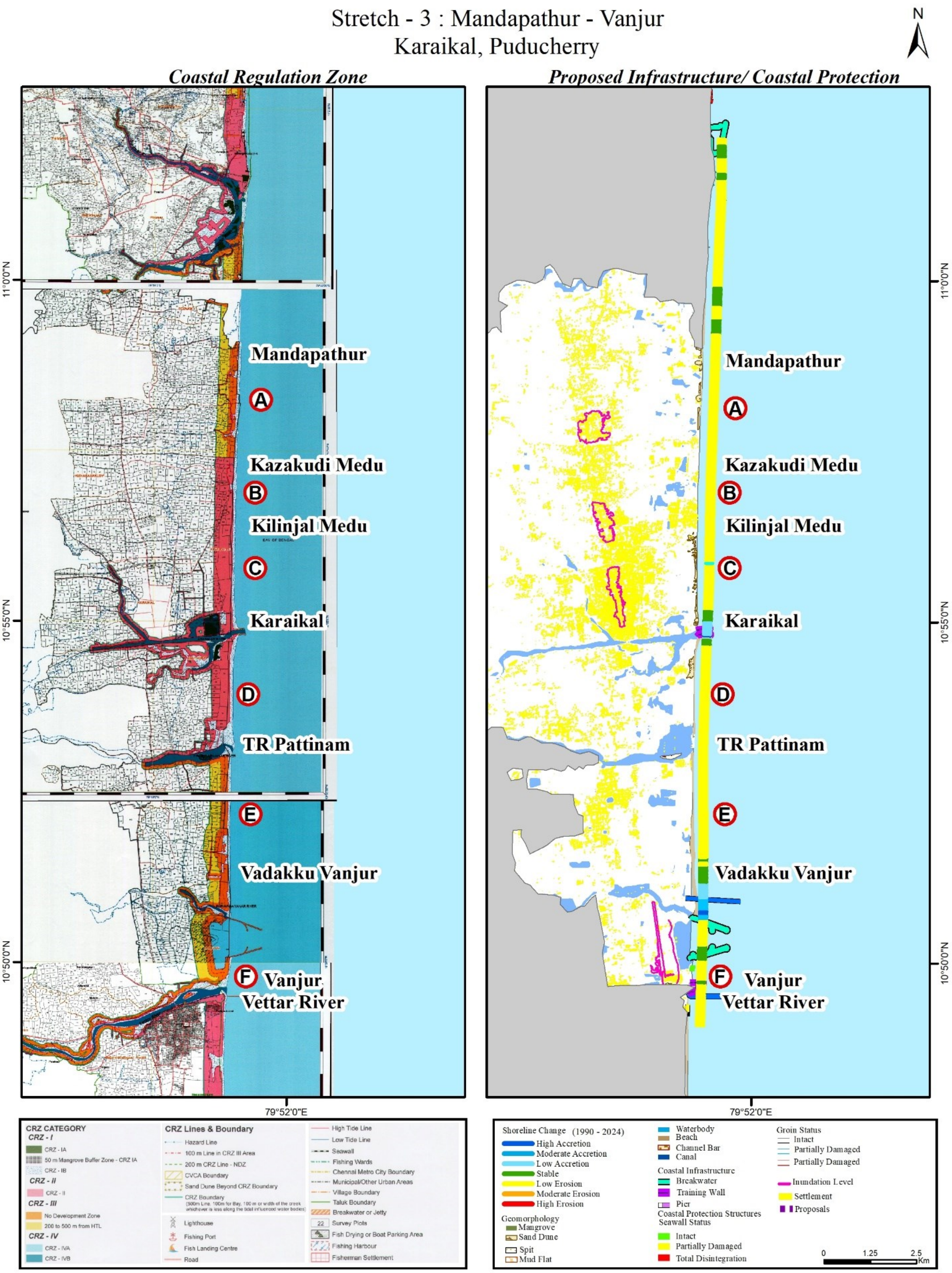


Figure 76. Management Stretch from Mandapathur to Vanjur

Stretch 4 – Mahé

The coastal stretch from Poozhithala Beach to Mahé Fishing Harbour encapsulates the urbanized sector (classified under CRZ II zone) of the Mahé region of Puducherry Union Territory, prominently featuring the Mahé fishing harbour. Key coastal structures in this area include partially disintegrated RMS wall of 300 m with thick vegetation cover and intact breakwaters of Mahé fishing harbour. After the construction of Mahé fishing harbour breakwaters, the southern coast is observed to be stable to accreting coast with beach widths of 10 to 15 meters, whereas, low erosion is observed towards the north. Only during extreme conditions the beach is lost and restored during fair weather period. Therefore, this stretch is to be continuously monitored to understand the coastal processes responsible for the dynamics of the coast. The overarching management strategy for this stretch emphasizes on the leveraging existing infrastructure to bolster economic opportunities for the local communities while maintaining coastal stability.

Table 26. Management Stretch for Mahé

Ref	Proposed Infrastructure / Coastal Protection	Observations / Recommendations	Environmental Safeguard
A	South of Mahé fishing harbour	It is observed to be stable to accreting coast. Only during extreme events the beach is lost and restored during fair weather period. Therefore, this stretch is to be monitored to understand the coastal processes responsible for the dynamics of the coast.	-

