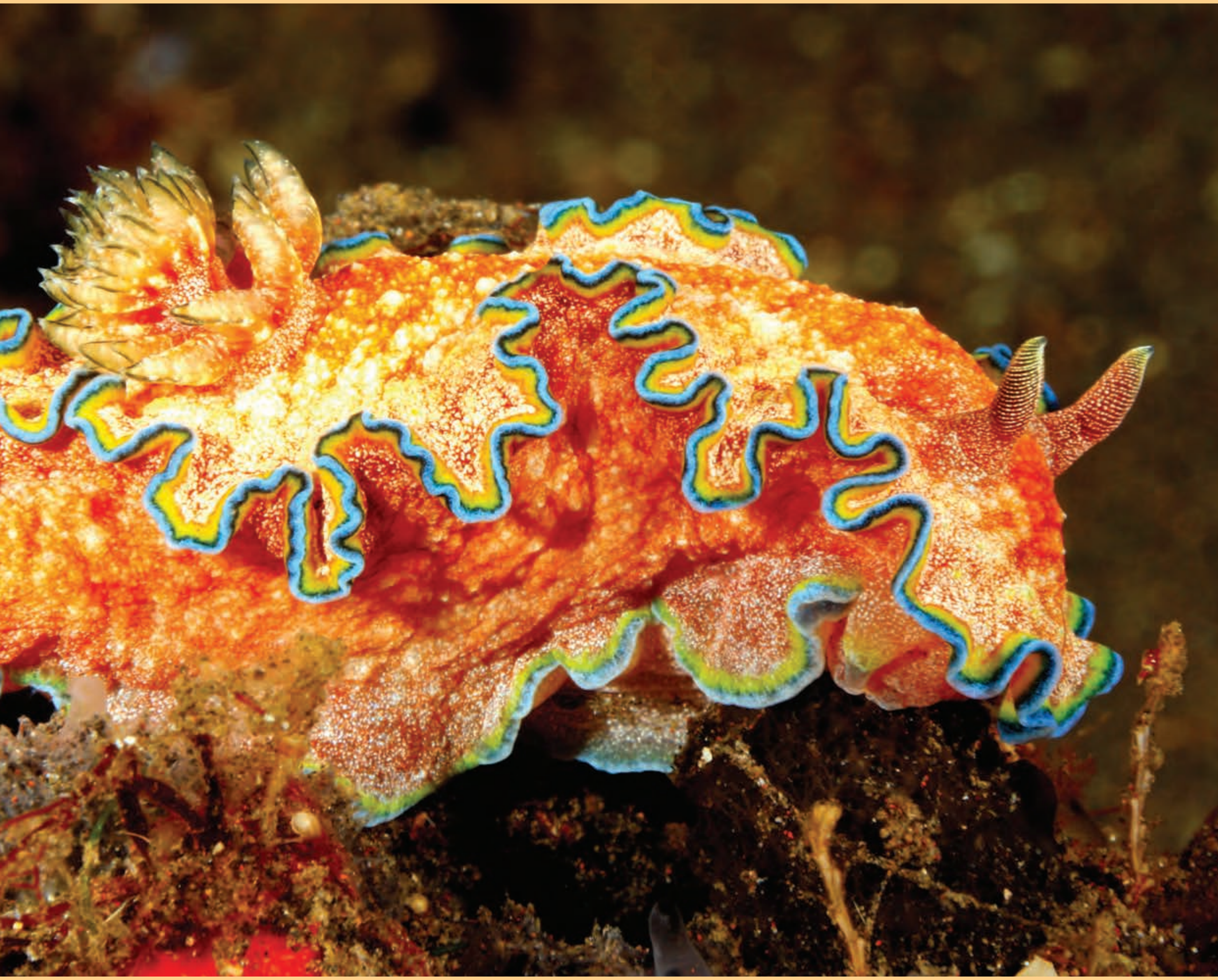
सत्यमेव जयते
Government of
India

Ministry of Environment,
Forest and Climate Change

CLIMATE CHANGE
AND
THE VULNERABLE INDIAN COAST

R Ramesh | J R Bhatt



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सत्यमेव जयते

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GOVERNMENT OF INDIA
MINISTER OF ENVIRONMENT, FOREST &
CLIMATE CHANGE

MESSAGE

I am pleased to observe that the Ministry of Environment, Forest and Climate Change (MOEFCC) has decided to release a book on "Climate Change and the Vulnerable Indian Coast" on the occasion of 24th session of Conference of Parties to the United Nations Framework Convention on Climate Change at Katowice, Poland in December 2018.

India has a long coastline which includes thousands of small and big islands, encompassing several districts in maritime states and Union Territories. A large number of country's population lives in coastal areas. Majority of our growing urban and economic centers of strategic importance are located near the coast. The coastal ecosystem of India harbours rich biodiversity comprising corals, mangroves, seagrasses, estuaries, lagoons, mud flats and salt marshes. The coastal ecosystems act as a natural defence against events like high tides and cyclone and provide valuable ecosystem services with socio-cultural-economic co-benefits while sustaining the local coastal population.

Marine and coastal areas, across the world, are adversely affected by ascending sea levels, rising ocean temperatures and increasing ocean acidity. The coastal areas are under threat from increasing erosion, pollution and degradation of ecosystems from anthropogenic activities posing challenges in their management. The sea level rise and increasing intensity of cyclones can aggravate coastal erosion, inundate coastal ecosystems, changing them from brackish to saline, flooding low lying areas and affecting coastal settlements especially the fisherfolk settlements and their activities. The small islands and low lying coastal areas are worst affected. Oceans are the world's largest inter-connected ecosystem with a tremendous potential to capture and store blue carbon which is declining due to climate change. This trend is expected to aggravate in the years to come and will adversely affect all maritime countries across the world.

Marine and coastal sector is of strategic importance to India. Hon'ble Prime Minister Shri Narendra Modi once observed that "to me, the blue chakra of the wheel in India's national flag represents the potential of the blue economy". Recently, Government of India has introduced a number of programs to sustainably harness the potential of the blue economy while building the climate resilience of the ecosystem and local coastal communities. However, the implementation of

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these climate adaptation measures on a massive scale and in a time-bound manner requires substantial financial support and vibrant knowledge exchange between the maritime nations. Such collective actions of the global community will directly contribute to meeting Aichi Biodiversity Targets as well as Sustainable Development Goals. No country can do it on its own. It's time to join hands and act in accordance with the principles of Common but Differentiated Responsibilities and Respective Capabilities, Equity and Climate Justice.

I am glad that this book has dealt in detail the contribution of coastal ecosystems in reducing the climate change impacts by enhancement of carbon sequestration and adaptation of mangrove ecosystems. It also contains extensive information on the vulnerability of climate change to coastal erosion, the extent of vulnerability to flooding by drawing hazard line, freshwater scarcity, an abundance of fisheries and social impacts. This documentation is proposed to build and strengthen the climate-resilience of the marine and coastal sector in India. I congratulate all the authors for their valuable contributions for bringing out an informative publication.

Date: 30.11.2018

(Dr. Harsh Vardhan)

सी.के.मिश्रा
C.K.Mishra

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FOREWORD

Climate change is a global concern impacting sustainable development affecting economic growth, compromising ecosystem services and biodiversity; and increasing vulnerability of the vast majority of the coastal population who depend on natural resources for their sustenance.

With a long coastline supporting dense population and rich biological diversity, the coastal ecosystems of India are vulnerable to the impacts of climate change which could include sea level rise, increased temperature, storms, inundation and flooding of coastal wetlands, intrusion of salt water in aquifers, changes in the habitats and species distribution and population. India has to look at the adaptation and mitigation strategies to combat the effects of climate change. India has rich coastal ecosystems consisting of corals, mangroves, seagrasses, estuaries, lagoons, mudflats and salt marshes which provide valuable ecosystem services and remain a source of sustenance for coastal communities. Though there are efforts to conserve and manage the coastal ecosystems through policies and programmes, there are still many challenges which could be multidimensional.

Apart from the extant policies, measures and participation of local communities, one of the key paths towards conservation is the understanding of ecosystem from a scientific viewpoint, as this could value add to the adaptation and mitigation strategies being adopted. This book titled "Climate Change and the Vulnerable Indian Coast" provides an overall picture of current status in terms of scientific research in the coastal sector specifically to the ecosystem responses.

I compliment the contributing authors and appreciate and acknowledge the efforts put in by Dr. Arun Kumar Mehta, Additional Secretary and Dr. J. R. Bhatt, Scientist-G, Ministry of Environment, Forest and Climate Change in bringing out this valuable publication on the occasion of the 24th session of Conference of Parties to the United Nations Framework Convention on Climate Change at Katowice, Poland in December 2018.

[C.K. Mishra]

Dated: **29th November, 2018**
Place: **New Delhi**

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COASTAL SENSITIVITY

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CLIMATE ADAPTATION

CLIMATE MITIGATION

GOVERNANCE

Abbreviations

AC	Adaptive Capacity
AD	Anno Domini (CE - Common Era)
AGB	Above-ground biomass (leaves/sheaths)
ALOs	Alternative Livelihood Options
ANCOST	Andaman Nicobar Centre for Ocean Science and Technology
AR	Assessment Report
ASB	Annual severe bleaching
BBDB	Backward Bent Ducted Buoy
BC	Before Christ (BCE- Before Common Era)
BGB	Below-ground biomass (roots/rhizomes)
BBMB	Bhakra Beas Management Board
BMD	Bangladesh Meteorological Department
BPL	Below Poverty Level
CAG	Comptroller and Auditor General of India
CBAS	Coral Bleaching Alert System
CAPE	Convective Available Potential Energy
CASMB	Centre of Advanced Study in Marine Biology
CBD	Convention on Biodiversity
CBDR	Common but Differentiated Responsibilities
CCIF	Climate Change Informed Fisher Community
CD	chart datum
CDA	Chilika Development Authority
CDM	Clean Development Mechanisms
CER	Certified Emission Reduction
CGWA	Central Ground Water Authority
CIN	Convective Inhibition Energy
CISK	Convective Instability of the Second Kind
CITES	Convention on International Trade in Endangered Species of Wild Flora and Fauna
CMFRI	Central Marine Fisheries Research Institute
CMS	Convention on Migratory Species of Wild Animals (the Bonn Convention)
CMZ	Coastal Management Zone
COMAPS	Coastal Ocean Monitoring and Prediction System

COP	Conference of Parties
CPCB	Central Pollution Control Board
CReVAMP	Climate resilient village adaptation and mitigation plan
CRMP	Coastal Resource Management Program
CRZ	Coastal Regulation Zone
CRZ	Coastal Regulation Zone
CSIR	Council of Scientific and Industrial Research
CSP	Concentrated solar power system
CVCA	Critically Vulnerable Coastal Areas
CVI	Coastal Vulnerability Index
CZM	Coastal Zone Management
CZMP	Coastal Zone Management Plans
DC	Direct Current
DEM	Digital Elevation Model
DHDs or DDs	Degree Heating Days
DHM	Degree Heating Month
DHWs	Degree Heating Weeks
DOD	Department of Ocean Development
DRIP	Dam Rehabilitation and Improvement Programme
DS	Draw solution
DSAS	Digital Shoreline Analysis System
DST	Department of Science and Technology
E(P)A	Environment (Protection) Act
ECMWF	European Centre for Medium-Range Weather Forecast
ED	Electrodialysis
EEZ	Exclusive Economic Zone
EI	Exposure Index
EIA	Environmental Impact Assessment
EICC	East India Coastal Current
E-MPI	Emanuel's Maximum Potential Intensity
ENSO	El Niño–Southern Oscillation
ESA	Ecologically Sensitive Areas
FAO	Food and Agriculture Organisation
FDFW	Fishing Down Marine Food Web

FO	Forward Osmosis
FSI	Forest Survey of India
GAMs	Generalized Additive Models
GBR	Great Barrier Reef
GCRMM	Global Coral Reef Monitoring Network
GFRA	Global Forest Resource Assessment
GHG	Green House Gases
GIS	Geographical Information Systems
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH or GIZ
GoI	Government of India
GoM	Gulf of Mannar
GPP	Gross Primary Productivity
GPP	Gross Primary Productivity estimations
GSD	Ground Sample Distance
GULLS	Global Learning and Understanding for Local Solution
GWEC	Global Wind Energy Council
HadISST1	Hadley Centre Sea Ice and Sea Surface Temperature Data Set
HAT	Highest Astronomical Tide level
HDI	Human Development Index
HDPE	High Density Poly Ethylene
HRZ	High Risk Zone
HTL	High tide line
HWL	High Water Line
ICOADS	International Comprehensive Ocean Atmosphere Data Set
ICRZ	Island Coastal Regulation Zone
ICZM	Integrated Coastal Zone Management
IIMP	Integrated Islands Management Plan
IITM	Indian Institute of Tropical Meteorology
ILC	Inter-laboratory calibration
IMD	India Meteorological Department
IMMT	Institute for Minerals and Materials Technology
IMSL	Indian Mean Sea Level
INCCA	Indian Network for Climate Change Assessment
INCOIS	Indian National Centre for Ocean Information Services

INDC	Intended Nationally Determined Contribution
INR	Indian Rupee
IPCC	Intergovernmental Panel on Climate Change
IPZ	Island Protection Zone
IREDA	Indian Renewable Energy Development Agency Limited
IRS P6 LISS-3 & LISS -4	Indian Remote Sensing Satellite P6- Linear Imaging Self –Self Scanning Sensor
SAC	Space Application Centre
ISRO	Indian Space Research Organisation
ITCZ	Inter-tropical Convergence Zone
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
LAI	Leaf Area Index
LAT	Lowest Astronomical Tide level
LDPE	Low Density Polyethylene
LiDAR	Light Detecting And Ranging
LIT	Line Intercept Transect
LRR	Linear Regression Rate
LRZ	Low Risk Zone
LTL	Low tide line
LTM	Long Term Mean
LTTD	Low Temperature Thermal Desalination
LU/LC	Land Use Land Cover
MARPOL	International Convention for the Prevention of Marine Pollution from Ships
Mbgl	Metres Below Ground Level
MCB	Mass Coral Bleaching
MCS	Mesoscale Convective System
MD	Membrane Distillation
MED	Multi Effect Distillation
MED	Multi-Effect Desalination
MED	Multi-effect Thermal Desalination system
MEH	Multi Effect Humidification
MEI	Multivariate ENSO Index
MHHW	Median Highest High Water
MLLW	Median Lowest Low Water

MMM	Maximum Monthly Mean or climatology
MMRF	Marine Microbial Reference Facility
MODIS Global SST	Moderate-resolution Imaging Spectroradiometer Surface Sea Temperature
MoEFCC	Ministry of Environment, Forest and Climate Change
MoES	Ministry of Earth Sciences
MoWR	Ministry of Water Resources, River Development and Ganga Rejuvenation
MPA	Marine Protected Areas
MPPTs	Maximum Power Point Trackers
MRZ	Moderate Risk Zone
MSF	Multi Stage Flash
MSL	Mean Sea Level
NAPCC	National Action Plan on Climate Change
NATCOM	National Communication to the United Nations Framework Convention on Climate Change
NASA	National Aeronautics and Space Administration
NHPC	National Hydroelectric Power Corporation Ltd
NCCR	National Centre for Coastal Research (formerly Integrated Coastal and Marine Area Management Project Directorate, ICMAM PD)
NCD	Normalised Catch Deviation
NCESS	National Centre for Earth Science Studies
NCP	Net Community Productivity
NCSCM	National Centre for Sustainable Coastal Management
NCTPS	North Chennai Thermal Power Station
NDVI	Normalized Difference Vegetation Index
NE	North East
NEP	National Environment Policy
NIO	National Institute of Oceanography
NIOT	National Institute of Ocean Technology
NIWE	National Institute of Wind Energy
NOAA AVHRR	Advanced Very High Resolution Radiometers NOAA
NOAA	National Oceanic and Atmospheric Administration
NOAA NESDIS	National Environmental, Satellite, Data and Information Service
NPP	Net Primary Production
NSM	Net Shoreline Movement

NW	North West
OS	Oil sardine
OSL	Optically-Stimulated Luminescence
OTEC	Ocean Thermal Energy Conversion
OTEC	Ocean Thermal Energy Conversion
OW	Okubo-Weiss parameter
OWC	Oscillating Water Column
OWC	Oscillating Water Column
PA	Positive SST Anomaly
PAR	Photosynthetically Active Radiation
PN	Net Canopy Photosynthetic Productivity rate
PRA	Participatory Rural Appraisal methods
PRACRITI	PRogrAmme on Climate change Research In Terrestrial environment
PV	Photovoltaic
PV	Potential Vorticity
R	Community respiration
RBQ	Rank Based Quotient
RCP	Representative Concentrated Pathway
REDD	Reduction of Emission from Deforestation and Forest Degradation
RCB	Regional Coral Bleaching
RO	Reverse Osmosis
RPD	Rossby Penetration Depth
RRA	Rapid Rural Appraisal
RRR	Repair, Renovation and Restoration of water bodies' scheme
SAC	Space Applications Centre
SCI	Scottish Development International
SDGs	Sustainable Development Goals
SE	South East
SFR	State of Forest Report
SGD	Submarine groundwater discharge
SLR	Sea Level Rise
SPARSO	Bangladesh Space Research and Remote Sensing Organisaton
SSHA	Sea Surface Height Anomaly
SST	Sea Surface Temperature

SW	South West
SWQM	Seawater Quality Monitoring
TCM	Tropical Cyclone Motion
TL	Thermoluminescence dating
TMI	Tropical Rainfall Monitoring Mission Microwave Imager
TVC	Total Viable Count
UA	Urban Agglomerations
UNCED	United Nations Conference on Environment and Development
UNCHE	United Nations Conference on Human Environment
UNCLOS	United Nations Convention on the Law of the Seas
UNDP	United Nations Development Programme
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
USEPA	United States Environmental Protection Agency
UT	Union Territory
VHRZ	Very High Risk Zones
VHT	Vertical Hot Towers
VI	Vulnerability Indice
WB	World Bank
WISE	World Institute of Sustainable Energy
WISHE	Wind Induced Surface Heat Exchange
WLPA	Wildlife (Protection) Act
WM	Warmest Month
WQ	Warmest Quarter
WRF	Weather Research Forecasting
WWF	World wide Fund for Nature
ZSI	Zoological Survey of India

Units

t. km^{-2}.yr^{-1}	Tonnes per Kilometer per year
lpcd	Litres/capita/day
m	Metre
Mb	Milli bar pressure
Mg C ha^{-1}	Megagram Carbon per hectare
Mg CO_2/ha	Megagram Carbon di-oxide per hectare
MLD	Million Litres per Day
mm	Millimetre
MW	Megawatt
M/s	Metre per Second
ppm	Parts per million
Km^2	Square Kilometre
Tg C yr^{-1}	Terragram Carbon per year
μmol m^{-2} s^{-1}	Micro mole per square metre per second
Gg	Giga gram
BCM	Billion Cubic Meters
g C m^{-2}yr^{-1}	Gram Carbon per Square metre per year
cm	Centimetre
Gg CO_2e yr^{-1}	Gigagram Carbon di-oxide per year
Km	Kilometre

COASTAL VULNERABILITY

1

Hazard line for the coast of India and its implications in coastal management

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ABSTRACT

For the first time in India, the composite hazard line has been demarcated to map areas that are highly vulnerable to coastal hazards on a time period of 1 in 100 years. Using very high- resolution aerial photographs (9 cm GSD); the hazard line for the entire coast of India has been mapped by the Survey of India and the National Centre for Sustainable Coastal Management, MoEFCC. Typically, hazard line considers the susceptibility of coastal population and their assets, to coastal hazards such as cyclones, storm surges, tsunami and erosion including sea level rise for the entire coast of India. Since islands are twice as vulnerable to hazards, a case study of Sagar Island in West Bengal, India is presented with diverse vulnerability and risk levels. The importance of coastal/ marine ecosystems in naturally protecting the coast and the community emerges from visualizing the possible risk areas within the hazard line. Societal exposure to such coastal hazards can be minimized by understanding the physical forcing factors and the socio-ecological systems.