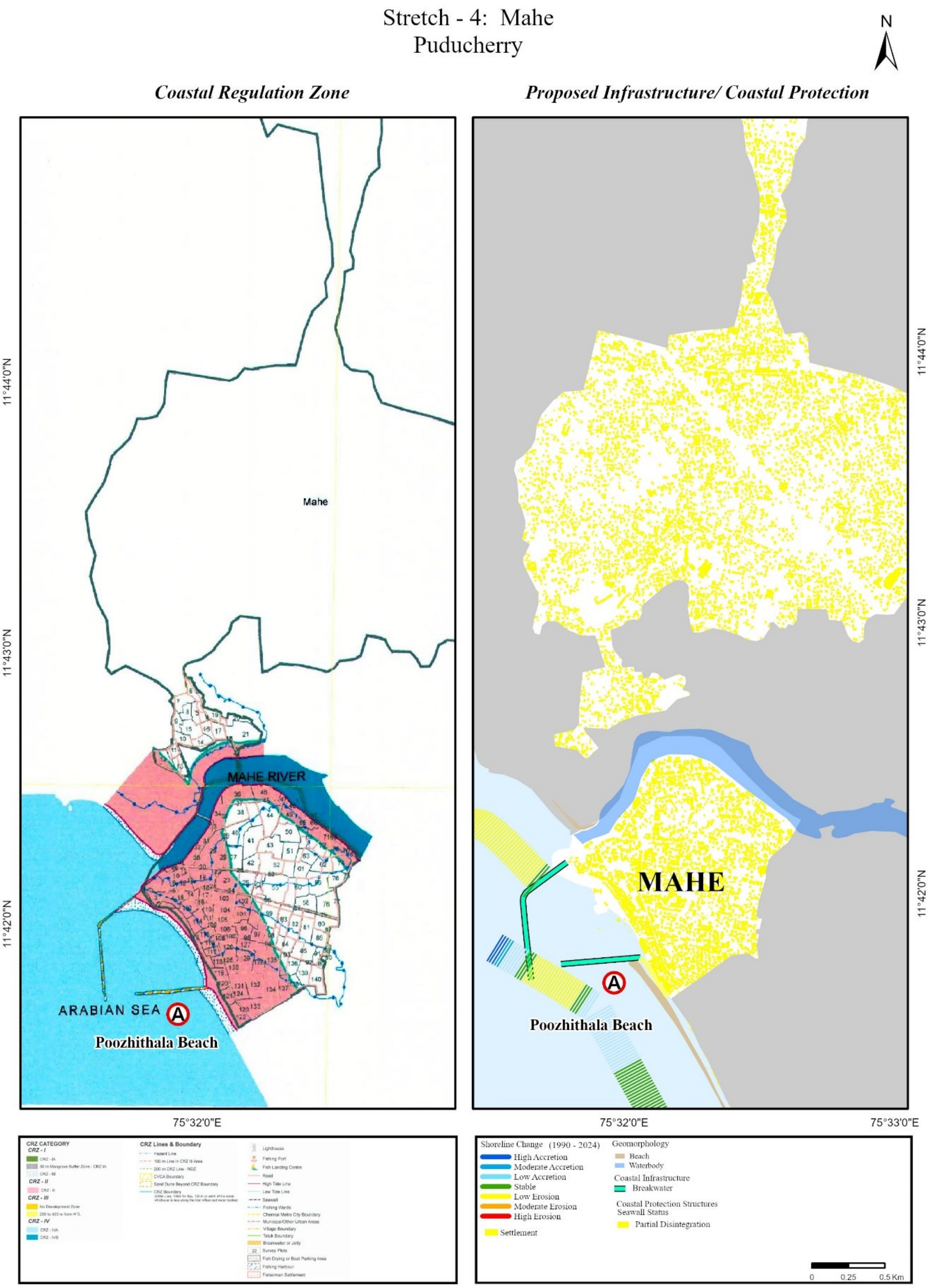


Figure 77. Management Stretch for Mahé

11.4 Modifications to SMP

The SMP has been formulated to migrate towards nature-based solutions, though predominantly, India has been practicing hard solutions for over 4 decades. Such structures have caused tremendous stress on the shoreline often creating large erosion issues on the adjacent areas. Therefore, a ladder has been proposed on the order of preference (Figure 78)

11.4.1 Climbing down the ladder

The option of climbing up the ladder is recommended. However, if one wishes to climb down the ladder, then detailed scientific studies (listed in Section 11.4.4) are to be carried out and reported to the agency before pursuing.

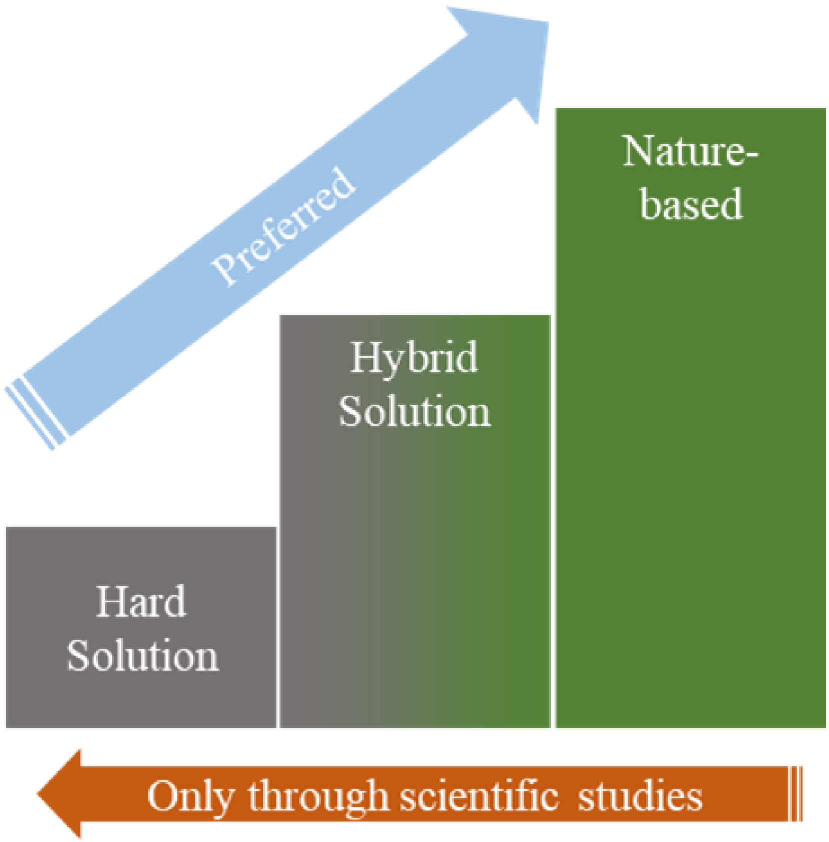


Figure 78 Ladder of Preference

11.4.2 Nature-based solutions

Wherever nature-based solutions such as beach nourishment, dune replenishment have been proposed and the same has been carried out for two seasons and the rate of erosion has not subsidized, then hybrid solutions maybe carried out after scientific studies listed in Section 11.4.4, with reasoning of the failure of the previously implemented nature-based solution as recommended by SMP.

11.4.3 Monitoring site

After monitoring the recommended coast for at least two seasons, and the erosion is seen as aggravating/ there is a loss of infrastructure/ community assets, then suitable management strategy preferably nature-based solution, followed by hybrid and in extreme cases, hard solutions can be implemented only after detailed scientific studies listed in Section 11.4.4.

11.4.4 Scientific Studies

The following thorough assessments and scientific studies are to be carried out:

1. In the case of coastal infrastructure, a feasibility study of using the existing/ nearby infrastructure has to be detailed in the studies undertaken,
2. Site-specific seasonal field measurements such as bathymetry, topography, sediment sampling, wave, tide, etc.
3. Long-term and short-term shoreline change analysis of the region
4. Understanding of the source/ cause of the issue and the sediment budget of the region and sediment management
5. Numerical modelling of the coastal processes,
6. Shoreline morphology due to the intended structure,
7. Social and environmental impact assessment of the project, and
8. Cost-benefit analysis of the proposed project

Post-monitoring of the site is necessary for all structures to understand the shore's evolution and structural performance.

11.5 Integration of New Proposals into SMP

If any new proposal of ports, fishing harbours or tourism project is envisaged apart from those collected during the stakeholder interaction and the government, the guideline for suitable action is provided in the following section.

11.5.1 Proposed Ports

Coasts play a pivotal role in global trade, serving as gateways for the efficient movement of goods and fostering economic development. Ports, as essential components of coastal regions, face a myriad of challenges arising from dynamic environmental conditions, climate change impacts, and increasing human activities. Developing a comprehensive coastal management strategy for ports is imperative to ensure sustainable and resilient operations in the face of these challenges. The management of coastal areas involves a delicate balance between promoting economic growth through port activities and safeguarding the ecological integrity of the surrounding environment. Recognizing the intricate interplay between human development and natural ecosystems is crucial for devising strategies that prioritize both economic objectives and environmental conservation. Implementation of port infrastructure generally involves the implementation of breakwaters to provide tranquil conditions inside the port. However, in most cases, these breakwaters stop the sediment transport along the coast. In general, along the east coast of India, net sediment transport is from south to north. So, construction of port will cause accretion in the south and erosion in the north of the Port. Apart from this, a navigational channel is also generally provided for meeting the draft requirements of the vessels and are subjected to siltation. These navigational channels are regularly dredged to maintain the draft requirements. The removal of sediments from these navigation channels hinders the bypassing of the sand to north, further aggravating the erosion in the north.

The following guidelines are to be followed for the ports that are to be established in this coast. The following guidelines are for the ports that are already proposed and that, that to be proposed between the next revision:

a) The shoreline change analysis at a radial distance of 6 km pre- and post- construction of port has to be assessed and suitable mitigation strategies should be implemented.
b) The effect of climate change leading to increased wave energy, sea level rise, increase precipitation, storm surge should be predicted and taken into consideration during the design stage of the port.
c) The breakwater is to be designed for minimal siltation of the channels and minimal impact of the sediment transport along the shore, as much as possible without affecting the function of the port.
d) The possibility of utilising capital and maintenance dredging as nourishment for mitigating erosion should be explored before seeking for any structural interventions.
e) The inlet dynamics and the effect of the port on inlets is to be assessed.
f) Whenever possible, construction of port as natural port shall be examined so as to minimize capital dredging and impact on the shore.
g) The effect and impact of adjacent structures should be taken into consideration
h) The beach profiles should be collected every 6 months and satellite studies on the shoreline change during and after the implementation of the port is to be carried out.

11.5.2 Proposed Fishing Harbours

Fishing harbours are specialized ports or harbours designed and equipped to support the fishing industry. They serve as key infrastructure for the fishing sector, providing facilities for the landing, processing, and distribution of fish and seafood products. In the Indian context, fishing harbours are of paramount importance due to the nation's extensive coastline and the significant role played by the fishing sector in supporting livelihoods, ensuring food security, and contributing to economic growth. The strategic placement of fishing harbours along the coast facilitates efficient seafood production, distribution, and export, underscoring their vital role in sustaining coastal communities and fostering the overall development of India's marine resources. Implementation of fishing harbour, like Ports, generally involves the implementation of breakwaters to provide tranquil conditions inside for landing of boats. However, in most cases, these breakwaters stop the sediment movement along the coast. This causes accretion on one side and erosion on the other side of harbour. Therefore, effective and adaptive strategies are essential for sustainable management of coast at proposed fishing harbours.

The following are the general guidelines that has to be followed for better shoreline management near fishing harbours.

i) The shoreline change analysis at a radial distance of 6 km pre- and post- construction of harbour has to be assessed and suitable mitigation strategies should be implemented.
j) The harbour should be preferred inside the inlet or creaks, where ever possible to minimise the dredging issues.
k) The entrance of harbour should ensure easy access for fishing vessels, taking into account navigation channels and approach routes. At the same time the orientation should ensure effective bypassing of sand to minimise the maintenance dredging and down drift erosion.
l) Evaluate the potential for natural shelter for boats during storms and waves.
m) The possibility of utilising capital and maintenance dredging as nourishment for mitigating erosion should be explored before seeking for any structural intervention.
n) The effect and impact of adjacent structures should be taken into consideration
o) The beach profiles should be collected every 6 months and satellite studies on the shoreline change during and after the implementation of the fishing harbour is to be carried out.

11.5.3 Proposed Tourism

Effective coastal management is essential for the sustainable development and planning of tourism in beach destinations. The economic importance of beaches and coastal tourism is undeniable. With the global allure of coastal areas attracting tourists, there is an urgent need to implement robust management strategies that harmonize the demands of tourism with the preservation of the coast. The integration of shoreline management plans with sustainable tourism development offers a pathway to achieve a balance between economic growth, environmental conservation and community well-being in coastal regions. This holistic approach not only fosters resilience but also enhances the attractiveness of destinations for tourists while safeguarding the natural assets of the region in an eco-friendly manner. Beaches serve as both natural treasures and vital contributors to the livelihoods of local communities.

While planning tourism developmental activities in the beaches, it is essential to adopt a comprehensive approach that addresses the challenges posed by environmental changes. The planning process should carefully consider the dynamic nature of shoreline analysis, especially when establishing permanent infrastructure for tourism development at any beach. It is also to be understood that the potential impacts of climate change, such as sea-level rise and increased storm intensity, should be considered while planning beach development. The infrastructure is to be designed in such a way to be resilient in the face of changing environmental conditions. It is imperative that the shoreline change rate for the locations are the main considerations to establish any tourism infrastructure on the beach.

The beaches with tourism potential can to be classified into 4 categories viz. 1) High to moderate erosion, 2) Low erosion, 3) Stable to low accretion, and 4) Moderate to high accretion based on the shoreline change analysis of NCCR. For each category suitable management strategy has been proposed as given in Table 27. In addition, few best practices that are common for all locations are also proposed for sustainable conservation and development.

Table 27 Management Strategy for Tourism for different shoreline status

No.	Shoreline Change Status	Management Strategy
1	High Erosion	No new tourism development
	Moderate Erosion	
2	Low Erosion	May develop tourism with minimal intervention
3	Stable	Tourism Development
	Low Accretion	
4	Moderate Accretion	Tourism Development with adaptation.
	High Accretion	

a) High and Moderate Erosion Region

This region experiences erosion at the rate of above 3 m/year. No development of permanent infrastructure is proposed for tourism developments in this region. For well-established tourist destinations that fall under this, the focus should be on minimal infrastructure development to ensure the sustainability of the beach. In such cases, implementing nature-based or hybrid solutions becomes a key strategy to mitigate erosion and preserve the beach's integrity. Continuous monitoring of the beach is necessary to understand the shoreline trend. An emergency action plan is also to be developed for each specific site to address potential disasters and a suitable mitigation plan, especially during extreme events.

b) Low Erosion Region

The rate of erosion is between 0.5 m/yr. to 3 m/yr. Tourism development in these sites requires careful planning and implementation to minimize environmental impact and ensure the safety of both visitors and the natural surroundings. The following points are to be addressed when considering beach development in the low-erosion region.

- Conduct a thorough geological and environmental assessment to understand the extent and causes of erosion in the area.
- Setback for the location is to be planned taking into consideration the rate of erosion at the site and the maximum inundation during extreme events based on historic data.
- Implement continuous monitoring to track changes in the erosion patterns and respond promptly to any deviations.
- Design tourism infrastructure with materials and construction techniques that can withstand erosion and coastal dynamics. Avoid permanent building of structures close to the shoreline; opt for elevated structures that allow natural processes to occur without interference.
- Develop and communicate clear emergency preparedness plans to address potential risks associated with erosion, storms, or other natural disasters.
- Consider beach nourishment to replenish eroded shorelines with sand, wherever sediment sources are available to enhance the stability of the coast.
- Wherever sensitive ecosystems and geological features are present, implement ecosystem restoration initiatives to enhance the resilience of the coastal area and promote natural habitat recoveries such as mangrove plantation, Casuarina plantation, seagrass cultivation, dune restoration and dune replenishment, wherever applicable to promote eco-tourism.

c) Stable and Low Accretion Region

This region experiences minimal to no deposition of sediments normally leading to stable beaches. In reality, no management strategy needs to be adopted here however, certain precautions, as stated below shall be considered.

- Avoid removing natural vegetation that is already present, especially in the coastal region.
- Establish setback requirements to prevent construction too close to the shoreline. This helps maintain a natural buffer zone and reduces the risk of damage during storm events.
- If any infrastructure is deemed necessary near the beach, design it carefully to minimize adverse impacts on the natural sediment transport processes and to safeguard the ecosystem.

d) Moderate and High Accreting Region

This region experiences the deposition of sediments normally leading to an increase in the length, width of the beaches and height of the beach dunes. Though generally erosion is considered problematic, without proper planning accreting beaches may also cause hindrance to tourism activities and community in the long run.