1. Introduction

The coast is a unique environment where land, sea and atmosphere interact continuously influencing a strip of spatial zone defined as coastal zone. India has a coastline of ~7,500 km, of which the mainland accounts for ~5,500 km. The country has a total of 1382 offshore islands, comprising of 514 islands along the mainland coast and 868 islands in the island territories (Andaman & Nicobar and Lakshadweep). Among the 1382 offshore islands, 346 islands are inhabited.

The Indian coastline has a vast extent of diverse sensitive ecosystems such as coral reefs, mangroves, tidal mudflats, seagrass beds and salt marshes. Apart from these ecosystems, the coastline has diverse landforms which include sandy beaches, sand dunes, cliffs, rocks etc. All the ecosystems and geomorphological features play an important role in protecting the coast and the coastal communities from strong winds, cyclones, tidal surges, tsunami, flooding etc. The coastal areas also have an important role in the socio-economic development of the country primarily because seaborne trade remains the economical method of transporting large quantities of goods over long distances. Areas around the coast are also developed for fisheries, agriculture, settlements, tourism, energy infrastructure, marine infrastructure and industries. The coast is highly vulnerable, confronted by multiple hazards that originate from the sea such as cyclones, storms and tsunami. There are also newer hazards due to climate change including sea level rise, increase in sea-surface temperatures and changing weather conditions.

1.1 Activities on the coast

Fishing is the primary activity, with over an estimated 4.0 million people depending on the marine fisheries resources for their livelihoods (National Policy on Marine Fisheries 2017). In the last century, supported by ports and power plants, the coast has become the preferred location for industries; this in turn has triggered extensive urbanization of the coast. The second most dominant activity is coastal tourism, with more beaches being visited on an annual scale. However, this has also led to a number of problems in coastal areas of which pollution of coastal waters, extensive change in land use and loss of sensitive ecosystems and coastal erosion are prominent.

1.2 Coastal Geomorphology

The Western Coast of India extends from Gujarat in the north and extends through Maharashtra, Goa, Karnataka, and Kerala. It can be classified into two sectors, the Konkan and the Malabar Coast. Most rivers originating from the Western Ghats are perennial and fast-flowing. Major rivers include Tapi, Narmada, Mandovi and Zuari, which drain into Arabian Sea (Figure 1). In addition, several small rivers discharge huge sediment load to the west coast, however the high energy conditions do not allow delta formation. Furthermore, the west coast is also characterized by seasonal upwelling facilitating exchange of temperature and nutrients between the surface and sub-surface water layers, enhancing primary productivity.

The Coastal Plain in the eastern part of the country is a wide stretch extending from Tamil Nadu in the south to West Bengal in the east. The Ganges, Mahanadi, Godavari, Cauvery, and Krishna are some of the major river deltas (Figure 1) that drain these plains the width of which varies between 100 and 130 km. The west and east coasts of India exhibit unique geomorphic features such as predominant hard rock coast (Figure 1) with narrow sandy beaches (Figure 2) drained by rivers on the west coast and wide perennial rivers forming deltas, swamps and estuaries on the east coast. This unique assemblage of coastal geomorphic features has led to the development of a variety of coastal and marine ecosystems along the coast, important in supporting coastal populations apart from providing a variety of ecosystem services and contributing to coastal stability.

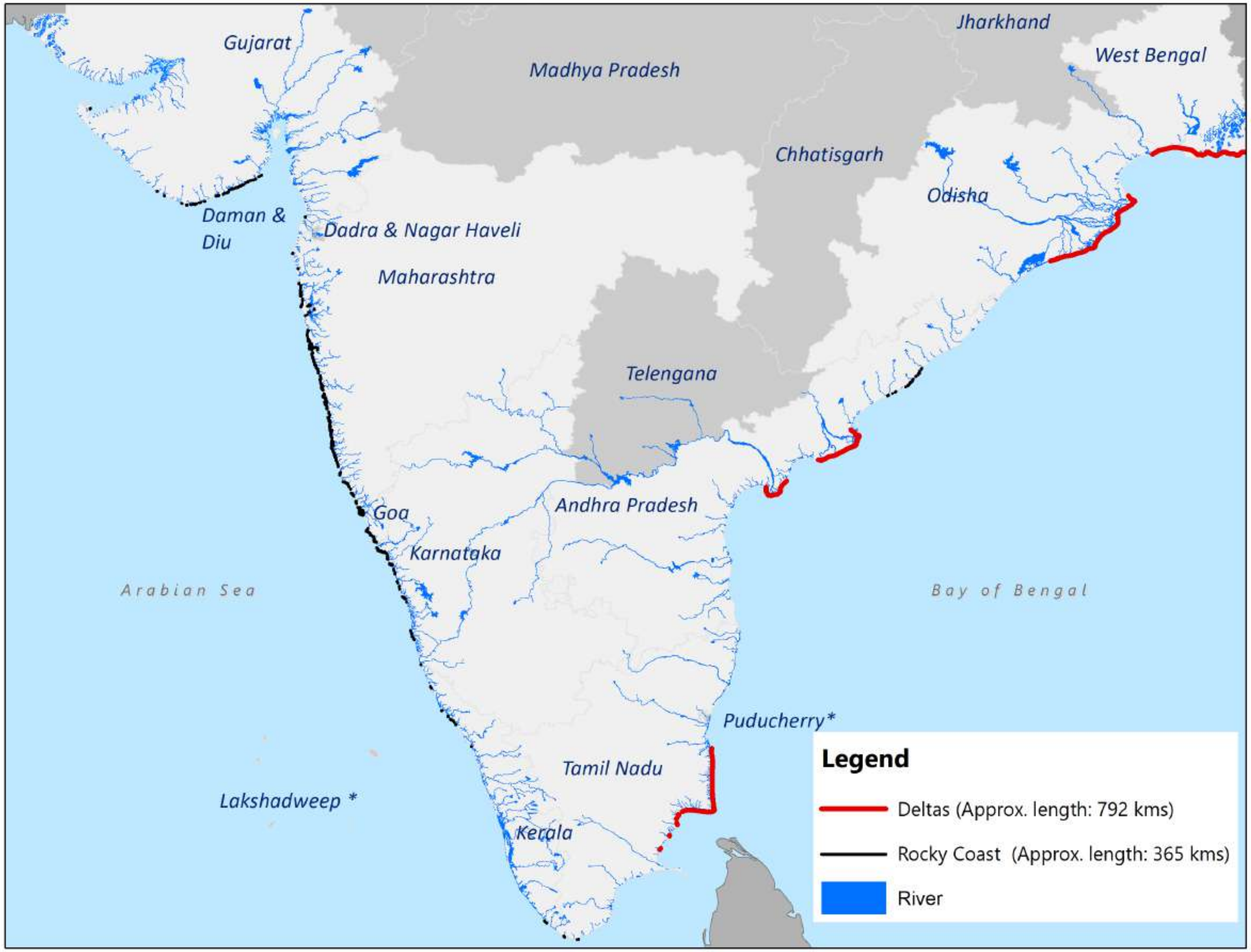

Figure 1: Major rivers, deltas and rocky coasts of India

Figure 2: Beaches/ sandy coast and mainland islands

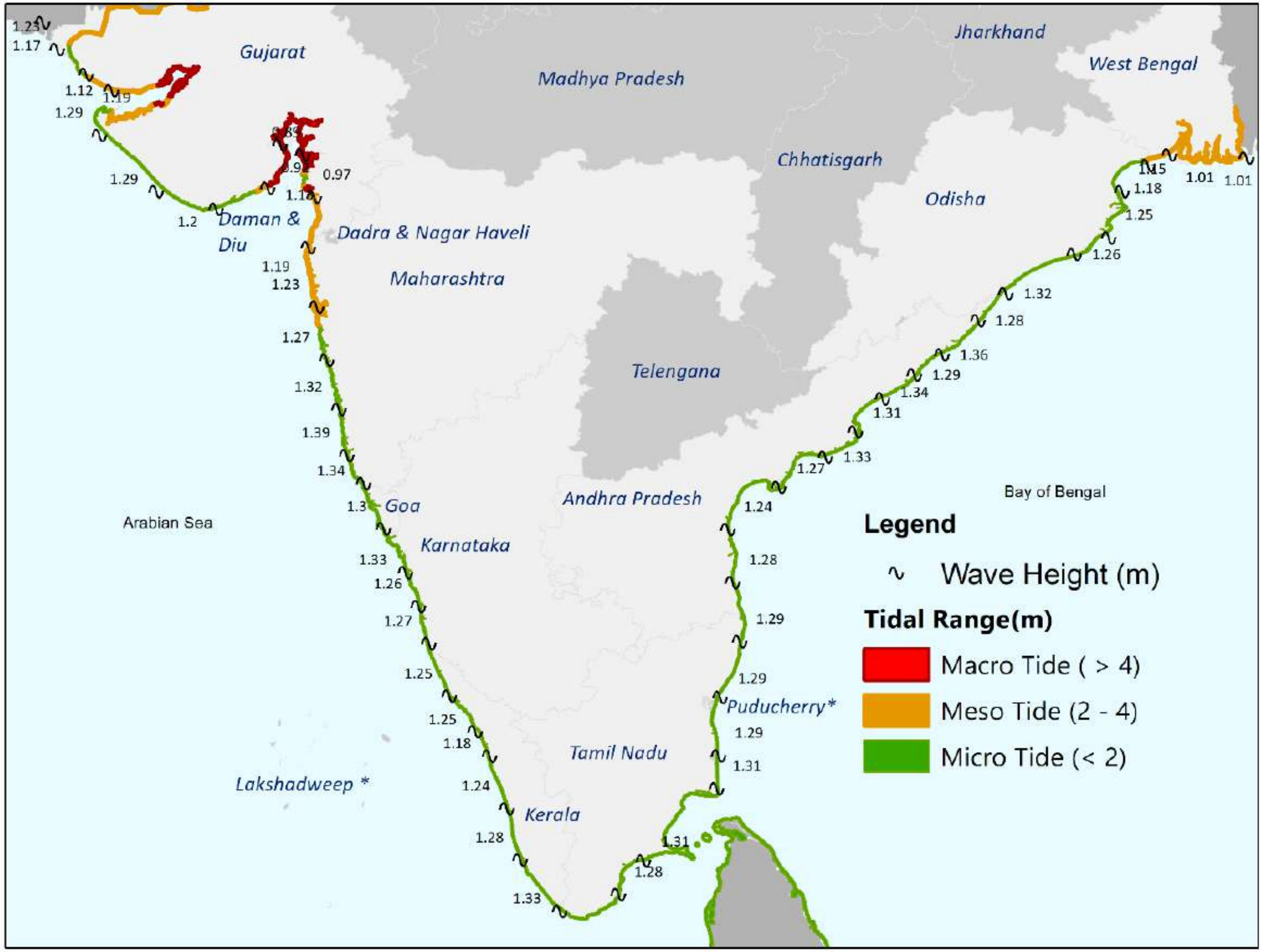

Figure 3: Significant wave height and tidal range along the coast of India

1.3 Waves and Tides

Waves and tidal range play the major role for the analysis of coastal vulnerability. Significant wave height was obtained from satellite altimetry data at 1°x1° resolution (www.aviso.altimetry.fr) for entire Indian coast from 2009-2015. The averaged significant wave height varied from 0.97 m to 1.39 m along the east and west coast of India (Figure 3). On west coast the highest wave height of 1.39 m (mean) was observed along the coast of Maharashtra, while on east coast it was 1.36 m along Odisha coast. The tidal range along the Indian coast varied between 1 and 6 m (Figure 3). Macro tides (>4 m) were observed at the Gulf of Khambat and Kachchh of Gujarat coast and meso tides between 2 and 4 m along the coast of West Bengal.

1.4 Coastal Ecosystems

The Indian coastline has diverse sensitive ecosystems such as mangroves, seagrass (Figure 4); coral reefs, salt marshes (Figure 5); mudflats and sand dunes (Figure 6); estuaries, lagoons, and other vegetated wetlands. Many of these coastal ecosystems are known for their rich biodiversity and some coastal wetlands offer unique habitats or seasonal nesting sites for endangered marine organisms. India is one of the richest countries in the world in terms of biodiversity and this natural variation in life is also reflected in the demography of the land. Although the causes behind biodiversity and demographic diversity are different, the human population of the land has depended on the biodiversity in many ways for a long time.

India is home to about 10% of world's species that includes 91,000 species of animals and 45,500 species of plants and is recognized as one among the 17 "mega-diverse" countries in the world. In the case of marine biodiversity, about 15,000 marine species of flora and fauna have been reported in India which is about 5.33% of the world's marine diversity. Around the world, at least 35 areas qualify as biodiversity hotspots. These sites support nearly 60% of the world's plant, bird, mammal, reptile, and amphibian species, with a very high share of endemic species.

There are designated four biodiversity hotspots in India viz., Himalayas, Indo-Burma region, Sundalands (which includes Nicobar group of Islands in India) and the Western Ghats. The species in these biodiversity hotspots are being threatened due to habitat destruction, resource mismanagement, poaching and climate change. With respect to coastal and marine biodiversity in India, a number of areas of high biodiversity can be identified. These include the Gulf of Mannar and Gulf of Kachchh; areas with extensive mangroves such as the Sunderbans, Bhitarkanika, Coringa and Pichavaram as well as the Nicobar Islands.

India Coastal & Marine Biodiversity

A mega-biodiverse country, India supports about 8% of the world's biodiversity. Coasts and islands form 2.8% of India's total geographical area. Coastal ecosystem consists of 43230 km^2 of coastal wetlands with 97 major estuaries and 34 major lagoons; 6740 km^2 of mangroves with 31 mangrove areas, 5 coral reef areas. Towards protection and management, India has designated 25 Marine Protected Areas (MPA) in peninsular India covering 8231 km^2 and 106 MPAs in the Andaman & Nicobar and Lakshadweeo Islands. Coastal species diversity comprises of over thirteen thousand plants and animals species consisting of marine algae (844), seagrass (14), mangroves and associates (2321), crustaceans (2934), molluscs (3370), echinoderms (765), hard corals (218), fishes (2546), reptiles (31), marine mammal (25).

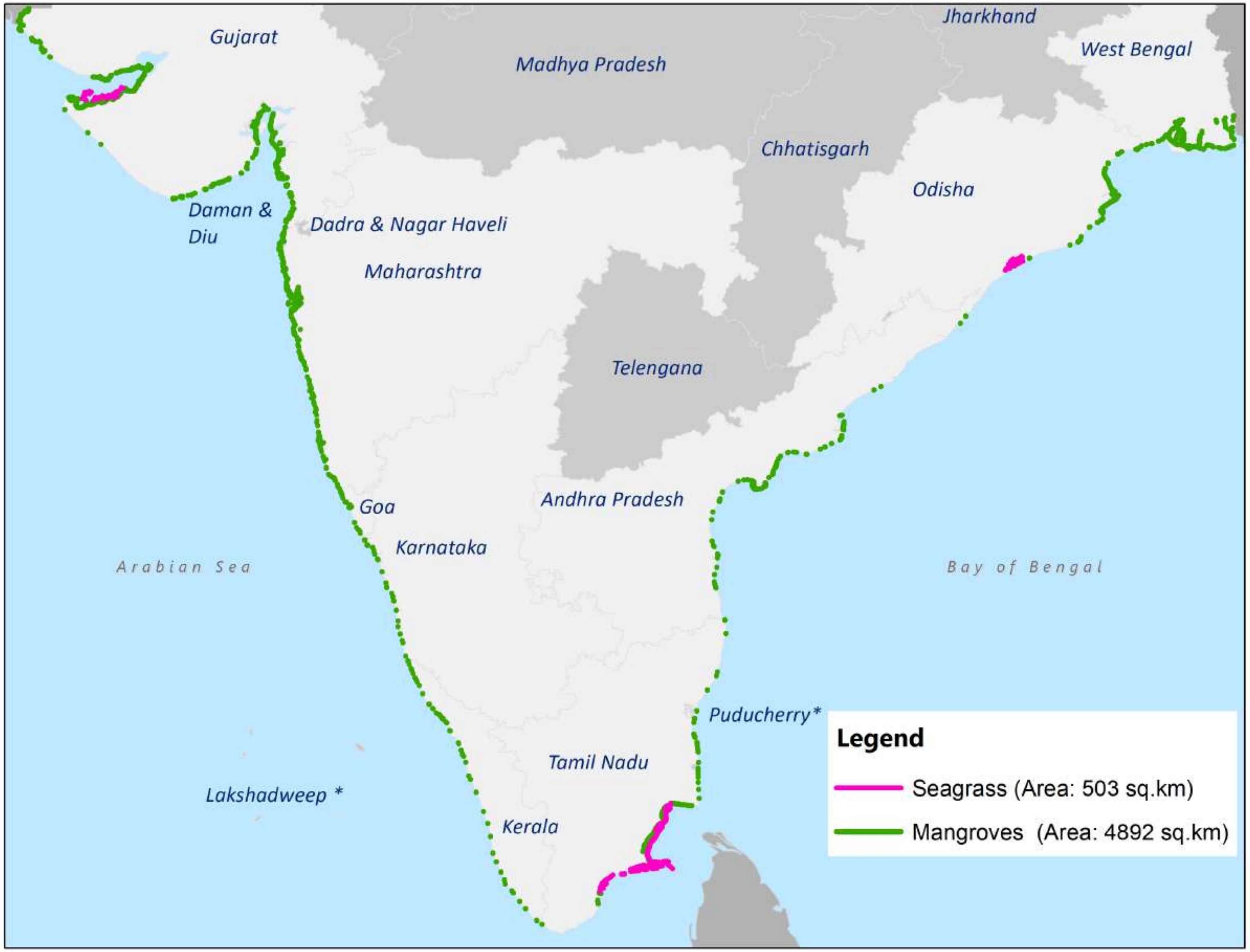

Figure 4: Mangrove and seagrass ecosystems of India

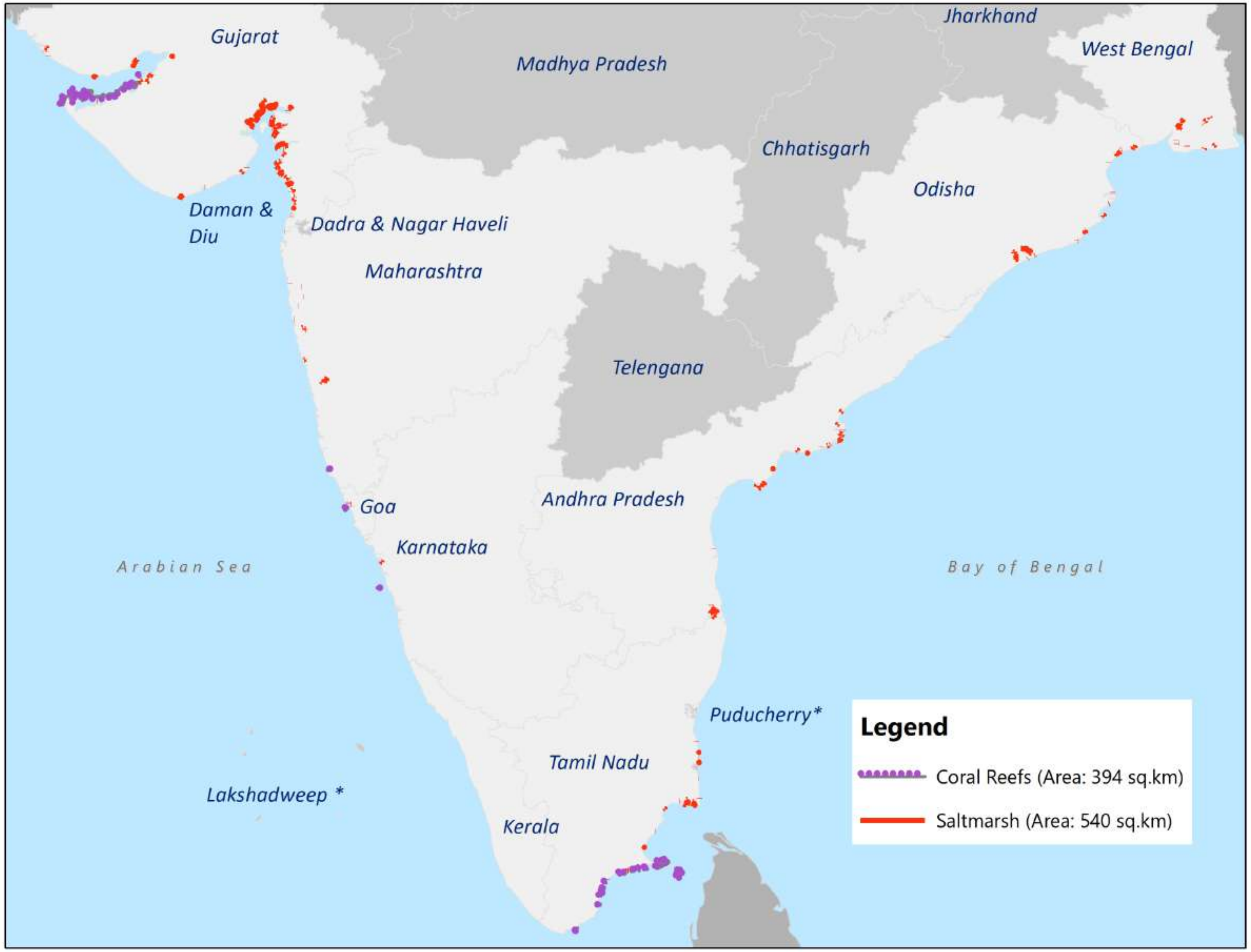

Figure 5: Coral reef and saltmarsh ecosystems of India

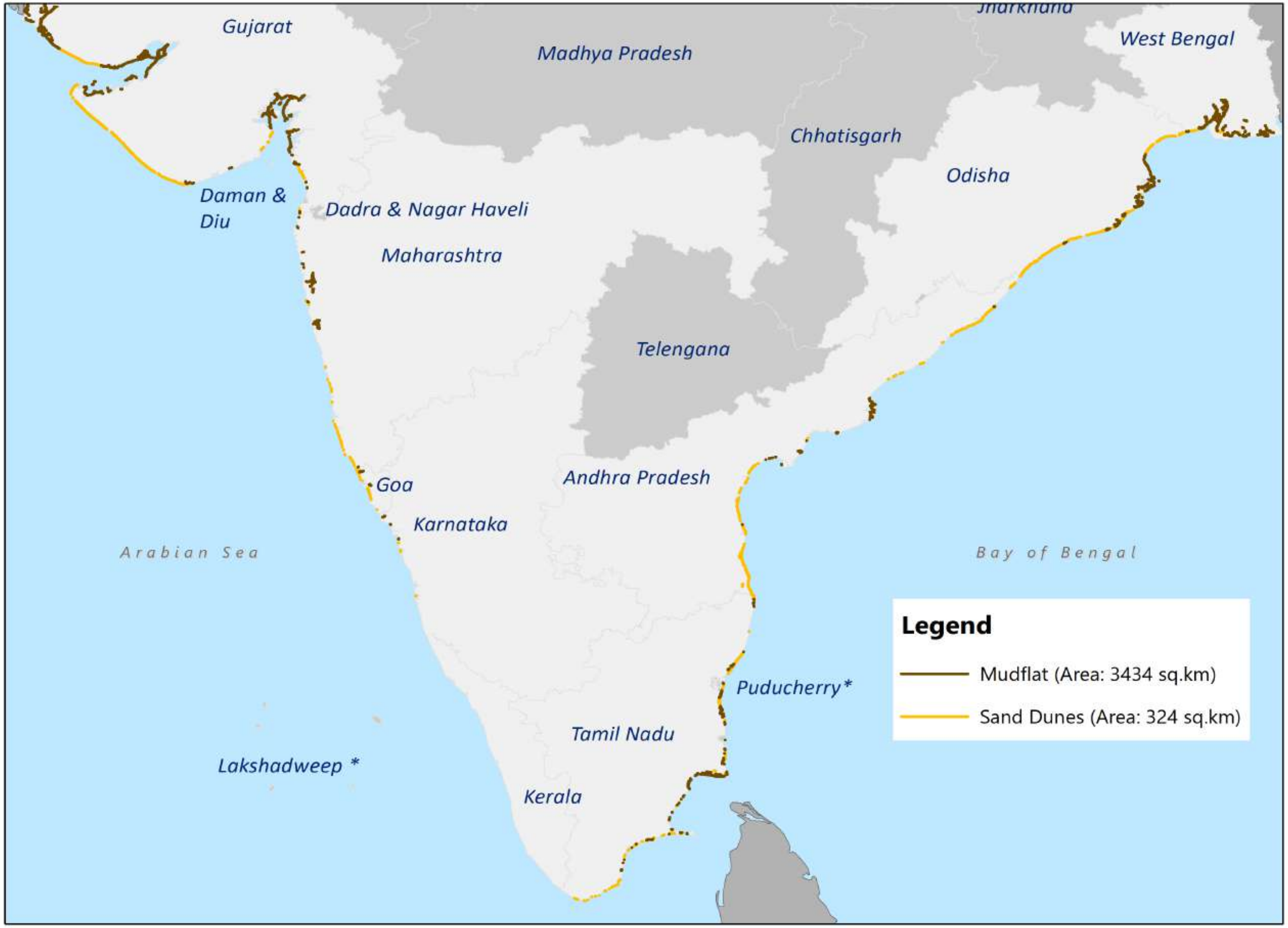

Figure 6: Mudflats and sand dune ecosystems of India

1.5 Human Attributes and Coastal Demographics

India's mainland coast is divided administratively into nine states and two Union Territories (UT); the island groups also have UT status. Each State/UT is further subdivided into districts. Including those in the island groups, there are 79 coastal districts with a total population of over 20 million as per census of India, 2011. The district- wise distribution of population and density is given in Table 1.

Table 1: Coastal districts and demography of India

State/ UT	District	Total Population	Area (Sq.km)	Population Density
A & N Islands*				
	Nicobar	36842	1691.74	22
	South Andaman	238142	2568.3	93
	North & Middle Andaman	105597	2875.72	37
Andhra Pradesh				
	East Godavari	5154296	11945.69	431
	Guntur	4887813	12477.18	392
	Krishna	4517398	9366.55	482
	Nellore	2963557	14072.24	211
	Prakasam	3397448	19204.68	177
	Srikakulam	2703114	7072.47	382
	Visakhapatnam	4290589	12691.29	338
	Vizianagaram	2344474	6242.14	376
	West Godavari	3936966	8531.8	461
Daman & Diu*				
	Daman	191173	84.14	2272
	Diu	52074	33.41	1559
Goa				
	North Goa	818008	1820.65	449
	South Goa	640537	2104.6	304

State/ UT	District	Total Population	Area (Sq.km)	Population Density
Gujarat				
	Ahmadabad	7214225	9170.37	787
	Amreli	1514190	8494.05	178
	Anand	2092745	4074.48	514
	Bharuch	1551019	5520.31	281
	Bhavnagar	2880365	7535.26	382
	Devbhumi Dwarka	752784	4817.91	156
	Gir Somnath	1350307	4463.12	303
	Jamnagar	1407635	7369.76	191
	Junagadh	1392775	5727.77	243
	Kachchh	2092371	22113.08	95
	Morbi	701752	4209.84	167
	Navsari	1329672	2545.79	522
	Porbandar	585449	2652.09	221
	Surat	6081322	8536.25	712
	Valsad	1705678	3446.95	495
Karnataka				
	Dakshina Kannada	2089649	4856.7	430
	Udupi	1177361	4112.18	286
	Uttara Kannada	1437169	10964.34	131

State/ UT	District	Total Population	Area (Sq.km)	Population Density
Kerala				
	Alappuzha	2127789	1469.12	1448
	Ernakulam	3282388	2501.81	1312
	Kannur	2523003	3108.33	812
	Kasaragod	1307375	2072.73	631
	Kollam	2635375	2564.92	1027
	Kozhikode	3086293	2442.46	1264
	Malappuram	4112920	3725.18	1104
	Thiruvananthapuram	3301427	2243.23	1472
	Thrissur	3121200	3149.22	991
Lakshadweep*				
	Lakshadweep	64473	477.07	135
Maharashtra				
	Mumbai	3085411	106.19	29055
	Mumbai Suburban	9356962	429.33	21794
	Ratnagiri	1615069	9109.22	177
	Raigarh	2634200	7862.74	335
	Sindhudurg	849651	5526.53	154
	Palghar	1646714	5346.85	308
	Thane	9413434	5428.1	1734
Odisha				
	Baleshwar	2320529	4500.52	516
	Bhadrak	1506337	2855.52	528
	Ganjam	3529031	9604.18	367
	Jagatsinghapur	1136971	1979.84	574
	Kendrapara	1440361	2818.47	511
	Khordha	2251673	3131.66	719
	Puri	1698730	4037.03	421

State/ UT	District	Total Population	Area (Sq.km)	Population Density
Puducherry*				
	Karaikal	200222	159.96	1252
	Puducherry	950289	312.41	3042
	Yanam (enclave in Andhra Pradesh; part of Puducherry district)	55626	41.46	1342
	Mahe (enclave in Kerala; part of Puducherry district)	41816	1.81	23146
Tamil Nadu				
	Chennai	4646732	187.77	24747
	Cuddalore	2605914	3881.68	671
	Kancheepuram	3998252	4749.45	842
	Kanniyakumari	1870374	1736.55	1077
	Nagapattinam	1616450	2559.38	632
	Pudukkottai	1618345	4837.91	335
	Ramanathapuram	1353445	4357.47	311
	Thanjavur	2405890	3769.59	638
	Thiruvarur	1264277	2171.45	582
	Tirunelveli	3077233	7006.74	439
	Thiruvallur	3728104	3538.82	1053
	Thoothukkudi	1750176	4775.45	366
	Viluppuram	3458873	7555.17	458
West Bengal				
	North 24 Parganas	10009781	12286.59	815
	Purba Medinipur	5095875	5021.70	1015
	South 24 Parganas	8161961	4647.73	1756

*** Union Territories**






1.6 Cities and Towns

As per the Census data of 2011, there are 486 census towns along the coast of India, accounting for a population of 41.7 million constituting 20.7% of the total coastal population. Of the 486 towns, 42 are classified as Class-I towns that have a population of > 100,000 persons (Table 2 and 3).

Table 2: Classification of cities based on population

Town Classification	Population
Tier-1	100,000 and above
Tier-2	50,000 to 99,999
Tier-3	20,000 t0 49,999
Tier-4	10,000 to 19,999
Tier-5	5,000 to 9,999
Tier-6	Less than 5000

India has two coastal megacities apart from a number of cities with more than one million population (Table 4) located on the coast. Many of these cities are port cities or have major industries. Apart from these, there are a number of towns and cities located along the coast where agriculture and fishing are major livelihoods.

1.7 Fishing Villages

There are 3,288 marine fishing villages distributed among the nine maritime states and two union territories. There are 42, 53,451 people belonging to 18,340 families in 8, 64,550 marine fishermen households[1]. Of these, 90% belong to traditional fisher families. Tamil Nadu has the largest population of marine fishers (0.8 million), followed by West Bengal (0.634 million) and Kerala (0.61 million).

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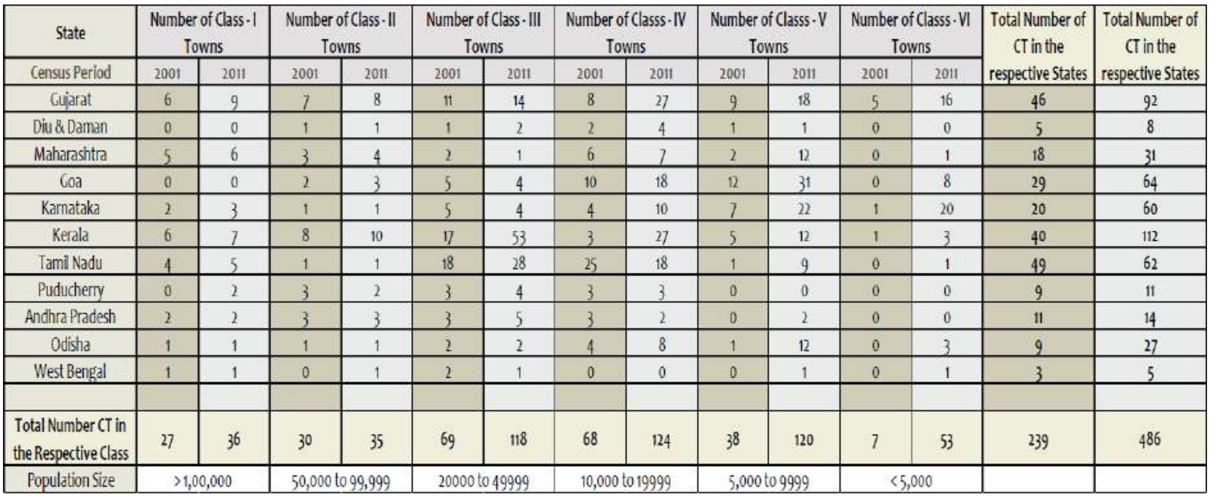
[1] https://indianfisheries.icsf.net/en/page/609-General%20Overview.html

Table 3: State-wise number of different classes of towns between 2001 and 2011



State	Number of Class - I Towns		Number of Class - II Towns		Number of Class - III Towns		Number of Classs - IV Towns		Number of Classs - V Towns		Number of Classs - VI Towns		Total Number of CT in the respective States	Total Number of CT in the respective States
Census Period	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011		
Gujarat	6	9	7	8	11	14	8	27	9	18	5	16	46	92
Diu & Daman	0	0	1	1	1	2	2	4	1	1	0	0	5	8
Maharashtra	5	6	3	4	2	1	6	7	2	12	0	1	18	31
Goa	0	0	2	3	5	4	10	18	12	31	0	8	29	64
Karnataka	2	3	1	1	5	4	4	10	7	22	1	20	20	60
Kerala	6	7	8	10	17	53	3	27	5	12	1	3	40	112
Tamil Nadu	4	5	1	1	18	28	25	18	1	9	0	1	49	62
Puducherry	0	2	3	2	3	4	3	3	0	0	0	0	9	11
Andhra Pradesh	2	2	3	3	3	5	3	2	0	2	0	0	11	14
Odisha	1	1	1	1	2	2	4	8	1	12	0	3	9	27
West Bengal	1	1	0	1	2	1	0	0	0	1	0	1	3	5
Total Number CT in the Respective Class	27	36	30	35	69	118	68	124	38	120	7	53	239	486
Population Size	>1,00,000		50,000 to 99,999		20000 to 49999		10,000 to 19999		5,000 to 9999		<5,000			

Table 4: Coastal cities/ Urban Agglomeration(UA) with population >1 million

S.No.	Coastal City	State	Population
1	Greater Mumbai	Maharashtra	18,414,288
2	Chennai	Tamil Nadu	8,696,010
3	Surat	Gujarat	4,585,367
4	Kochi	Kerala	2,117,990
5	Kozhikode	Kerala	2,030,519
6	Vadodara	Gujarat	1,817,191
7	Vishakhapatnam	Andhra Pradesh	1,730,320
8	Puri	Orissa	1,697,983
9	Thiruvananthapuram	Kerala	1,687,406
10	Kannur UA	Kerala	1,642,892
11	Vasai Virar City (Municiple Corporation)	Maharashtra	1,221,233
12	Kollam UA	Kerala	1,110,005

2. Delineation of Composite Hazard Line

The varying demographic, socio-economic, physical and geomorphological conditions described above, indicate the sensitive nature of India's coast and its islands. Natural and man-made hazards with accelerated climate change consequences have compounding effects on the life and livelihood of coastal communities. For this purpose, the Ministry of Environment, Forest and Climate Change (MoEFCC) has demarcated the country's hazard line through the Survey of India, and NCSCM, MoEFCC. The hazard line delineates land areas that are at risk from coastal erosion (erosion line) and coastal flooding (flood line). The "Composite Hazard Line" would show the most landward of the two – the flood and erosion lines.