- The elevation of the infrastructure is to be designed taking into consideration the change in elevation due to accretion. It is also to be observed if there is a possibility of the aeoline deposition inside the structure.
- If any infrastructure is deemed necessary near the beach, design it carefully to minimize adverse impacts on the natural sediment transport processes and the existing coastal ecosystem.
- In case of dredging or excavation of the accreted sand, a proper sand management plan is to be in place, to properly dispose or re-use the dredged sand in the same or nearby area for any beach nourishment purposes.
- Implement sediment management plans to ensure that any dredged or excavated material is properly disposed of or reused in an environmentally responsible manner.

e) Additional recommendations for tourism

Some of the common measures to be adopted in all beaches that are to be developed for tourism are as follows, irrespective of their shoreline change status:

- Educate tourists about the sensitivity of the environment by providing information about local ecosystems, erosion processes and safety guidelines to enhance visitor awareness.

- Proper display boards/ notices to the tourists and locals about the importance of clean beaches, pollution hazards and ensuring the protection of the coast for future generations has to be mounted.
- Enforce strict regulations on construction and tourism activities to prevent unauthorized development and environmental degradation.
- Plan for public access and recreational activities in a way that minimizes disturbance to the natural environment. Designate specific areas for tourism development, preserving natural buffers and sensitive ecosystems to develop eco-tourism.
- Establish a monitoring program to track changes in beach morphology, vegetation, and wildlife over time. Implement adaptive management strategies to adjust the development plan based on monitoring results to prevent any erosion or loss of the ecosystem at the site.

11.6 SMP and Coastal Zone Management Plan (CZMP)

Another guideline that is generally referred to concerning the shoreline is the Coastal Zone Management Plan, also known as CZMP. The interrelationship is crucial in determining the type of strategy to address the vulnerability, considering the site classification defined in the CZMP.

11.6.1 Evolution of Coastal Regulation Zone

The Coastal Regulation Zone (CRZ) in India serves as a regulatory framework designed to manage and supervise developmental activities along the country's extensive coastline. Enacted under the Environment Protection Act of 1986, this legislation granted the central government the authority to institute measures for the protection and enhancement of the environment. In 1991, the first CRZ notification was introduced, marking a significant step in regulating and curbing specific activities within delineated zones along the coastline. This initiative aimed to thwart environmental degradation while fostering a harmonious equilibrium between economic development and environmental conservation. Subsequent to its inception, the CRZ framework underwent amendments in 2002, with the issuance of a comprehensive CRZ notification in 2011. This revision categorized coastal areas into distinct zones, each governed by specific regulations to guide permissible activities. Notably, it underscored the importance of safeguarding Ecologically Sensitive Areas (ESAs) and introduced provisions to promote sustainable development practices. A new version of the CZMP map was issued in 2019. This iteration emphasised the conservation and management of Ecologically Sensitive Areas (ESAs), encompassing vital ecosystems such as mangroves, coral reefs, and turtle nesting grounds. Additionally, it prioritized enhancing livelihood security for local communities dwelling in coastal areas. The CRZ is categorized into four major zones based on 2019 Notification as shown in (Figure 79) and (Table 28).

11.6.2 Need of SMP for implementation of CRZ

While the Shoreline Management Plan deals with the management of the shore and the impacts of the vulnerability such as erosion and inundation, the CZMPs offer a comprehensive management plan for the coast along a certain distance from the shore. Thus, SMP and CZMP are complementary and work towards management of the coast in various allied aspects.

To ensure the effective implementation of Coastal Regulation Zone (CRZ) policies, a comprehensive understanding of detailed insights, local context, and specific management strategies tailored to the shoreline is imperative. Shoreline Management Plans (SMPs) plays this pivotal role in providing this essential knowledge.

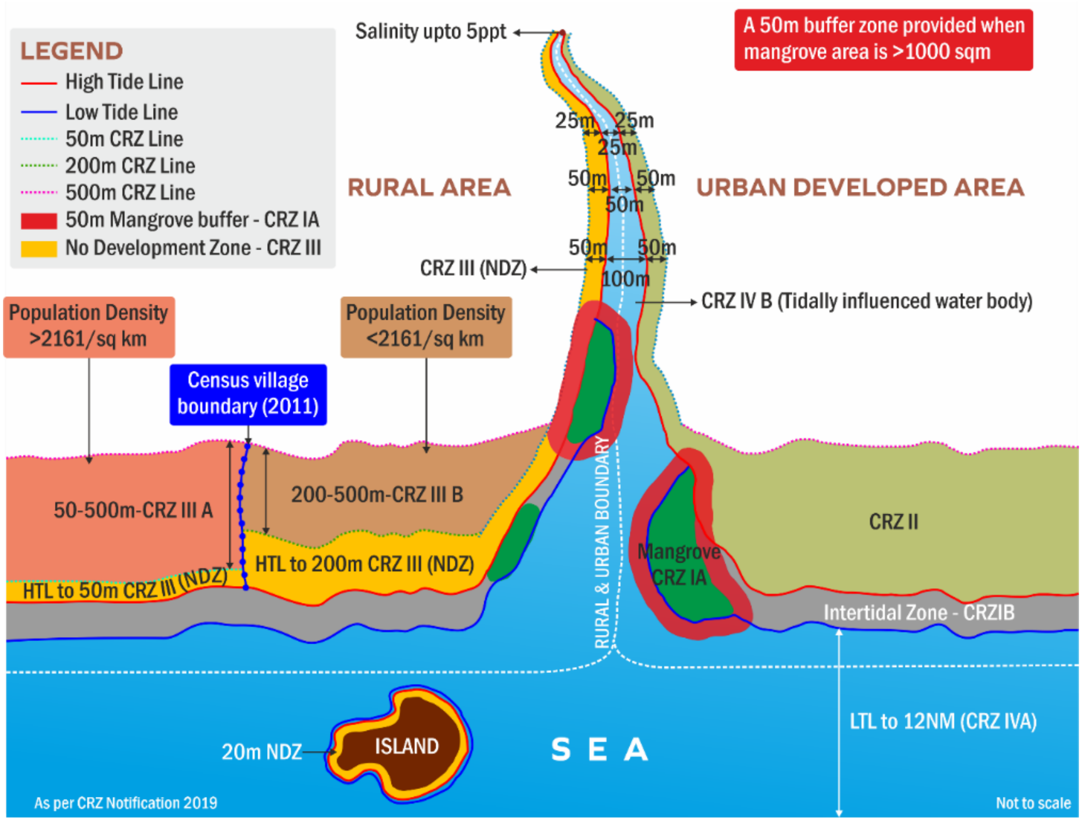


Figure 79. Conceptual diagram of coastal zone management plan (CZMP)
[Source: NCSCM]

Table 28. Shows the coastal regulation zone (CRZ) categories

CRZ Type	Description
CRZ - IA	Ecologically sensitive areas
CRZ - IB	Intertidal Zone i.e. the area between Low Tide Line (LTL) and HTL

CRZ - II	Developed Land Areas (Municipal Limits / Urban Areas)
CRZ - IIIA	Undeveloped rural areas where the population density is more than 2161 per square kilometre as per 2011 census base, is designated as CRZ–III A and area up to 50 meters from the HTL on the landward side shall be earmarked as the 'No Development Zone (NDZ)
CRZ - IIIB	Undeveloped rural areas where the population density of less than 2161 per square kilometre, as per 2011 census base, is designated as CRZ-III B and the area up to 200 meters from the HTL on the landward side shall be earmarked as the 'No Development Zone' (NDZ)
CRZ - IVA	The water area and the sea bed area between the LTL up to 12 nautical miles on the seaward side
CRZ - IVB	The water area and the bed area between LTL at the bank of the tidal influenced water body to the LTL on the opposite side of the bank, extending from the mouth of the water body at the sea up to the influence of tide, i.e., salinity of five parts per thousand (ppt) during the driest season of the year

By identifying suitable areas for development and recognizing sensitive zones requiring conservation, SMPs contribute to a balanced and sustainable approach in implementing CRZ regulations. In supporting informed decision-making, SMPs provide data-driven recommendations and management strategies. This, in turn, assists regulatory bodies in formulating and implementing CRZ regulations that align with the overarching goal of sustainable coastal management. Thus, SMPs serve as an indispensable foundation for effectively implementing CRZ regulations. By providing detailed, site-specific information and management strategies, the synergy between SMPs and CRZ enhances the overall success of coastal management initiatives. This collaborative approach ensures a delicate balance between development, environmental conservation, and meeting the diverse needs of local communities in specific coastal areas.

The SMP was derived by considering the classification of the zone in CZMP maps before providing a suitable management strategy. CRZ I is for eco-sensitive area and only nature-based solution has to be implemented at these locations. In cases of very high erosion in eco-sensitive regions, hybrid solutions maybe taken up after detailed numerical studies specifically in the region, considering the eco-sensitive nature of the region. In fully urbanized regions (as in CRZ II) where population are found very close to the shore, then, based on the rate of erosion, the solution is proposed to be ranging from hard to hybrid solution, to protect the society in that region. In CRZ III, the protection ranges from hybrid to nature-based solution, depending on the intensity of the erosion. CRZ IV A generally consists of ports/ harbour and fishing harbours. The downdrift regions adjacent to these structures are generally highly eroding and also have, incidentally, huge supplies of sediment that they dredge to maintain navigation. Therefore, port management by nourishing the dredged sediment to prevent erosion, is provided. This shall also be advantageous for the Port and fishing harbour to deposit the sediment onshore rather than deposit it at the disposal location, offshore. The confluence of river and the sea/ ocean are the area of interest with respect to SMP which are zoned as CRZ IV A. In light of that, any training works carried out will be accompanied by dredging. Therefore, hybrid solutions, mainly with dredging, need to be provided. The abstract of the classification and the proposed management strategy is in Table 29.

Table 29 Integration of SMP with CZMP

No.	CRZ	Description	Shoreline Management Option
1	I A	Eco-Sensitive Area (Corals, Mangroves, Sea Grass, Mud Flats and Sand Dunes)	Nature Based Solution
2	II	Fully Developed Area (Urban Areas)	Hard Solution – High Erosion Hybrid Solution – Moderate to Low Erosion
3	III	Low Developed Areas (Rural Areas)	Hybrid Solution – High to Moderate Erosion Nature Based Solutions and Monitoring - Low Erosion
4	IV A	Open Sea (Ports/ Harbors/ Fishing Harbors)	Hybrid Solutions
5	IV B	Rivers (Inlets)	Hybrid Solutions

By identifying suitable areas for development and recognizing sensitive zones requiring conservation, SMPs contribute to a balanced and sustainable approach in implementing CRZ regulations. The data collected during SMP preparation, including geological, ecological, and socio-economic information, plays a crucial role in defining and refining CRZ zoning. This ensures CRZ regulations accurately reflect the characteristics, and needs of different zoning along the coast.

In supporting informed decision-making, SMPs provide data-driven recommendations and management strategies. This, in turn, assists regulatory bodies in formulating and implementing CRZ regulations that align with the overarching goal of sustainable coastal management. Thus, SMPs serve as an indispensable foundations for the effective implementation of CRZ regulations. By providing detailed, site-specific information and management strategies, the synergy between SMPs and CRZ enhances the overall success of coastal management initiatives. This collaborative approach ensures a delicate balance between development, environmental conservation, and meeting the diverse needs of local communities in specific coastal areas.

In conclusion, the implementation of coastal protection strategies provides a myriad of advantages that extend beyond the immediate safeguarding of coastal communities. These measures not only reduce erosion and mitigate inundation but also contribute to the overall resilience of coastal regions. By preserving critical infrastructure, protecting property, and fostering economic activities, coastal protection strategies ensure long-term sustainability and public safety. Furthermore, the emphasis on sustainable and environmentally friendly approaches underscores a commitment to harmonizing human development with the preservation of coastal ecosystems. Ultimately, the proactive investment in coastal protection not only averts potential disasters but also yields significant cost savings in the long run while fostering a balanced and resilient coastal environment for current and future generations.

12 SUMMARY AND RECOMMENDATION

The coast of Puducherry is anthropologically significant with a wide geomorphological and ecological variation. At present, there are three ports in UT Puducherry, 3 fishing harbours and 22 fish landing points are in operation along the coast. Any proposed developmental activities needs to be considered the sustainability of the coast. Therefore, it is pertinent to develop a well-defined plan that seeks to treat the shoreline and its associated issues in a more integrated, strategic way for sustainable development, which can be achieved by a Shoreline Management Plan.

> **"Recommend management plans for sustainable development for economic betterment without impacting the coastal environment based on the scientific understanding of the coast and its processes**

To understand the coast and its associated factors for shoreline management plan, the following aspects are assessed:

b) Influence of the existing coastal protection measures and coastal infrastructure,
c) Historical shoreline changes trend of the coast,
d) Coastal geology, geomorphology and ecology of the region,
e) Coastal processes and the sediment budget,
f) Priorities and conflicts of/ between the stakeholders and policy makers, and
g) Proposed infrastructure along the coast.

The study indicates that Puducherry is blessed with a varied geomorphology mainly due to its distribution along the South Indian States. The coastal geomorphology is inclusive of Cauvery delta and 7 inlets that drain into the Bay of Bengal. Dunes are observed along Nallavadu and few coastal stretches of Karaikal. Sandbar formations within the river mouth and spit formations in the southern river mouth have been observed for the Thirumalairajan river in Karaikal. Sandy beaches are particularly prominent near Pondy-Marina beach, Veerampattinam beach, Eden beach, Paradise beach, and Pudhukuppam beach. Dunes, spits, and sandbars are the other major landforms along the coast.

The infrastructure along the coast consists of about 3 operational ports and 3 operational fishing harbours. The tourism has already been well-established through heritage tourism visiting the Union Territory. Eden beach is a blueflag beach of the UT of Puducherry. Considering the huge potential for tourism along the Puducherry coast, there is a need for sustainable development and economic growth of the local community.

The need for a sustainable development of the coastal infrastructure and also the economy, is especially important in the case of Puducherry as the decisions of the state might have irreparable consequences to its neighbouring state too due to its political boundaries interspersed with the neighbouring States. Shoreline change analysis carried out for Indian coast over a period of 28 years (1990-2018) indicates Puducherry is the most affected by coastal erosion.