Much of the increase in coastal hazard risk in India particularly that associated with coastal erosion and flooding is due to:

- development located in close proximity to the coastline
- changes in hydrodynamics due to obstruction of natural coastal dynamics and function of beaches and dune systems
- conversion and development of low-lying coastal areas that are naturally prone to inundation

The primary purpose of the hazard line is to identify hazard zones along the coastline that reflects a potential danger and risk to people and their property. It is imperative to point out that such a Hazard Zone would not preclude development if this was deemed necessary by the State Government as part of their Integrated Coastal Zone Management Plan. Rather the advice would be to restrict such development if at all possible. However, if after due reflection, an area within the Hazard Zone was designated for future development, then such development should be provided with appropriate coastal defenses in order to lower the risk to people and property. In heavily developed areas, coastal hazard maps may be used simply for public education and awareness purposes, or to inform evacuation for storm-tide or tsunami warnings (Ramsay et al., 2012).

India's hazard line has been demarcated based on a composite line of the shoreline changes and sea level rise due to climate change, tides and waves. This includes collection and presentation of data, identifying flood lines over the last 40 years (which includes sea level rise impacts), and a prediction of erosion to take place over the next 100 years and digital photogrammetric processing of high resolution Aerial photography data. The methodology for demarcating the hazard line involves the following steps:

a. Tidal data processing

i. Collection of historical tidal data (annual highest high tide level) of 21 major/ primary ports/tidal stations and 180 minor/secondary ports/tidal stations, covering the Indian coast.

ii. Determination of tide level with 100 years Return Period for primary ports, using Weibull statistical distribution.

iii. Interpolation/ extrapolation for determining the tide level with 100 year return period for Secondary ports.

iv. Interpolation of tide level with 100-year Return Period for intermediate stations i.e., at transects at every 250 m between secondary ports.

v. Adding the effect of projected sea level rise in 2100 of 60 cm, as per the RCP 6.0 scenario

b. Generation of Digital Elevation Models (DEM)

i. Very high resolution Digital Aerial Photographs of 9 cm Ground Sampling Distance (GSD) of the entire coastal region of the country from Gujarat in the west to West Bengal in the east covering an area of over 78,000 sq. km. was generated.

ii. Photogrammetric surveys and digital terrain model for the entire mainland coast was prepared.

c. Delineation of Flood line

i. The 100-year return period tidal elevations computed at the intermediate transects at every 250 m along the coast were plotted onto the 0.1 m contour data generated from high resolution DEM.

ii. The locus of these points is the flood line.

Computation of 100 year returns period tide levels

Survey of India has been carrying out systematic tidal observations and data acquisition since 1887 and thus has a long series of tidal records systematically collected over the years all along the Indian Territory. From these tidal records, the hourly tide levels were extracted manually. These hourly tide levels form the basic data for computation of tidal constituents, tidal predictions, Highest Astronomical Tide (HAT) level, Lowest Astronomical Tide (LAT) level and Mean Sea Level (MSL).

The observed tidal heights were generally represented as sea level above the ***chart datum*** (CD) at a particular point of time. All heights on the land were represented as height above mean sea level, in the present case; it is Indian Mean Sea Level (IMSL). When the tidal heights were transferred to land, these heights were converted to height above mean sea level using the relation between IMSL and CD at that particular port. Using this relationship, the tidal heights were reduced to IMSL. The advantage of converting to IMSL is that the tidal heights which are computed in terms of 100 year return period can directly be used for delineating the hazard line on the ground by connecting the standard bench marks by means of differential levelling techniques. There are numbers of statistical methods in use to determine the tide level with 100 years Return Period. In the present analysis, Weibull distribution method was used.

In the Weibull's method, the basic assumption made is that the data is representative i.e., the individual values are independent. From the dataset of each port, the Annual Maximum Tide Level for each year is identified and tabulated after reducing them to the height above IMSL. These tidal heights are arranged in the descending order and rank is assigned to each of the Annual Maximum Tide Level. "Ranking" is a procedure by which the data set is arranged in a decreasing or increasing order of magnitude and its order number is assigned. When the ranking is in descending order, the highest high water is assigned a rank of one (**m=1**), the next highest high water is given rank two (**m=2**) and so forth. By ranking, the number of the times any particular event is equaled or exceeded during the total period of record, **N** is determined.

The 'recurrence interval' is defined as the mean time in years for the **m**th largest value among annual maxima series of length **N** to be equaled or exceeded once on the average in **n** future trials, we can have the mean number of exceedances($\overline{X}$) in future **n** years as

$$\overline{X} = n.\frac{m}{N+1} \qquad \text{......(1)}$$

If the mean number of exceedances $\overline{X}$=1, the 'probability', **p** of a high water of given **m**th rank, occurring in the **n** next years simplified to 'relative frequency' as

$$p = \frac{m}{N+1} \qquad \text{......(2)}$$

The percent probability of which is px100 per cent. The probability that it will not occur in a given year is the probability of non-exceedance, p' which is

$$p' = 1 - p \qquad \text{.......(3)}$$

Equation (2) is commonly referred to as Weibull's plotting position formula for unspecified distributions. Now the recurrence interval (also called 'return period') as defined earlier is the average number of years during which a high water of a given magnitude, m will be equaled or exceeded. This denoted as T - year or T is given by

$$T = \frac{1}{p} \text{ year} = \frac{N+1}{m} \qquad \text{....... (4)}$$

T is **N+1** year for the highest high water and **T** is 1-year for the lowest high water.

The annual highest high water data of any port, highest high water frequency in terms of return period **T** for every **m**th rank in the data is scaled and plotted along the abscissa of a semi-logarithmic graph paper (starting with common logarithm value 1, in Excel sheet the same is plotted by taking 1 at origin) with high water height along ordinate. Best fit line/Linear Trend line is drawn to calculate the tide level with 100 year return period. The same can also be calculated by using equation of trend line on logarithmic scale.

The tide level with 100 year return period was computed in two steps. In the first step, the tide level with 100 year return period was calculated at 21 primary ports using Weibull's method. In the next step, using these tide levels at primary ports, the 100 return period tide levels at secondary ports was computed by interpolation/ extrapolation in two methods viz., (i) Direct method and (ii) Indirect/HAT ratio method.

The annual highest high water data of any port, highest high water frequency in terms of return period for every th rank in the data is scaled and plotted along the abscissa of a semi-logarithmic graph paper (starting with common logarithm value 1, in Excel sheet the same is plotted by taking 1 at origin) with high water height along ordinate. Best fit line/Linear Trend line is drawn to calculate the tide level with 100 year return period. The same can also be calculated by using equation of trend line on logarithmic scale.

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Computation of tide level with 100 year return period at Primary ports:

From the dataset of each Primary port, the Annual Maximum Tide Level for each year is identified and tabulated after reducing them to the height above IMSL. These tidal heights were arranged in the descending order and rank was assigned to each of the Annual Maximum Tide Level. Using the Weibull distribution, the plotting positions of each of the Annual Maximum Tide level was computed and plotted against return period on logarithmic scale. The Best Fit line was plotted and extrapolated to 100 years which provides the tide level with 100 years return period at that port. A similar methodology was adopted in respect of other primary ports as well. Thus, 21 tide levels of 100 year return period were obtained all along India's coastline. Similarly, computation of tide level with 100 year return period at secondary ports and transect points was carried out using interpolation.

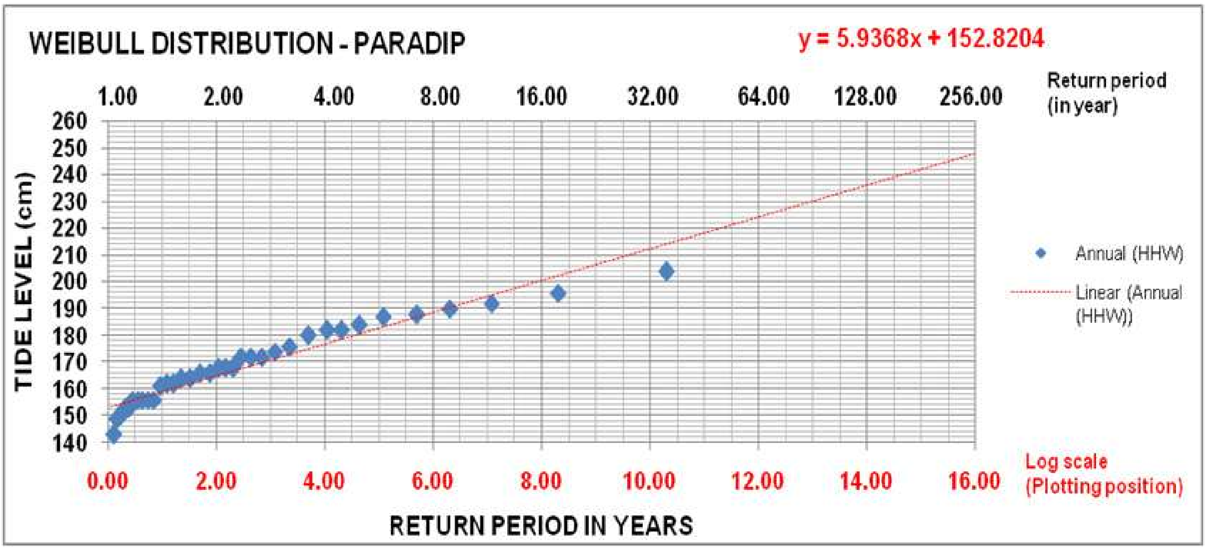


Figure 7: Example of Weibull distribution and return period computation for Paradip Port

d. Delineation of Erosion line

i. Georeferencing the time series high resolution satellite imagery for the period from 1972 to 2012

ii. Delineation of the periodic shorelines from the satellite imagery for the period from 1972 to 2010 and from the high resolution aerial ortho-image of 2012.

iii. Computation of annual rate of erosion/accretion using the Digital Shoreline Analysis System (DSAS) at transects points at every 300 m along the coast, in terms of annual displacement from a fixed base line.

iv. Extrapolation to compute the 100-year erosion/accretion rates at these transect points, in terms of the distances from the fixed base line.

v. Plotting the above transect points on high resolution satellite image.

vi. The locus of these points is the erosion line

e. Demarcation of the Hazard Line

i. Overlaying the Flood line and the Erosion line in a GIS environment.

ii. Marking the segments of the Flood line /Erosion line which is the most landward, to obtain the Hazard line (Figure 8).

iii. Transferring the hazard line to topographic maps for public dissemination.

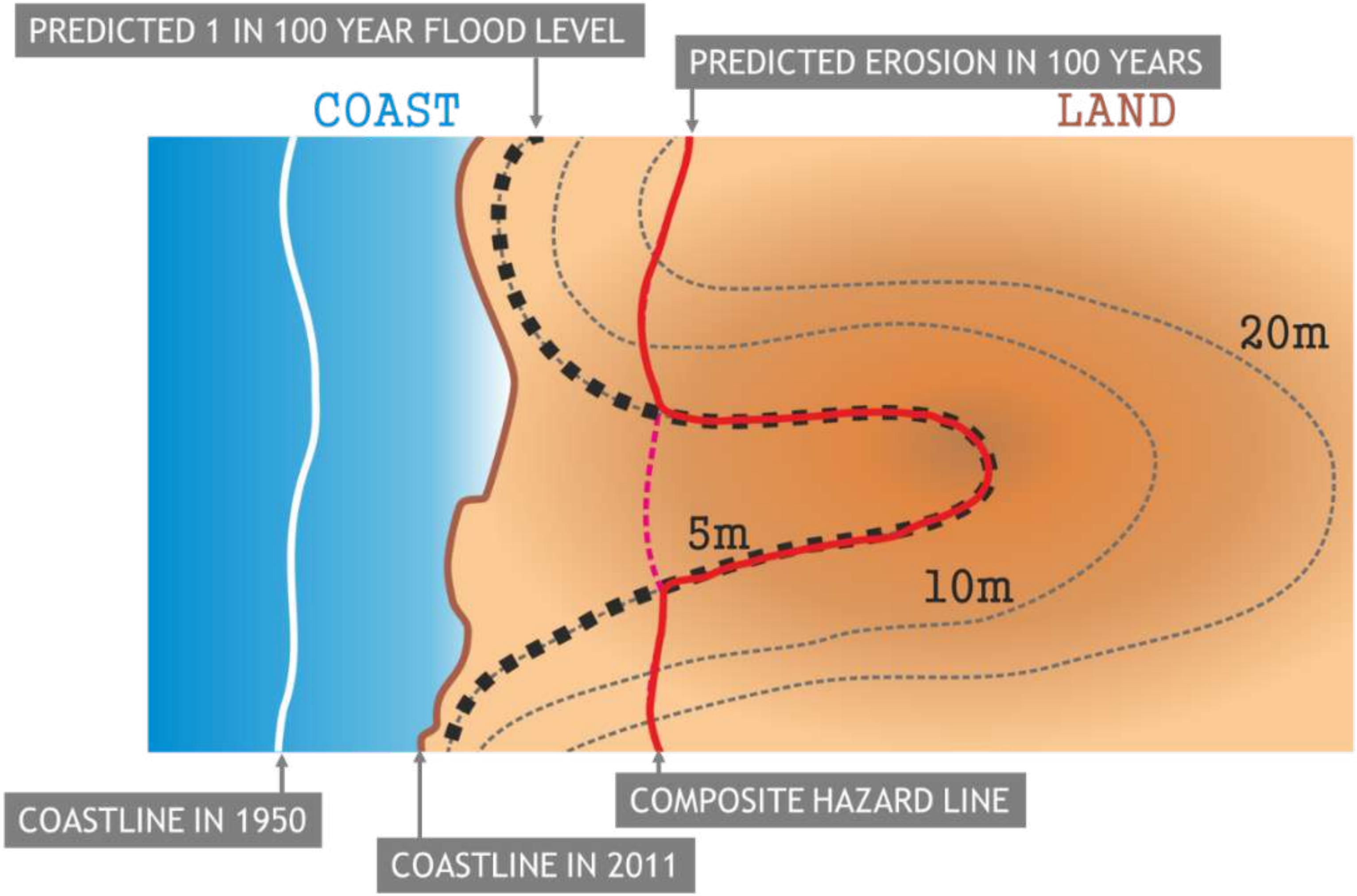


Figure 8: Concept of composite Hazard Line

3. International best practices in delineating Hazard line

Internationally, Hazard Line is also commonly known as coastal setback line (Table 5) and is defined as "**the landward limit of a buffer zone along the coastline where building restrictions or prohibitions are applied. The width of this buffer will depend on the associated physical, environmental and socioeconomic criteria**".

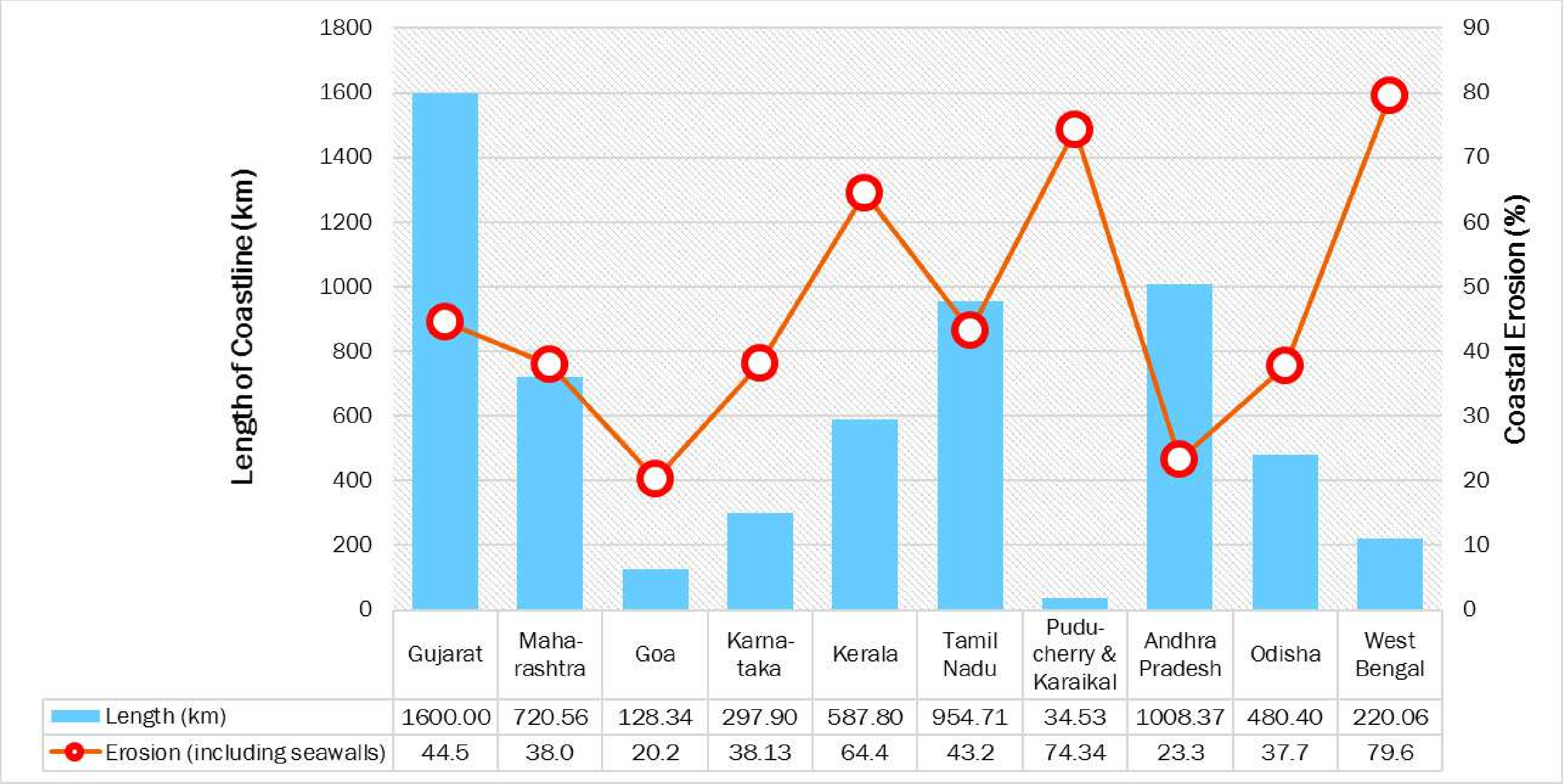
Table 5: International best practices to determine setback lines

S.No.	Country	Flooding	SLR	Erosion	Setback Zone	Methods used	Accuracy
1	Australia	1:100 year storm	100 years of sea-level rise	The erosion trend (if found to occur) applied for a 100 years	In South Australia, setbacks take into account the100-year erosional trend plus the effect of a 0.3-m sea-level rise to 2050. Building sites should be above storm-surge flood level for the 100-year return interval.	Aerial Photogrammetry	Vertical accuracy: ±0.1 m (±0.3 m at most).
						LiDAR (Light Detecting And Ranging)	Horizontal accuracy: ±0.5 to ±1.0 m
							A corridor of 200 m to 500 m inland of the spring low waterline should be measured
2	USA		The 30 year erosion determination does not factor in sea level rise. Sea level rise is a hazard that is only indirectly addressed in the Coastal Resource Management Program (CRMP)	The average annual rate of recession times 100 years or An erosion allowance of 30 meter	Variable in Coastal States - setback lines based on erosion rates are set 30 or 50 times the erosion rate annual erosion rate	Aerial Photogrammetry & LiDAR (Light Detecting And Ranging)	
					The states of Maine, Massachusetts, Rhode Island, and South Carolina have implemented various forms of rolling easement policies to ensure that wetlands and beaches can migrate inland as sea level rises.		