The successful restoration of the Promenade beach through the hybrid solution has successfully proved that sustainable beach development is indeed possible if proper studies on its impact and sediment transport is carried out. This has also brought about the confidence in the Shoreline Management Plan and its importance for the sustainable coast.

Based on the current shoreline change analysis through satellite data, 5 locations have been identified as erosion sites and 3 sites have been identified as structural priority sites for the safety and functionality of the structures and have been included, in detail, in the SMP. For ground truthing the information, stakeholder interactions were carried out along coast. The district-wise summary for Puducherry is given in the following section.

12.1 Puducherry

The Puducherry district, encompassing 23.5 km from Ganapathychettikulam to Pillaichavady and from Serenity Beach to Pudhukuppam, is distinguished by its unique geomorphological features such as dunes, sand bars, river mouths and mangroves. The sand bar formations at the Chunnambar river mouth near Eden beach attract many tourists and a designated blue flag beach. The district includes 9 villages with a population density of 3232 per sq. km., where residents are engaged in activities like fishing, tourism, and port operations. Approximately 13 km is under CRZ II and the remaining stretch is encompassed under CRZ-III.

The coastal protection structures in the district include seawalls, groins, and artificial reefs along the central stretch of the coast, safeguarding fishing villages and tourist spots. The primary coastal infrastructure of harbour breakwater is at Pondy Marina, which supports the fisheries sector. Coastal developments feature the construction of transitional groins along Kalapet, Pillaichavady, Auroville and Serenity beach, combined with beach nourishment, creating a hybrid solution for coastal protection. Additionally, the proposal for a southern reef at Promenade beach aims to enhance tourism by stabilizing the newly formed beach areas along Puducherry's main coastal stretch. The southern coastal expanse, notably along Eden beach, Paradise beach, Nallavadu and Pudhukuppam, with its wide beaches and sand dunes, benefits from nature-based solutions that promote ecological balance.

There are 4 erosion and 2 structural priority sites identified and the management methodology chosen are best suited for the sustainable development of the Puducherry district.

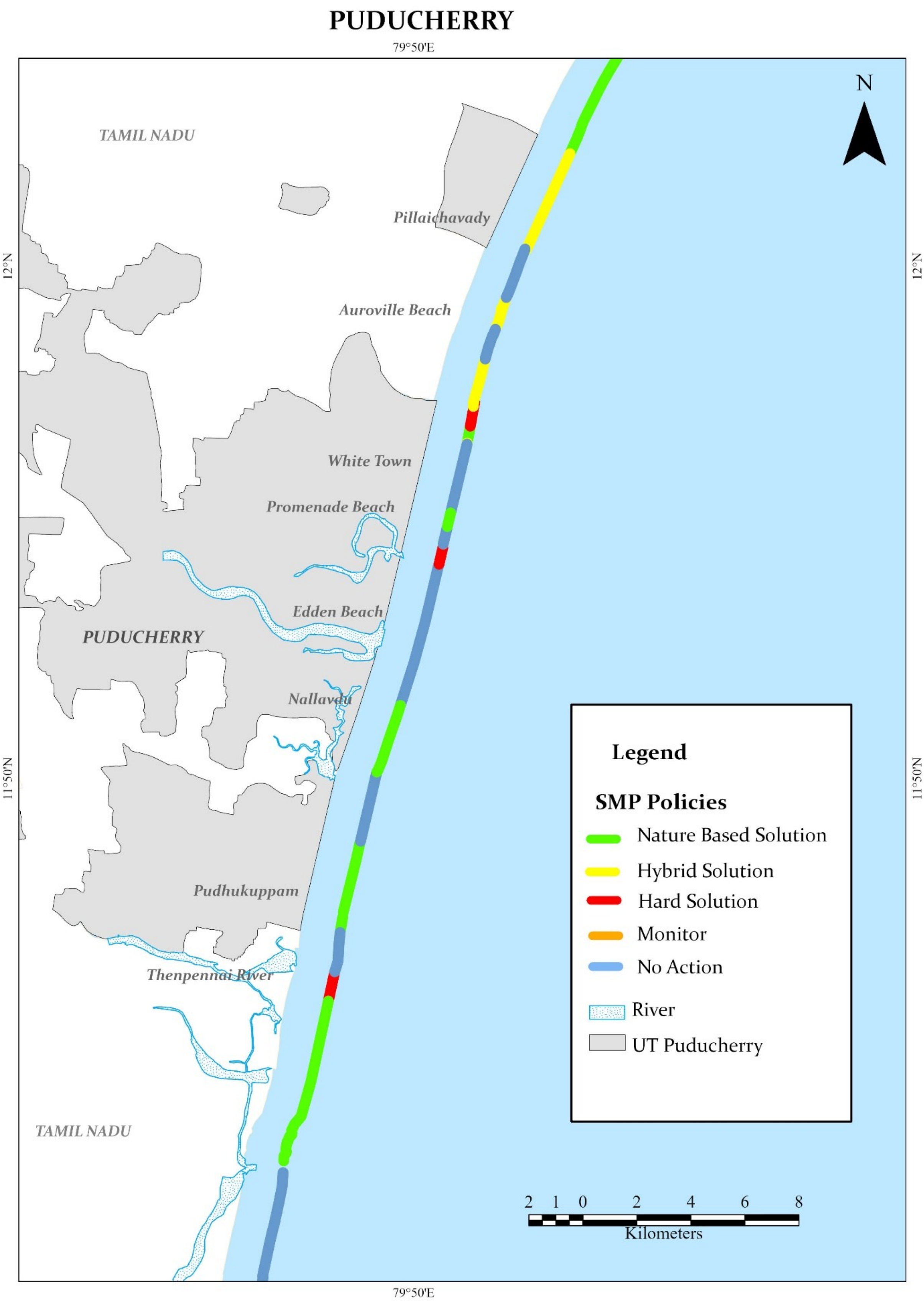


Figure 80. SMP for Puducherry

12.2 Karaikal

The Karaikal district of the Union Territory of Puducherry extends from Mandapathur to Vettar river, with a total coastal stretch of about 17 km. The coastal area exhibits diverse landforms, including a beach ridge, younger beach dune complex and river inlets with estuarine and mangrove ecosystems. There are 6 coastal villages in the Karaikal district with a population density of 1275 per sq.km., where people involved in activities such as fishing, tourism and port operations. Of the total 17 km of coastal length, 7 km belongs to CRZ II remaining 10 km stretch is under CRZ III.

The coastal protection structure in the district includes a short stretch of seawall constructed along southern end of the coast. In terms of coastal infrastructure, breakwaters are found at two locations Karaikal harbour and port. The bio-shield measures along Kalikuppam, Kazhakudimedu, Thirumalai Rajan Pattinam, and Vanjur strengthened using sand dunes which would protect the coast from erosion. The construction of transitional groynes with nourishment at Kilinjalmedu with bio-shield measure through plantation either side of the groyne field would promote the hybrid solution for protection. The periodic dredged sand from Karaikal fishing harbour and private port should be strategically placed at suitable location to protect the adjacent coast.