S.No.	Country	Flooding	SLR	Erosion	Setback Zone	Methods used	Accuracy
3	Canada	100 year flood elevation			Setback for new development is defined from the landward limit of coastal features. Various provinces have adopted a variety of setback policies, based on estimates of future coastal retreat.		
4	United Kingdom	100 year flood return interval		Flood and coastal erosion risk management should be planned over a long timeframe (often 100 years)	House of Commons in 1998 endorsed the concept of managed realignment as the preferred long-term strategy for coastal defense in some areas	Ortho-rectified aerial or satellite photos and Historic maps	
5	New Zealand	100 year Average Recurrence Interval		100 years: Historical rates of open coast erosion and accretion for the New Zealand coastline (ca. 1880 – 1980)	Primary Development Setback (PDS): includes the worst probable erosion likely to be associated with existing coastal processes plus an allowance of 10 m to ensure a protective buffer is maintained Secondary Development Setback (SDS): the second setback incorporates an allowance for the effects that may accompany predicted global warming over the next 100 years.	Aerial Photogrammetry & LiDAR (Light Detecting And Ranging)	

4. Shoreline Change for the coast of India

Considering the international best practices, only a few developed countries listed in Table 5 undertake mapping of such an extensive 1:100 year return intervals. India is a pioneer in this effort to comprehensively map and delineate the hazard line for the entire coast of India. The cumulative shoreline change along the coast of India indicates 42% erosion (high/ medium/ low erosion); 14% as stable (no change for the past 40 years); 37% accretion and 7% of the Indian coast is rocky (Figure 9). It is also observed that over 3% of the coast is highly eroding and nearly 20% of the highly eroding coastline is already protected by seawalls and other shore-protection structures.



	Gujarat	Maha-rashtra	Goa	Karna-taka	Kerala	Tamil Nadu	Pudu-cherry & Karaikal	Andhra Pradesh	Odisha	West Bengal
Length (km)	1600.00	720.56	128.34	297.90	587.80	954.71	34.53	1008.37	480.40	220.06
Erosion (including seawalls)	44.5	38.0	20.2	38.13	64.4	43.2	74.34	23.3	37.7	79.6

Figure 9: Erosion/ accretion characteristics (%) along the coast of India

Among the coastal states/ Union Territories, West Bengal on the east coast experiences severe erosion (79.6%), most of which is protected either by seawalls or embankments; followed by Puducherry (74%) and Tamil Nadu (43%). The west coast however is more or less stable due to the presence of rocky coast. Nevertheless, the west coast is already managed by armoring the coast with seawalls in heavily inhabited states such as Kerala (64%), followed by Gujarat (45%), and Karnataka and Maharashtra at 38% each. Goa has relatively stable coastline with less than 20% erosion (Figure 9).

The most direct and visible impact of coastal erosion is loss of coastal land. Coastal erosion can also result in the destruction of natural sea defenses such as dunes, or artificial defenses. This is often seen during extreme events such as storm surges or tsunamis. Such breaching of coastal defenses can result in flooding/ inundation of low lying areas along the coast and have a high economic impact. An indirect impact can be the salinization of coastal aquifers turning them brackish and resulting in investments to provide potable water to coastal communities.

Shorelines also change seasonally, tending to accrete slowly during the summer months when sediments are deposited by relatively low energy waves and erode dramatically during the winter when sediments are moved offshore by high energy storm waves. In addition, attempting to halt natural coastal process with seawalls and other hard structures only shifts the problem, subjecting down drift coastal areas to similar losses. Also, without the sediment transport, some of the beaches, dunes, barrier beaches, salt marshes, and estuaries are threatened and would disappear as the sand sources that feed and sustain them are eliminated. The increase in the population density within one km of the coast represents the increased risks to life and property due to various coastal hazards including shoreline erosion.

Studies have indicated that loss of beach space has a serious impact on fishing communities in India as much of the small scale fishery is beach based and the houses of fishermen are located close to the shoreline. Coastal erosion has led to loss of houses, boats as well as fish drying spaces (e.g. Odisha (Nayak, Das, & Behera, 2012) and reduction of beach width and forced shifting landwards (e.g. Andhra Pradesh (Guru Prasad & Narasimha Rao, 2014), and multiple and frequent repairs to coastal roads (Padmakumari, Jahan, & Radhakrishna, 2012). With large stretches of the Indian coast undergoing erosion despite various coastal protection measures, it is clear that a comprehensive strategy to address the issue of coastal erosion is necessary.

5. Hazard Line for the coast of India

Composite hazard line for the coast of India typically follows the flood line along ~95% of the coast (Figure 10). However, in areas such as Sagar Island in West Bengal, the erosion line supersedes flood line. Table 6 provides the maximum extent of inundation experienced in coastal districts of India. First analysis (Table 6) of the composite hazard line indicates the following major findings:

a. Large areas of Mumbai, a mega city along India's west coast would experience 51% of inundation due to coastal flooding. The city has a very high population density of 19,652/ km^2

b. Similarly, Alappuzha District in Kerala would experience 54% inundation with a population density of 1504/ km^2

c. Inundation of 47% and 35% at Kendrapada and Puri districts respectively of Odisha, indicate the role of major rivers/ delta systems (Mahanadi River) with generally low elevation enhancing flood levels. This is particularly amplified during extreme events such cyclones, which frequent this coast of Odisha during southwest monsoon season (June – September).

d. Union Territories such as Diu and Puducherry would experience 39% and 25% inundation respectively. Both these regions have a high population density of over 1300/ km^2.






Table 6: Maximum extent of inundation along with population densities within the hazard line along the coast of India

Coast	State Name	District	District Area (km^2)	Inundation Area (km^2)	% Area Inundation	Population (in ‘000s)	Population density / km^2
West Coast	Gujarat	Bharuch	6509	978	15	1600	238
		Bhavnagar	10034	1036	10.3	2900	287
		Kachchh	45674	1057	2.3	2100	46
	Daman & Diu	Diu	39	15	39.0	100	1335
	Maharashtra	Mumbai	157	81	51.3	3100	19652
	Goa	North Goa	1736	194	11.2	800	471
	Karnataka	Udupi	3582	151	4.2	1200	329
	Kerala	Alappuzha	1415	768	54.3	2100	1504
East Coast	Tamil Nadu	Nagapattinam	2559	373	14.6	1600	632
	Puducherry	Puducherry	41	10	25.1	100	1342
	Andhra Pradesh	Krishna	9367	1039	11.1	4500	482
		East Godavari	11946	1237	10.4	5200	431
	Odisha	Kendrapara	2818	1330	47.2	1400	511
		Puri	4037	1419	35.2	1700	421

Coastal hazard line is an input to coastal planning and management of the coastal zone enabling better decision making for infrastructure projects such as ports, shoreline protection measures etc. It is expected that the 66 million coastal communities in low-lying coastal areas of India are aware of coastal hazards and enables safeguard of their lives, livelihoods and property. This composite hazard line map (Figure 10) will lead to improved knowledge of hazards along the coast of India, informing decision making process for planning and management and eventually protecting important landforms, landmarks, infrastructure and ecological sites. Further detailed analysis of these initial results is currently underway by preparing risk zones and district-wise extent of inundation.

Figure 10: Composite Hazard Line for the coast of India. *Insert: West coast: Near Karwar, Karnataka and East Coast: Near Visakhapatnam, Andhra Pradesh showing 1 in 100 year flood line, 100-year predicted erosion line and composite hazard line*

6. Hazard Line and Island Vulnerability

Given the fact that India has large number of oceanic and mainland islands which are extremely fragile and the first victims of climate-induced risks, it is worthwhile to understand the importance of demarcating the hazard line towards better preparedness for management of island vulnerability. In this context, a case study of Sagar Island, West Bengal has been taken to better understand the implications of the hazard line on the life, assets and livelihood of the island.

Small islands such as Sagar are particularly vulnerable to global climate change, climate variability and sea level rise. As their population, agricultural land and infrastructure tend to be concentrated in the coastal zones, any rise in sea level will have significant and profound effects on their economies and living conditions. The very survival of this low lying island is highly threatened.

Sagar Island also known as Sagardwip is situated in the Ganges delta, located about 100 km south of Kolkata (Table 7). The island covers a large area of 224.3 sq. km, lying between 21°36′ to 21°56′ N and 88°2′ to 88° 11′ E. The overall length of the island is ~100 km covering an area of 234.64 km^2 (Figure 11). This island is in the administrative jurisdiction of South 24 Paraganas District. According to the Gangasagar Bakhali Development Authority (GBDA), Sagar Island comprises of 6 or 9 Gram Panchayats, comprising 9 mouzas with 43 villages with a population of 2, 12,037 constituting of 43,716 households (Census 2011). The entire island is under Sagar CD block and the largest village is Gangasagar. Sagar Island is a typical deltaic island with its apex at the north and the base at the south. The coast of the island is tide dominated and has recorded a tidal range between 5 and 6 m (Dinesh Kumar et al., 2007).

Table 7: Facts and Figures of Sagar Island, West Bengal, India

Sagar Island Details	Facts & Figures
Latitudinal and Longitudinal Extent	21°37′40″N to 21°55′20″N
	88°02′45″E to 88°10′30″E
Length of Coast (km)	70 km
Area of Island	213 km2
Number/ Name of Districts 1	(South 24 Parganas)
Population	212,037
Key Livelihood	Marine & Inland Fisheries, Religious Tourism, Agriculture, duckery, betel vine and Rabi Crops
Dominant Land use	Settlements, Agricultural and Wetlands
Ecologically Sensitive Areas (ESA) 26.9 sq.km	Sand Dune
	Mangrove
	Mudflat
	Saltmarshes
	Horseshoe Crab
Accretion & Stable Coast (km)	46.1 km
Erosion (km)	25 km
Key coastal infrastructure	Fishing Jetty, Tourism Infrastructure, Cyclone Shelter, Helipad, Light house, road network, drainage
Major coastal Issues	Cyclone, Sea level Rise, Coastal flooding, Pollution, over fishing
Sea Level Rise	3.14 mm/year
Areas of Tourist Importance	Kapil Muni Temple, Gangasagar Mela and Religious Tourism
Coastal Protection Structures	Seawalls and embankments

Risk Zones and Risk Categories within Hazard Line

The purpose of classification of DEM within the hazard line is to depict areas most prone to coastal hazards. The high resolution DEM of Sagar area has been classified in to 11 risk zones. Zone 1 is the least vulnerable i.e. areas > 4.5 m to 1.5 m being highly vulnerable, with elevation <0.5 m at 0.5 m interval. These maps are useful in assessing the population and facilities at risk, and therefore in micro-level planning for emergency responses. The 11 risk zones identified were further classified into 4 risk categories to understand physical vulnerability within the hazard line (Table 8). Based on elevation, the categories include Very High, High, Moderate and Low risks.

Table 8: Various categories of risk zones in Sagar plan area

Risk Category	Elevation (m)
Low	**>4.5m**
Moderate	**3 - 4.5m**
High	**>1.5 - 3m**
Very High	**<1.5m**

As mentioned earlier, at Sagar Island, the predicted erosion line surpasses flood line, due to very high rates of erosion (locally termed as "land under sea").The key activities and population living in areas within and surrounding the hazard line is provided in Table 9.

Table 9: Key activities and population living within the Hazard Line at Sagar Island

Key activity in Sagar Island

Land Use	Area (km²)
Aquaculture	4.4
Cropland	13.1
Plantation/ Orchard	3.7
Total number of villages in Sagar Island	43

Number of people	Number of villages*
≤ 2500	5
>2500-5000	10
>5000-7500	14
>7500-10000	4
>10000	1
Number of villages not within Hazard Line	7
Depopulated Villages	2

*partially covered within hazard line

Maps, data, and information to assess risks and vulnerabilities related to coastal flooding and hazards in Sagar Island are presented in Figures 11 to 17. The composite hazard line is overlaid with habitations within the island, population, cropland area, plantation and orchards and ecologically sensitive areas. These maps would directly indicate how floodwaters might impact the island and the related assets within it.

Sagar is a densely populated island, with over 200,000 people living in 43 villages. Of the 43 villages, the hazard line either partially or entirely covers 36 villages, with a population of 173,405.

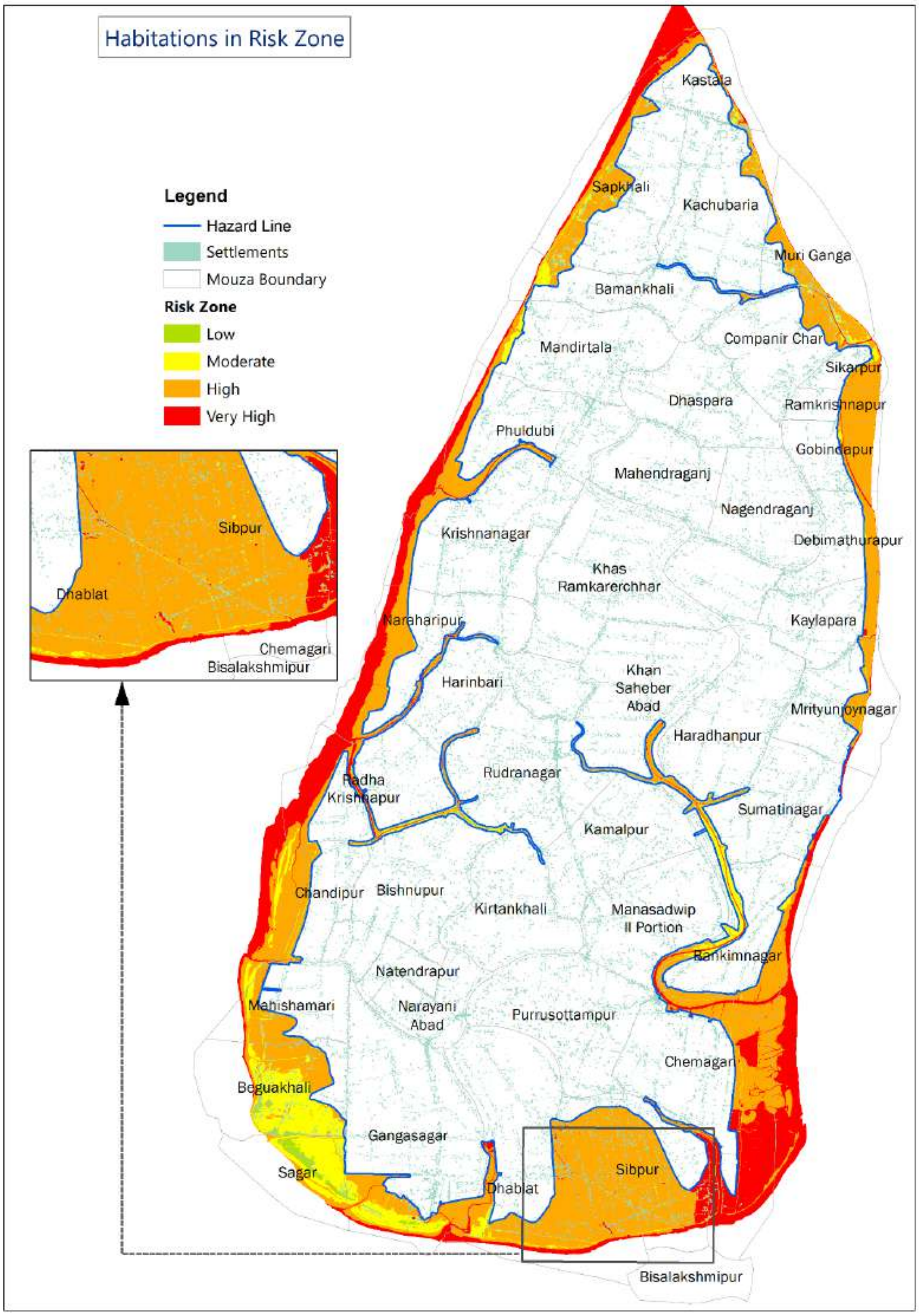


Figure 11: Habitations in Sagar Island, highlighting those within the risk zones

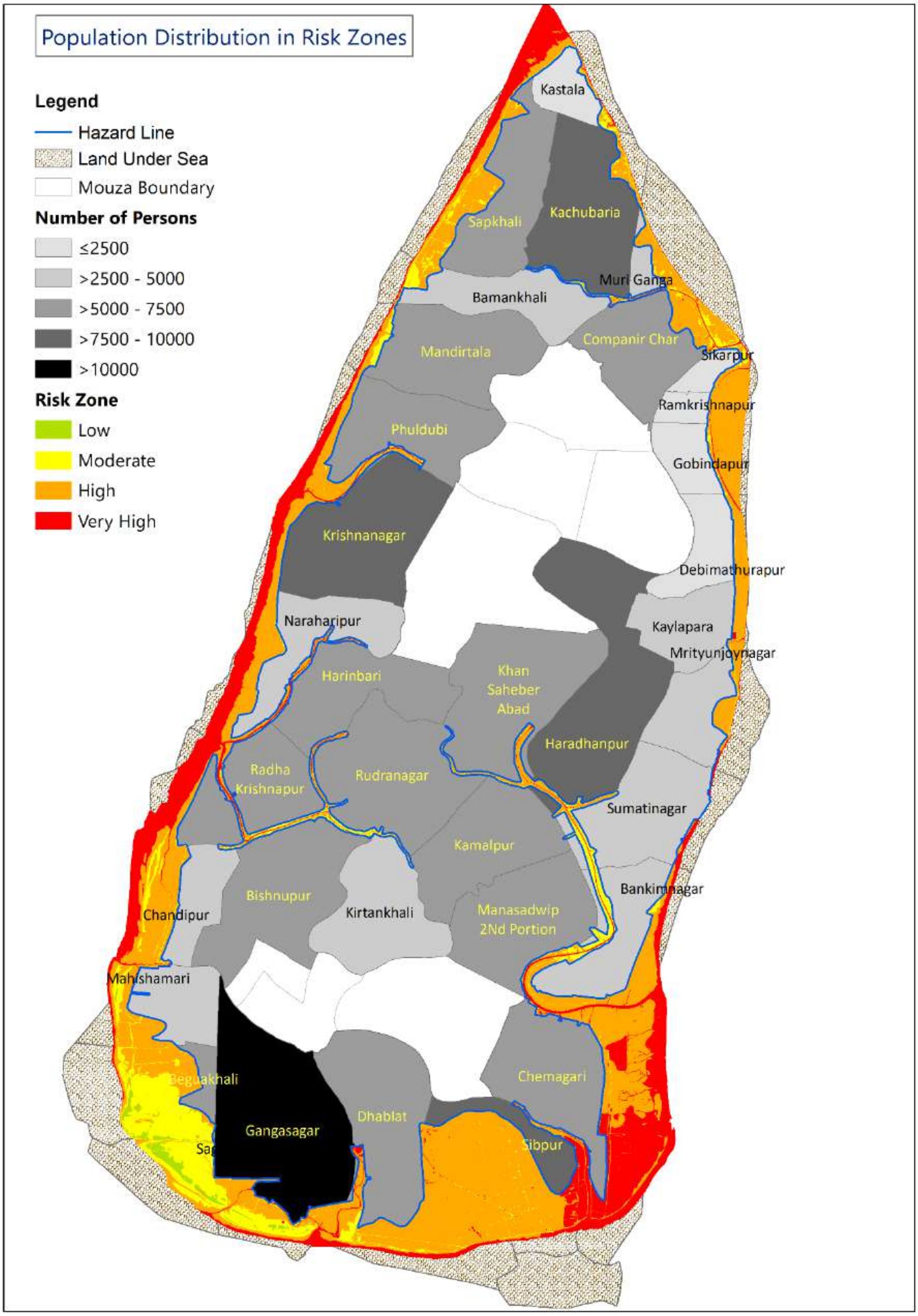


Figure 12: Population of villages located partially within the risk zones

Gangasagar with over 10,000 people is the most densely populated village in Sagar Island. Other villages in the zone of influence have a population between 7500 and 10,000 people. Sibpur village located along the southwest coast of the island would become highly affected if measures to safeguard the coast against erosion are not in place immediately.

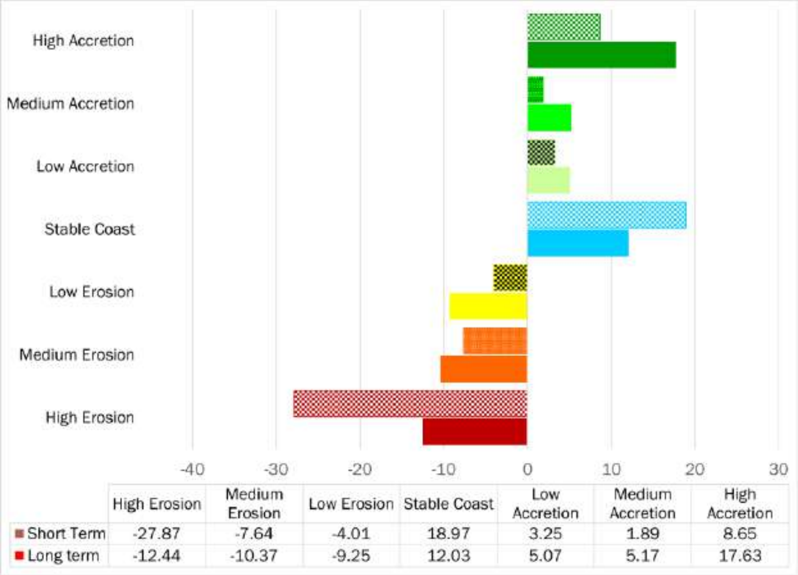
A detailed analysis of shoreline change (erosion/ accretion characteristics) was undertaken for Sagar Island on long-term and short-term time scales. Long-term measurements were undertaken for the period between 1972 and 2018, while short term changes were assessed for the period between 2000 and 2018 (Tables 10 & 11 and Figure 13). Changes to high erosion is obvious at three specific locations viz. i) mangroves adjacent to Sibpur ii) at Kachuberia and iii) Champatala along the northeast coast of Sagar (Figure 14). These were highly accreting, stable or experiencing medium erosion on long-term analysis. It is obvious that the erosion pattern is more recent (2000 – 2018) and is likely to enhance in the future.

Table 10: Long-term (1972 to 2018) shoreline changes at Sagar Island

Long-term Shoreline Classification	Length (km)	% of Erosion and Accretion	Cumulative % of Erosion and Accretion
Length of Coastline	71.96		
High Erosion	12.44	17.29	
Medium Erosion	10.37	14.41	
Low Erosion	9.25	12.85	44.55
Stable Coast	12.03	16.72	16.72
High Accretion	17.63	24.5	
Medium Accretion	5.17	7.19	
Low Accretion	5.07	7.04	38.73

Table 11: Short-term (2000 to 2018) shoreline changes at Sagar Island

Short-term Shoreline Classification	Length (km)	% of Erosion and Accretion	Cumulative % of Erosion and Accretion
Length of Coastline	72.29		
High Erosion	27.87	38.55	
Medium Erosion	7.64	10.57	
Low Erosion	4.01	5.55	54.67
Stable Coast	18.97	11.97	11.97
High Accretion	8.65	2.61	
Medium Accretion	1.89	4.5	
Low Accretion	3.25	0	7.11



	High Erosion	Medium Erosion	Low Erosion	Stable Coast	Low Accretion	Medium Accretion	High Accretion
■ Short Term	-27.87	-7.64	-4.01	18.97	3.25	1.89	8.65
■ Long term	-12.44	-10.37	-9.25	12.03	5.07	5.17	17.63

Figure 13: Changes in shoreline (km) on long and short term time scales at Sagar

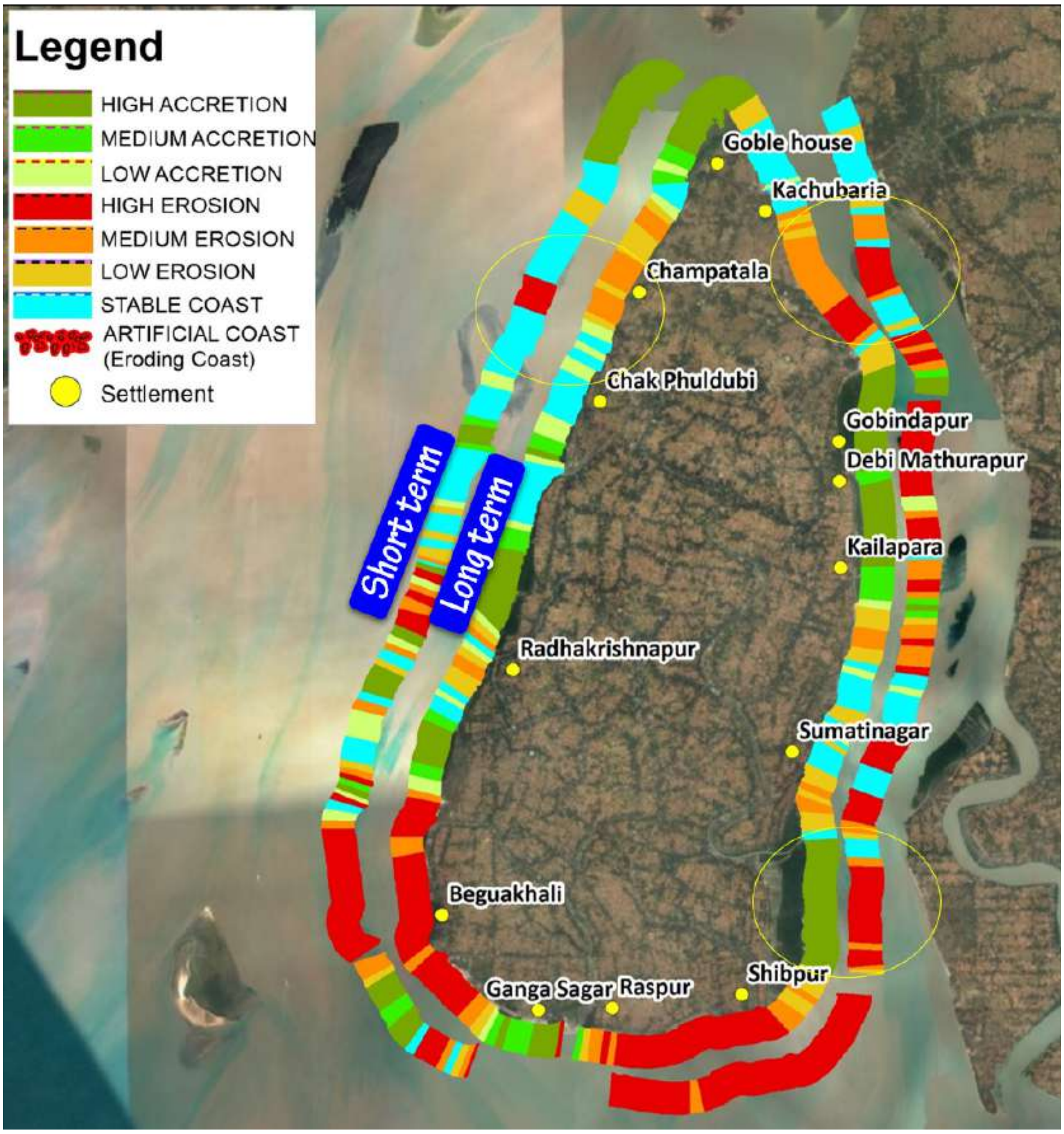


Figure 14: Long-term and short-term shoreline change in Sagar Island

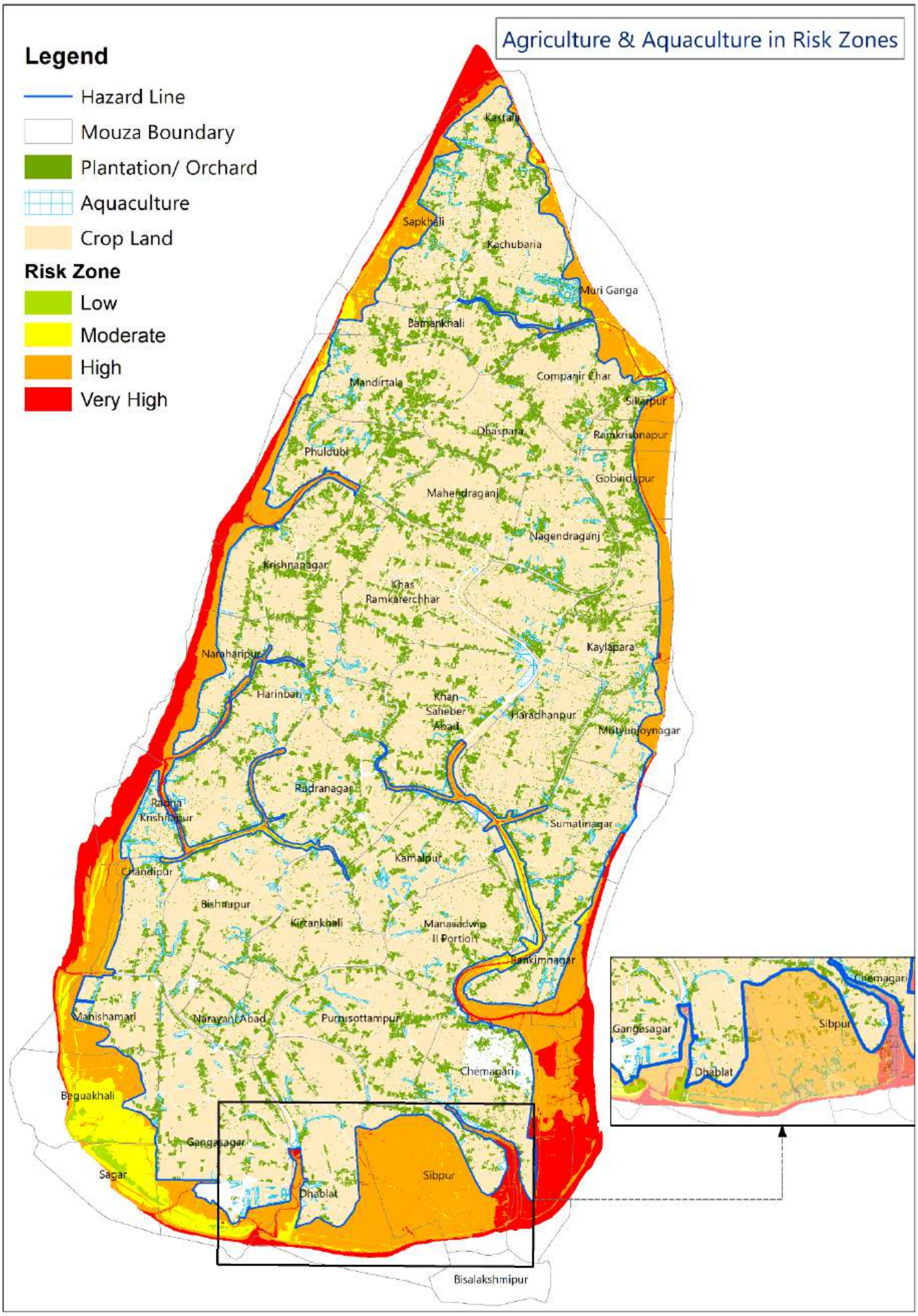


Figure 15: Key land use areas (e.g. cropland/aquaculture/plantation) at Sagar Island.
The blue line represents the composite hazard line with 4 risk categories.
The figure highlights key land use activities within the hazard line.
Insert: example of cropland and aquaculture areas within the hazard line at Sibpur

Nearly, ten per cent of the risk zones areas are agricultural croplands/ aquaculture areas and plantation areas, accounting to 21.2 km2. Those agricultural lands, which are predicted as the inundated agricultural lands, lies predominantly in the Sibpur village that is considered as the most vulnerable areas to coastal erosion, flooding and sea level rise (Figure 15).

Ecologically Sensitive Areas (ESA) in Sagar Island

Four key ESA are present in Sagar Island, covering 30.6 km^2 of the area (Figure 16 and 17). These ESAs, in particular, the mangrove and mudflat act as buffer zones from coastal erosion and flooding. Horseshoe crab habitats overlap mangrove and mudflat areas and the habitat is spread along the west and east coasts of Sagar (Figure 16). Since all these ecosystems are predominantly inter-tidal in nature, they experience high risk of flooding and erosion. In fact, as can be seen from Figure 15, mangroves located north of Sibpur on the east and a majority of the mangroves along the west coast of Sagar are eroding.

This is a cause for concern since the buffering capacity mangroves would be lost if the ecosystem continues to erode at current rates. Mangrove afforestation programs are already underway to restore the lost ecosystems and to regain the mangrove, mudflat and consequently, the horseshoe crab habitats along the coast of Sagar.

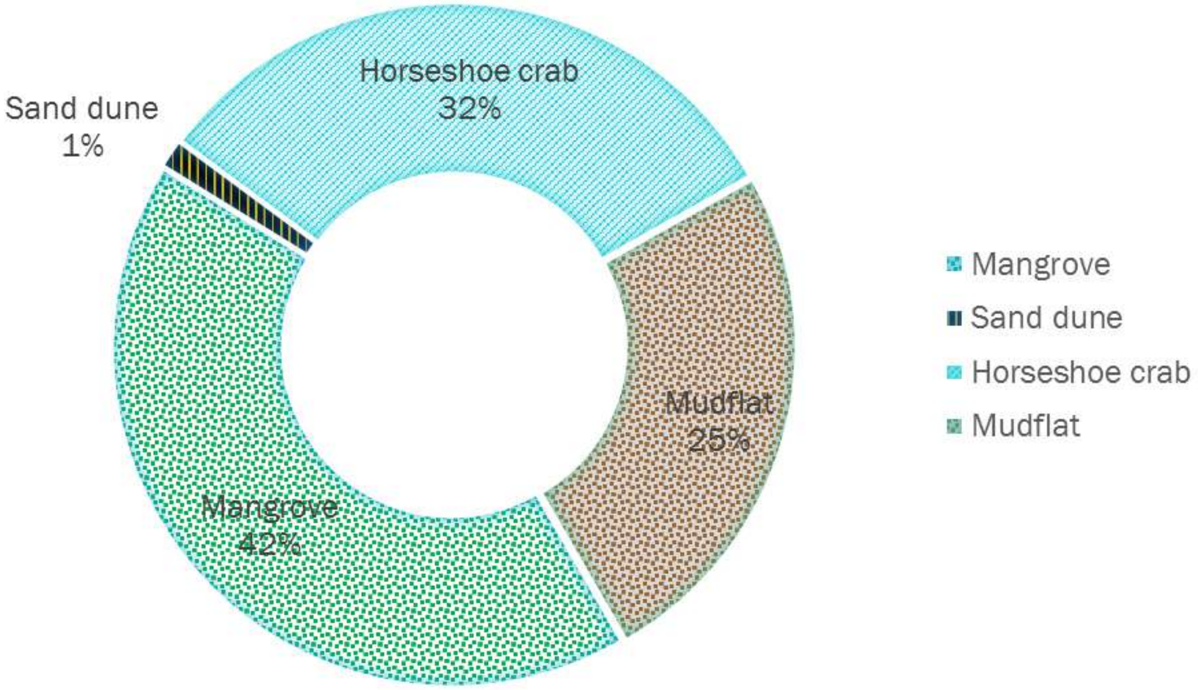


Figure 16: Major Ecologically Sensitive Areas and their abundance (%) at Sagar Island

Based on the results of DEM, it is evident that the areas which will be inundated due to the coastal flooding and coastal erosion is approximately 16%, 10% and 24% for the time period between 1952 & 2011, 2011 & 2100 and 1952 & 2100 respectively (Table 12; Figure 18). As can be observed, there is a net reduction in land area lost under sea (10%) between 2011 and 2100. This is primarily due to the enhanced coastal protection measures undertaken by the Government to secure the life and property of the island (Figure18). Despite such protection, Sagar Island continues to erode steadily due to the fact that flood control measures do not entirely remove the danger of floods and requires constant operation and maintenance as a part of the flood management policy.