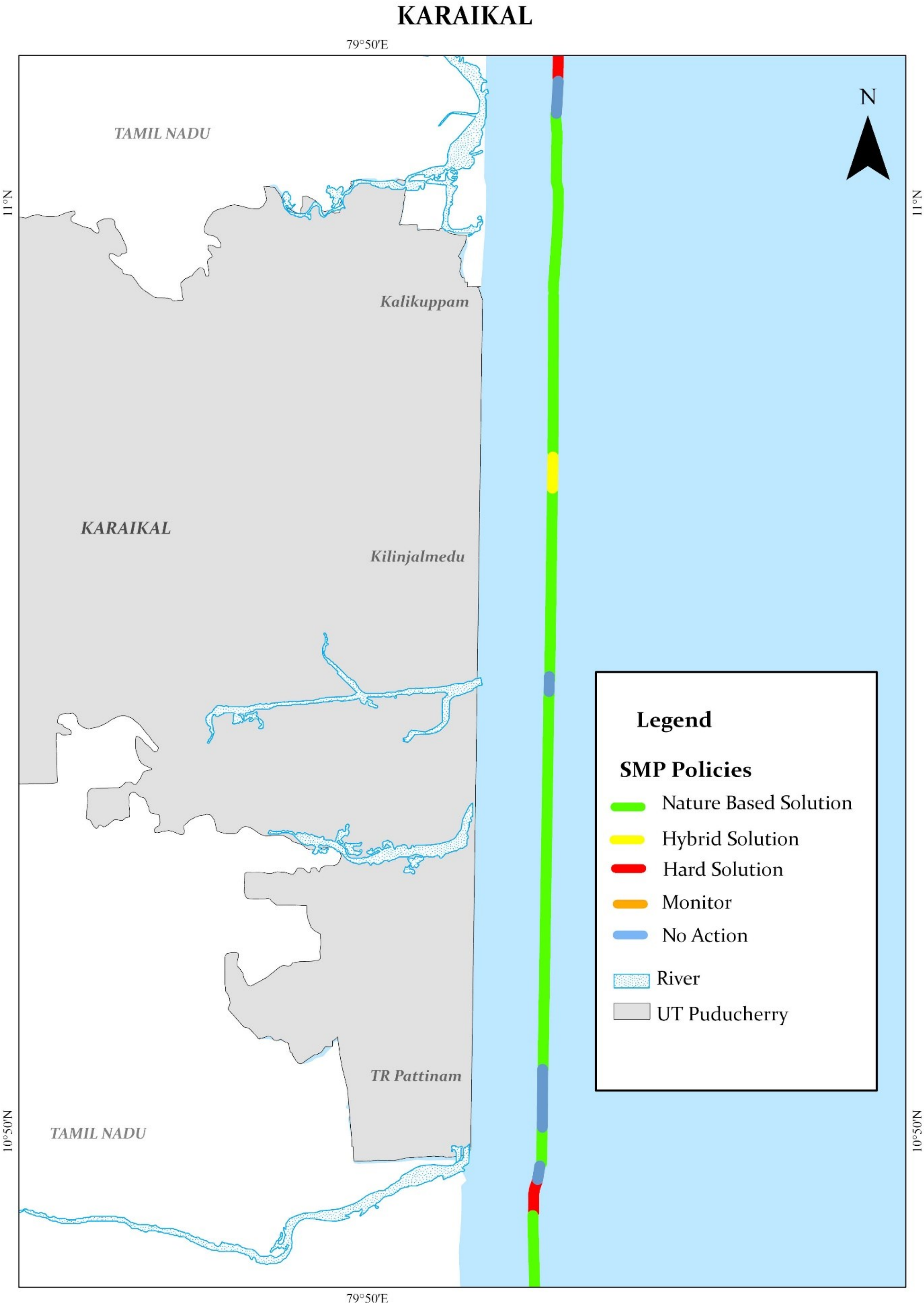


Figure 81. SMP for Karaikal

12.3 Mahé

The coastal stretch of Mahé constituting to 1.22 km is the shortest coastal stretch of UT Puducherry. Surrounded by the State of Kerala, Mahé is in the West coast of India when compared to the other districts of UT. Though minimal coastal stretch, the population density is about 4,646 per sq. km. with 1 coastal village. The Mahé river (Mayyazhi river) flows through the North and the southern stretch is bordered with Kozhikode district of Kerala. The entire coastal stretch is under the CRZ-II category reminiscing the urbanization of the stretch.

Although the shortest in length, Mahé features a seawall for coastal protection and a fishing harbour as its coastal infrastructure. The entire coastal stretch is developed, and the seawall shows partial damages with beach formations in the foreshore. This highlights the need for ongoing monitoring of the current conditions to ensure future coastal protection if necessary.