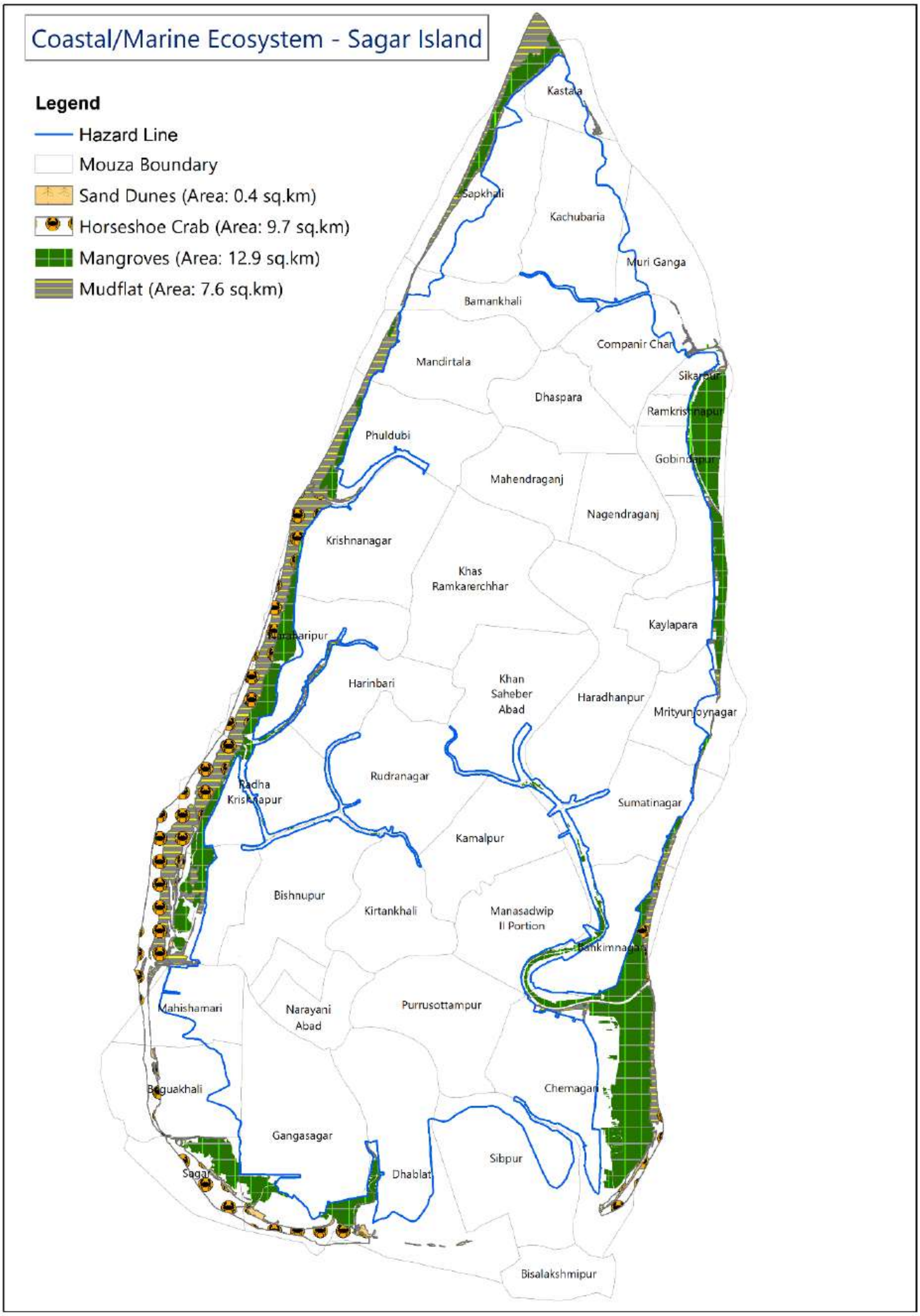


Figure 17: Major Ecologically Sensitive Areas along with hazard line at Sagar Island

Table 12: Area of land under sea from past (1952) to predicted future levels (2100)

Year	Area of Sagar (km2)	Timeframe	No. of years	Land under Sea (%)	Remarks
1952	253.8	1952 & 2011	59	16%	None/ limited shore protection
2011	213.28	2011 & 2100	89	10%	Strengthening of river embankments & proposed living shorelines
2100	193.02	1952 & 2100	148	24%	Cumulative predicted long-term change without and with shore protection measures

Shoreline Protection

On the basis of existing physical processes, the entire Sagar Island is divided into two major zones; the river-facing eastern and western stretch, and sea-facing southern stretch (Bandyopadhyay, 1997). The island is currently protected by different types of shore protection measures such as earthen embankments with sand bags and supported by wooden poles and concrete-paved coastal embankment. These protection measures are constructed to reduce the wave and flow field action on the shore. The river facing stretches are mostly protected by earthen embankment with brick pavements, whereas the sea-facing stretch is protected by concrete-paved coastal embankments to facilitate wave run-up. However, some of these locations along the southern stretch are exposed to open sea with limited protection from sporadic mangrove plantation.

Sibpur is one such coastal village with exposed shoreline on the south-east of Sagar Island. This coastal village has been experiencing severe erosion due to the combined effect of wave and tidal currents for many years. In 1987, a Casuarina equisetifolia farm forest was developed to stabilize the coast of Sibpur. However, it led to destruction of the dune belt and erosion continued along the coast (Bandyopadhyay, 1997). Model predictions using primary oceanic data such as water level, current and wave, clearly indicated the presence of a strong flow field in the Muriganga estuary, running west of Sagar Island. This flow field was primarily responsible for the continuous retreat of shoreline along south-east coast of Sagar Island. Numerous model simulation experiments have been carried out with different mitigation measures in various dimensions to reduce the severe erosion along the coast of Sibpur and subsequent impact on the adjacent coast. Finally, a conceptual convex shaped structure (such as riverine revetment) with 1.6 km (length) X 30 m (width) X 5.5 m (height) has been proposed to control coastal erosion of Sibpur village. This proposed shore protection measure should be maintained with coastal vegetation (e.g. mangrove) on the landward side. Such "**living shoreline**" will provide additional strength to the shore protection structures. It is expected that the underwater section of the structures would be "seeded" with oysters and mussels that would in turn form colonies and aggregate fishes and would eventually serve as fishing grounds for the local community at Sagar (Figure 19).

Incidentally, more landward, nearly 13 km^2 of cropland is envisaged to be inundated in the next 100 years. Under this scenario, various options for alternative crops for cultivation are proposed (Figure 20). These options include i) cultivation of halophytes ii) salt-tolerant paddy cultivation iii) expansion of salt marsh areas iv) cultivation of Bunchgrass (Vettiver), which also acts as a natural soil purifier and v) strengthening of bunds of aquaculture areas by mangrove plantation. These options need to be further evaluated for its economic value and ecosystem function.

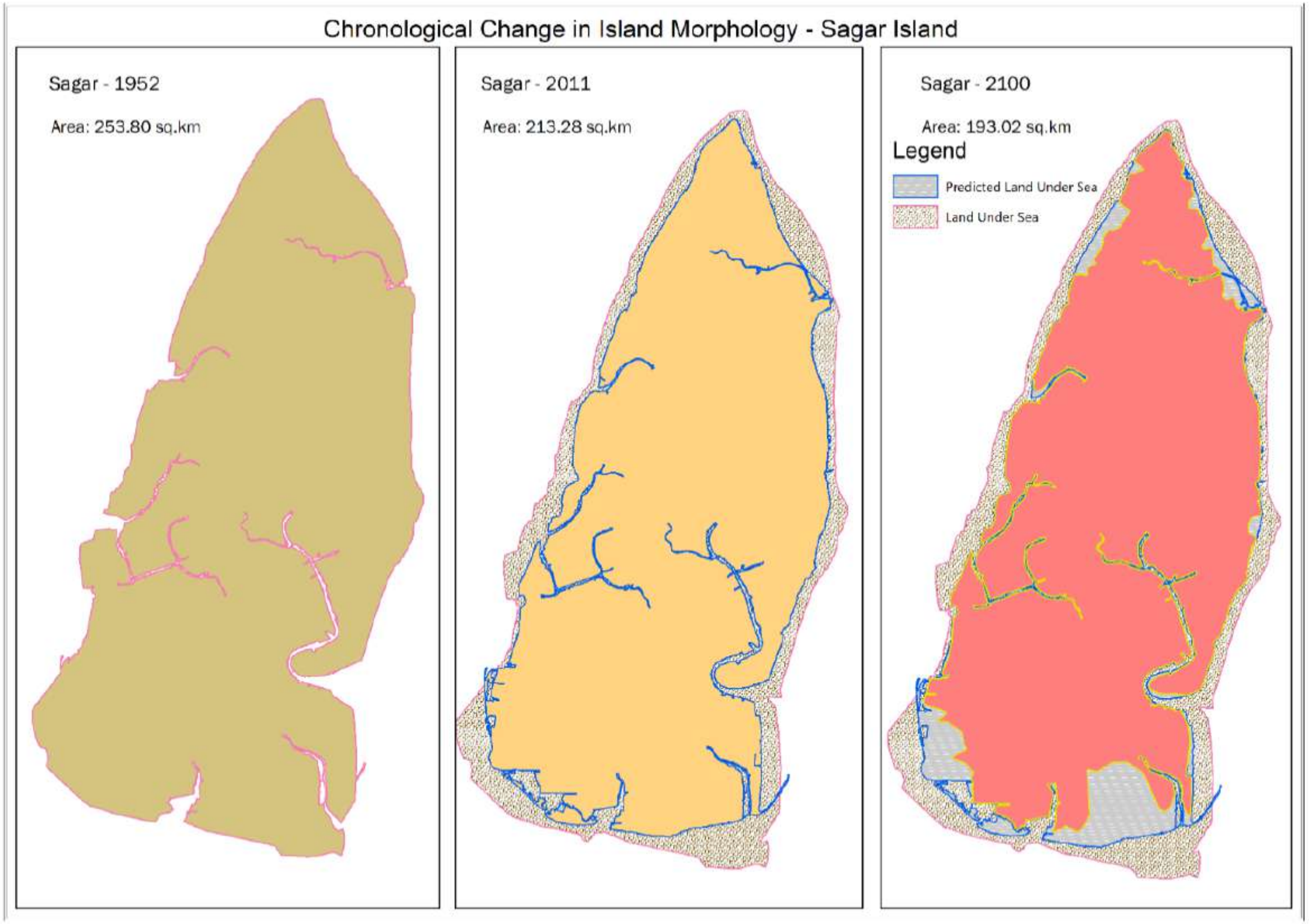


Figure 18: Chronological change in morphology of Sagar Island (1952 to 2011- Current; from 2011 to 2100-predicted)

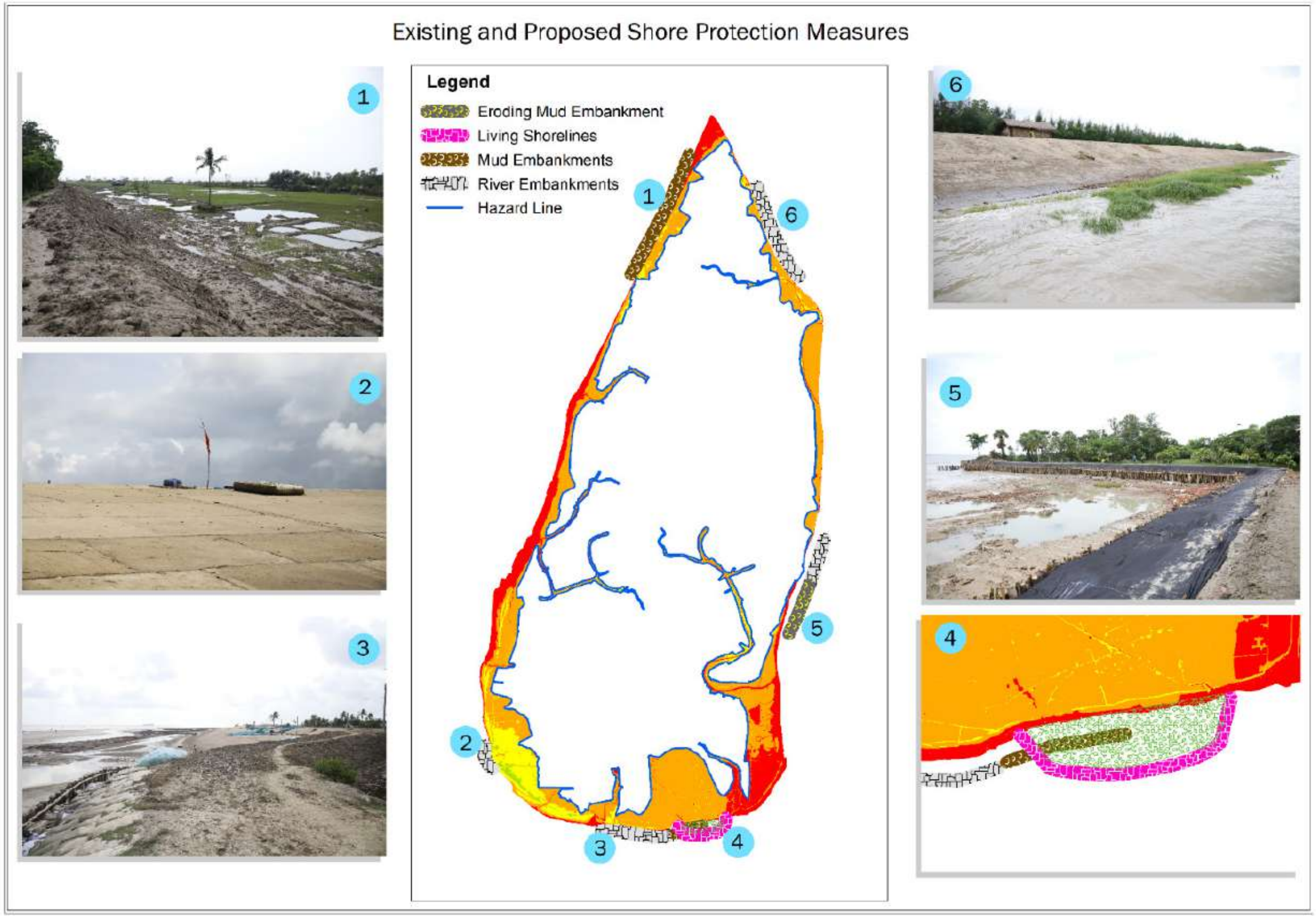


Figure 19: Current and proposed shore protection measures along Sagar Island. Insert: Field photographs of river embankments (1-3, 5-6); 4 depicts the proposed shore protection measure

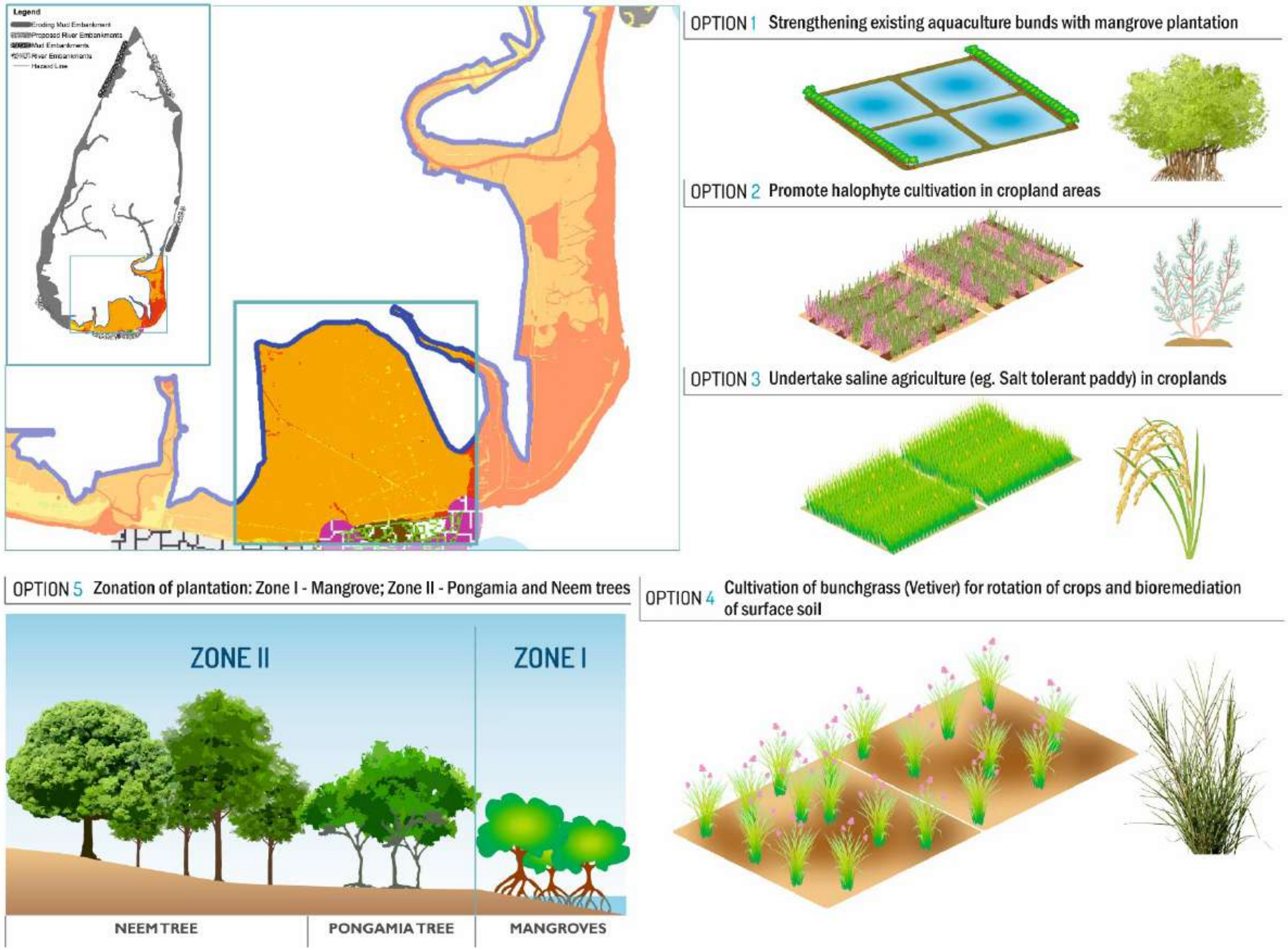


Figure 20: Options for alternate cultivation in cropland areas along with strengthening by additional coastal protection measures

Conclusions

The coast is a highly valued asset with abundant resources offering infinite opportunities for growth and development of the nation's economy and for the overall wellbeing of coastal communities. At the same time, these natural resources are at threat from over-exploitation and increased natural hazards. While most of India's coastline is considered "safe" as per the hazard line demarcated for the first time, certain coastal stretches are naturally vulnerable, at locations such as Mumbai (Maharashtra), Alapuzha (Kerala) along the west coast and Kendrapada (Odisha) and Sagar Island (West Bengal) on the east coast. The east coast is however more vulnerable than the west coast due to acute starvation of water and sediments from large river systems and increased intensity of coastal flooding and erosion. The hazard line clearly indicates that islands (e.g. Sagar Island) are more vulnerable than the mainland coastline. It is imperative for coastal managers and policy makers to safeguard the coastal ecosystem integrity, if further vulnerability due to the combined sea level rise-erosion-coastal flooding effects is to be minimized.