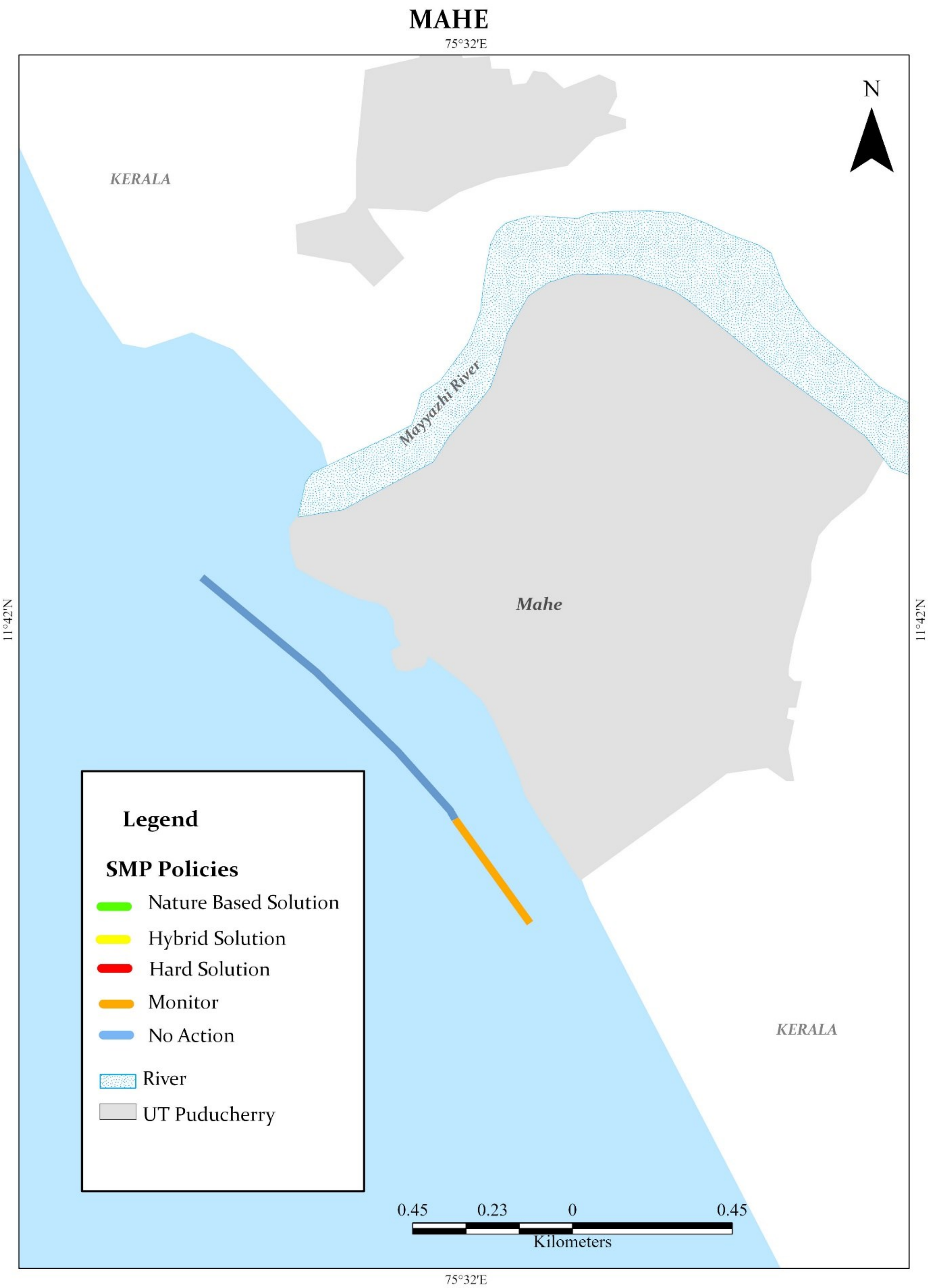


Figure 82. SMP for Mahé

To maintain the stability of the coast, it is proposed to draw suitable management plan to mitigate the impact due to infrastructure development. Construction of port breakwaters hinders the sediment movement, causing erosion to the North of infrastructure, specifically along the East coast of India. To mitigate this erosion, sediment dredged during development and operation of port should be used for nourishment on the Northern side. The same is applicable for fishing harbours too. In case of fish landing points that are being proposed on land in the coastal regions, it is advised to locate them at stable or low accreting beaches. In case the fish landing points are to be located in eroding stretches considering the livelihood of the local fishing hamlets, proper offset from the water line needs to be considered based on the rate of erosion in that region.

As part of this report, priority has been given to nature-based solutions, followed by hybrid and hard solutions. It is to be noted that although hard solutions have been suggested a few locations, it is always preferable to upgrade to hybrid solutions, if possible. If hybrid solutions are proposed, it is always preferable to upgrade to nature-based solutions. It is also advisable to undertake suitable site-specific studies before implementing any management strategies.

SMP will serve as a guideline for stakeholders and policymakers for sustainable development. As the coast is dynamic, it needs continuous monitoring of the coast and performance of intervention. SMP has to be revisited in five years span for incorporating changes, if any in shoreline management based on the performance of the implemented shoreline management strategies and the monitoring sites.

13 WAY FORWARD

> "Guideline has been provided on the way forward towards safeguarding our coastlines as a collective effort for the policy makers, stakeholders and scientific community, alike

With the formulation of a shoreline management plan, at this crucial juncture where intentions transform into tangible actions, propelling towards a sustainable future for our coasts. This plan will serve as a blueprint, crafted through extensive research, stakeholder consultation, and strategic foresight, aiming to address the complex interplay between natural processes and human activities along our shorelines. As a way forward, the focus shifts from conceptualization to execution, necessitating a concerted effort to translate vision into reality. In this introduction, we explore the transformative pathway ahead, marked by proactive measures, adaptive strategies, and the collective commitment of diverse stakeholders towards safeguarding our coastlines for generations to come.

13.1 Road Map for Shoreline Management

Once a shoreline management plan is formulated, the next steps involve its implementation, monitoring, and adaptation to ensure its effectiveness over time. A roadmap for the way forward is stipulated below:

(a) Implementation Strategy

An authority or cell is to be setup to understand and follow up on the policy development for protecting the shoreline. The cell needs to develop a detailed action plan outlining specific tasks, responsibilities, timelines, and budgetary requirements for implementing the shoreline management plan. This may involve securing necessary permits, allocating resources, and coordinating with relevant stakeholders and departments. They will also be responsible for detailed budgeting, identifying the funding for sponsoring the project.

(b) Stakeholder Engagement

Foster ongoing communication and collaboration with local communities, other Government agencies, sister State departments, NGOs, and other stakeholders. Seek their involvement in the implementation process to ensure buy-in and support. The engagement should also consist of detailed stakeholder interaction to understand their requirements and the likely impact a particular strategy will have on the local community.

(c) Effect of Climate Change

The vulnerability of the shoreline to erosion has been provided to the stakeholders. This atlas together with the study on climate change, land use and coastal regulation zones shall be utilized for carrying out detailed study and a suitable protection measure that elevates the livelihood of the local community and economy may be adopted. A detailed analysis on the proposed protection measure shall be carried out before implementation.

(d) Monitoring and Evaluation

Establish a robust monitoring and evaluation framework to track progress, measure performance indicators, and assess the impact of implemented measures on shoreline dynamics, ecological health, and community resilience. Monitoring to also be carried out at select locations identified in the SMP that are recommended to be monitored.

(e) Adaptive Management

This is the first version of Shoreline Management Plan that has been formulated. The SMP has to be periodically revised to understand the status of the coast and the efficacy of the implemented protection schemes. The previous version is to be reviewed and updated periodically, based on new information, monitoring data, feedback from stakeholders, and lessons learned from implementation efforts. The next version of SMP shall also include the inundation and effect of climate change on the shoreline and its measures.

(f) Policy Integration and Coordination

The stakeholder has to ensure the policies suggested are in alignment and coordination with relevant policies, plans, and regulations at the local, regional, and national levels. They shall also advocate for supportive policies and funding mechanisms to facilitate the implementation of the shoreline management plan.

(g) Partnership Development

It is also suggested to forge partnerships with academic institutions, research organizations, private sector entities, and international agencies to leverage expertise, resources, and funding opportunities for implementing the shoreline management plan. It is also recommended to involve these institutes in the detailed design of the protection measures and also in the decision-making cell for sustainable development of coastal infrastructure.

By following this comprehensive approach, stakeholders can effectively implement a shoreline management plan that promotes sustainable development, protects natural resources and enhances the resilience of coastal communities in the face of environmental change.

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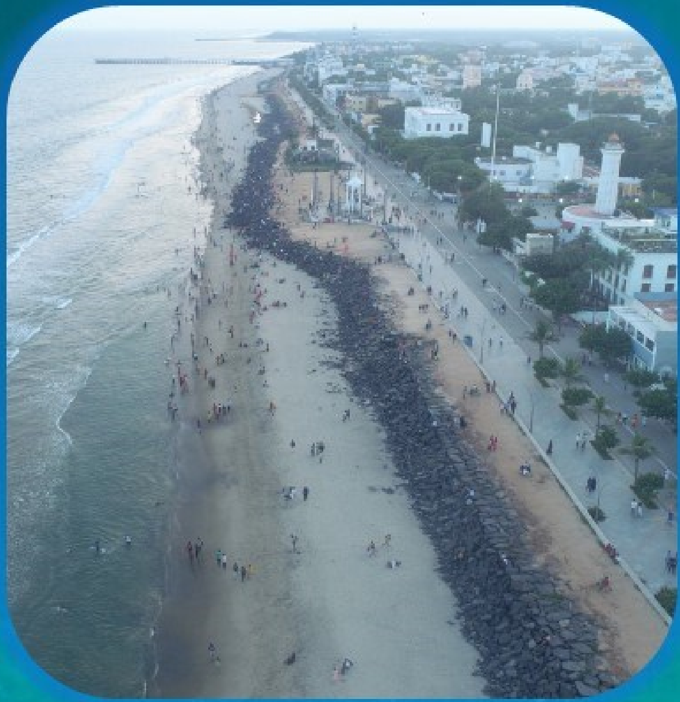

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