Acknowledgement

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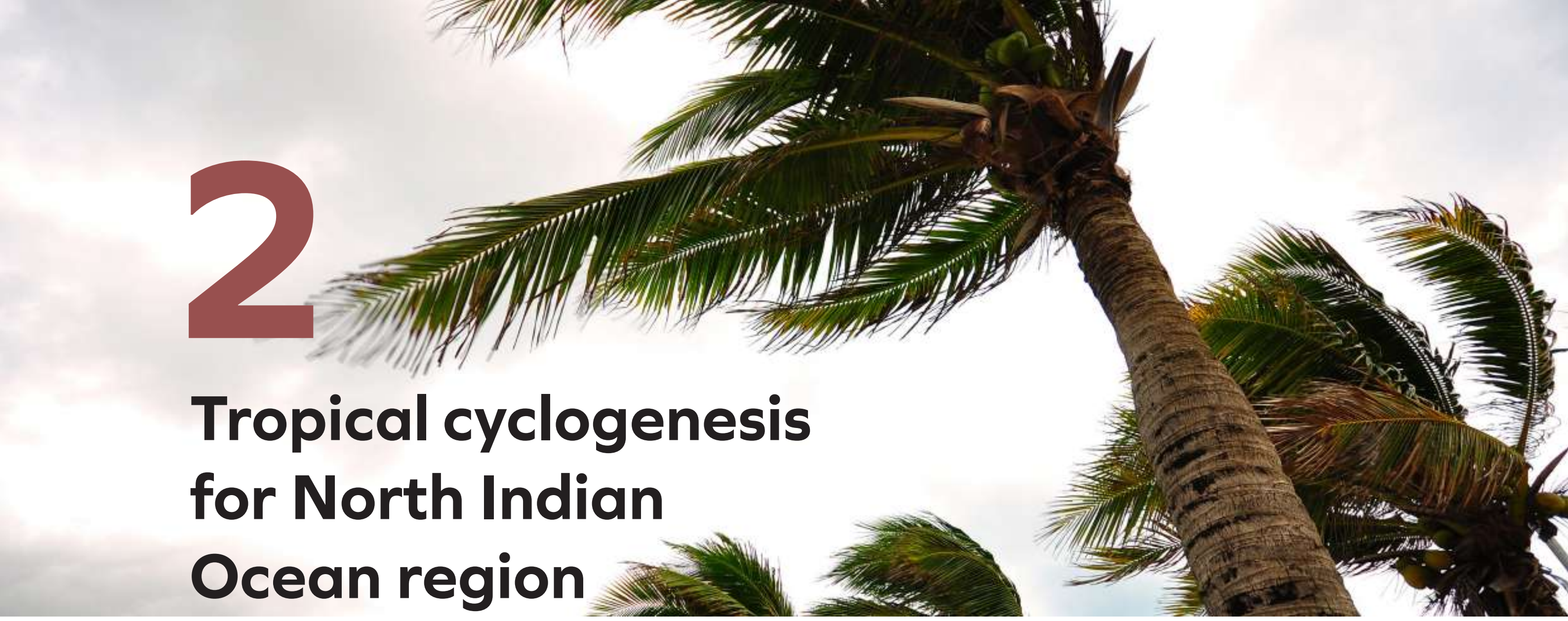

2

Tropical cyclogenesis for North Indian Ocean region

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ABSTRACT

An upsurge in the intensity and size of recent tropical cyclones that form over the North Indian Ocean basin linked with climate change has increased the focus of the scientific community. There is strong evidence that suggests that regional tropical cyclone activity in the North Indian Ocean basin is showing a paradigm shift that may be attributed to climate change. Though substantial progress has been achieved over recent years in tropical cyclone track prediction, intensity, and landfall, the present knowledge on tropical cyclogenesis remains elusive. An exhaustive verification of classical theories proposed for tropical cyclogenesis is still lacking and is warranted to ascertain its applicability for global and regional ocean basins. This chapter deals with a review of popular classical theories proposed for tropical cyclone formation, locations of tropical cyclogenesis based on historical records for the North Indian basin and also presents case studies conducted for global and Indian ocean basins. The key challenges, priority areas and knowledge gaps identified for detailed research on tropical cyclones have been highlighted.

1. Introduction

Tropical cyclones are extreme weather events that form over the warm tropical oceans and can result in massive destruction to life and property during the time of landfall. The reasons behind why and how tropical cyclones form are still elusive and understanding their genesis making it a scientific challenge today. During the life history of a tropical cyclone, the term '**cyclogenesis**', also referred as the formation of a tropical cyclone, is probably the least understood and remains an open puzzle in the field of tropical meteorology. The necessary and sufficient conditions that are required for cyclogenesis are known and have been documented several decades back (Gray, 1968; 1975). In a large-scale tropical environment, there are six identified features found necessary for tropical cyclogenesis. The necessary conditions outlined are: (i) sufficient thermal energy in the oceans (sea surface temperature greater than 26ºC to a depth of 60 m), (ii) sufficient moisture in the mid-level troposphere (pertains to relative humidity levels at 700 mb level), (iii) conditionally unstable atmosphere supporting deep convection, (iv) maximum relative vorticity in the lower troposphere, (v) low vertical shear of horizontal winds at genesis location, and (vi) location at least 5° latitude away from equator. The first three necessary conditions stated can provide a possible clue on the likelihood of deep convection in the affected region, and the remaining necessary conditions can provide a measure on the environmental conducive nature that can support genesis intensification. In the context of the Indian Ocean region, the summer monsoons are the major source for disturbances that eventually evolve into tropical cyclones (McBride and Keenan, 1982; Briegel and Frank, 1997). Initial studies focussed on how the intensification of initial vortex occurs and that extends from the sea surface boundary layer to mid-tropospheric levels (Emanuel, 1986, Rotunno and Emanuel, 1987). Pioneering work based on some recent observations (Karyampudi and Pierce, 2002) and prior studies by Simpson et al. (1997) advocate the importance and role of Mid-level Meso-scale Convective Vortex (MCV) interaction towards tropical cyclone formation. This chapter discusses and provides an overview of the various classical theories developed so far in context to tropical cyclogenesis and its application to the global ocean basins. The importance of Marsupial Pouch Vortex Merger Theory is elaborated and its application for Madi cyclone in the Indian Ocean basin as a case study is discussed. Further, the location of cyclogenesis formation in the North Indian Ocean region is elaborated covering both Bay of Bengal and Arabian Sea basins based on analysis of historical data-sets from India Meteorological Department. Finally, the chapter also highlights on some of the research areas and knowledge gaps in the scientific understanding of tropical cyclones that need to be investigated.

2. Tropical Cyclogenesis and Intensification theories

The dynamic process by which tropical cyclones evolve from loosely organized convective clusters into well-organized systems is still poorly understood. A number of theories, four of which are outlined below, have been proposed to explain this evolution characteristic. A variety of theories put forth to explain tropical cyclogenesis has prompted several in-depth studies aimed at evaluating their validity. Prior studies by Craig and Gray (1996) formulated a theory on Wind Induced Surface Heat Exchange (WISHE) and Convective Instability of the Second Kind (CISK), and neither of these satisfactorily explained the pre-genesis processes. Nolan (2007) used a high resolution cloud-resolving three-dimensional model simulation to understand the genesis and advocated the role of mid-level top-down mechanism. Houze et al. (2009) performed a study for the pre-Ophelia (2005) episode and found evidence of axi-symmetrization of vertical hot towers as per the observation of Montgomery et al. (2006). Both these studies acknowledged the possibility and role of multiple mechanisms in the genesis process. Recent field experiments have provided new opportunities to examine these theories using dense observations.

3. Stages in the Life Cycle of Tropical Cyclones

The life history of tropical cyclones possess extremely diverse nature and no single storm behaves exactly like an average one (Ooyama, 1969). The different stages during the life history of a cyclone can be described as: (i) incipient stage, (ii) deepening/immature stage, (iii) mature stage, and (iv) decaying stage. The incipient stage is connected to the transformation of tropical disturbance into organized weak vortex. It is a slow process and one that spans several days for the surface pressure to drop to 1000 mb. Incipient cyclones rapidly develop into a full-fledged cyclone with progress of time. It is unusual for surface pressure at the center to deepen to 10-20 mb in a 24 hr period during the deepening stage, while the area of strong winds is confined to relatively narrow band around the cyclone centre. Normally the typical time of immature stage is around 60-130 hr. During the mature stage, intensity in terms of maximum wind speed and mean sea level pressure reaches a limit and may gradually become less intense. Outward expansion of isobars and spreading of stormy area occurs during this stage. Size of tropical cyclones can vary considerably and indeed cyclones do not move out of the warm ocean area. In the final decaying stage, the dissipation of energy occurs and this dissipative process is quite rare in tropical warm ocean regions.

4. Classical Theories for Cyclogenesis

4.1 Top-down Vortex Merger Theory

Based on observational data and from the field experiment named Tropical Cyclone Motion (TCM-92) carried out in the western North Pacific basin, and subsequent modeling studies to understand the interaction of mesoscale vortex within large scale environment, the first theory named as 'Top-down Merger' was developed (Simpson et al., 1997; Ritchie and Holland, 1997). According to this theory, two or more small-scale (100-200 km) mid-level Mesoscale Convective Vortex (MCV) amalgamates leading to a more intense and larger MCV. It then penetrates into the top of boundary layer forcing a low-level vortex motion. The influence of this amalgamated larger MCV in the atmosphere can extend to deeper depth thereby triggering surface development over the ocean. The Rossby Penetration Depth (RPD) is an index that determines the vertical thickness of vortex penetration and that has a direct dependence on inertial frequency, vortex horizontal scale and stability number based on Brunt-Vaisala frequency. More intense vortices can have higher inertial frequency and deeper RPD. Numerical experiments also supported the fact that background rotation results in an efficient merging process resulting in larger vortex induced motion in vertical layer consistent with RPD (Ritchie and Holland, 1997). Figure1 illustrates the model depiction of the Vortex Merger Theory shown in terms of absolute vorticity and diabatic heating at different levels corresponding to 1 km, 4 km and 7 km.

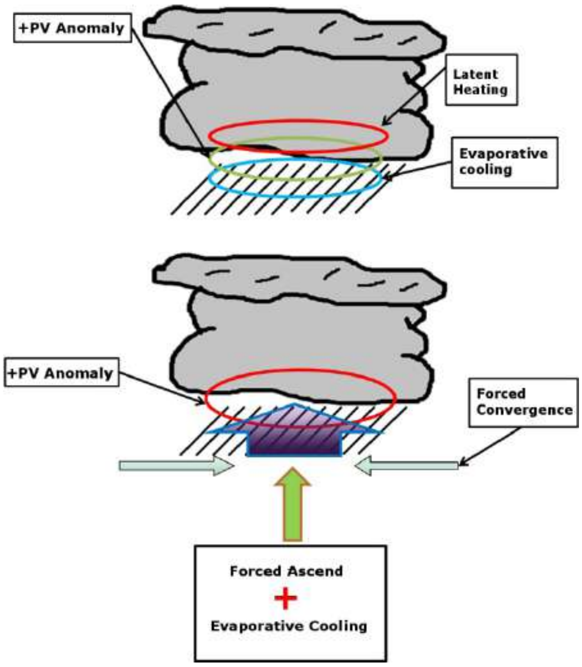

Figure 1: Illustration of the Top-down Vortex Merger Theory

Convergence that results from forced ascent, concentrates background vorticity leading to large scale spin-up (Source: Helms and Hart, 2012).

4.2 Top-down Showerhead Theory

The 'Top-down Showerhead' is a second theory (Bister and Emanuel, 1997) and an extension of the first theory that describes tropical cyclone core formation in a Mesoscale Convective System (MCS). An essential condition according to this theory is the requirement of a mid-level vortex in the MCS region (Figure 2). In this case, the MCV has warm/cold cores in upper/lower levels and is located above a region of warm and dry air. Sustained precipitation from higher vertical level can cool the lower level due to intense evaporation resulting in subsidence causing advection of positive vorticity in the downward direction. The pressure contours tend to bend downwards through thermal wind balance extending the mid-level circulation to propagate in the lower atmosphere. The cold core on reaching the boundary layer results in increased surface heat flux, and that generates the cyclonic vorticity. It has been substantiated using a non-hydrostatic model and observational data from TEXMEX field experiments.

A study by Bister and Emanuel (1997) suggested that moistening and cooling due to precipitation can destabilize the boundary layer and weaken convective downdraft. In contrast to the previous theories proposed by Ritchie and Holland (1997) and Bister and Emanuel (1997), another pioneering study by Nolan (2007) investigated the interaction between mesoscale and synoptic scale systems. According to Nolan (2007) the genesis of tropical cyclone can result from dynamic interaction between mid-level MCV and sustained precipitation. Raymond et al. (2011), based on observational data postulated that a mid-level vortex with cold/warm cores in lower/upper troposphere can essentially modify the profile of vertical mass flux. It then creates a thermodynamic conducive environment for the tropical cyclone formation.

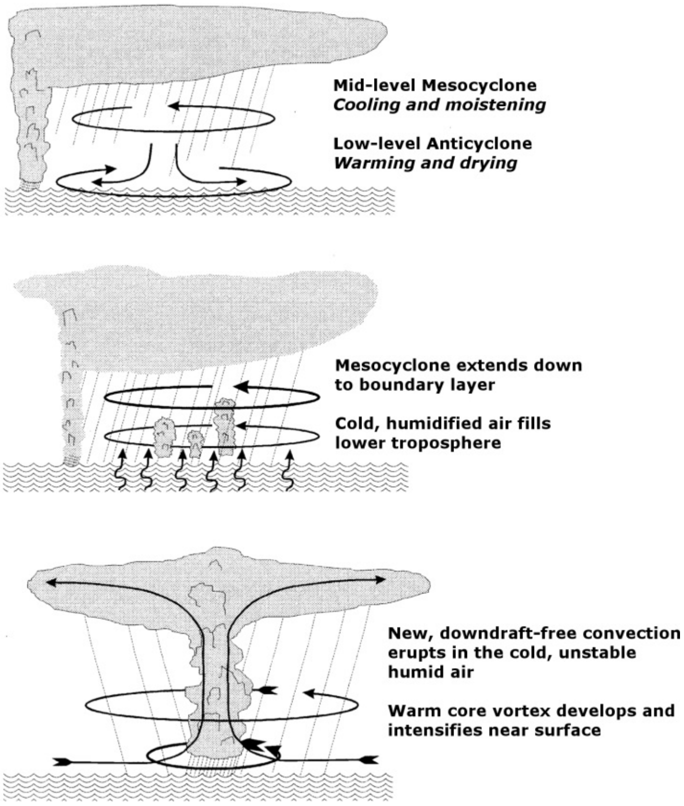

Figure 2: A conceptual illustration of the Top-down Showerhead theory (Source: Bister and Emanuel, 1997)

4.3 Bottom-up Vortex Merger Theory

Based on observational data pertaining to low-level vortex intensification (Zehr, 1992) and subsequent studies carried out by Montgomery and Enagonio (1998) and Enagonio and Montgomery (2001), elaborated on the convergence of ambient absolute vorticity in the convective updraft mechanism leading to the 'Bottom-up Vortex Merger Theory' (Figure 3). The additional parameter proposed in this theory is the Potential Vorticity (PV) anomalies generated by deep convective cores. This theory postulates on the enhancement of vorticity at low-levels within the convective zone through multiple Vertical Hot Towers (VHT) that results in vortex formation and finally merging into cyclone scale vortex (Hendricks et al., 2004). Montgomery et al. (2006) performed idealized experiments on VHTs within MCS using numerical models and their results signify that multiple VHTs merge to form stronger and larger low level vortex that promotes the genesis of tropical cyclone activity. According to this theory, the non-alignment of low-level vortex during initial stages with mid-level vortex becomes vertically aligned with MCV thereby resulting in a deep convective vortex. A better physical mechanism that explains about the low-level vortex formation on ocean surface within an environment of large- scale disturbance, and that eventually transforms into a tropical cyclone under favourable conditions is addressed in a more recent theory called as 'Marsupial Pouch Theory

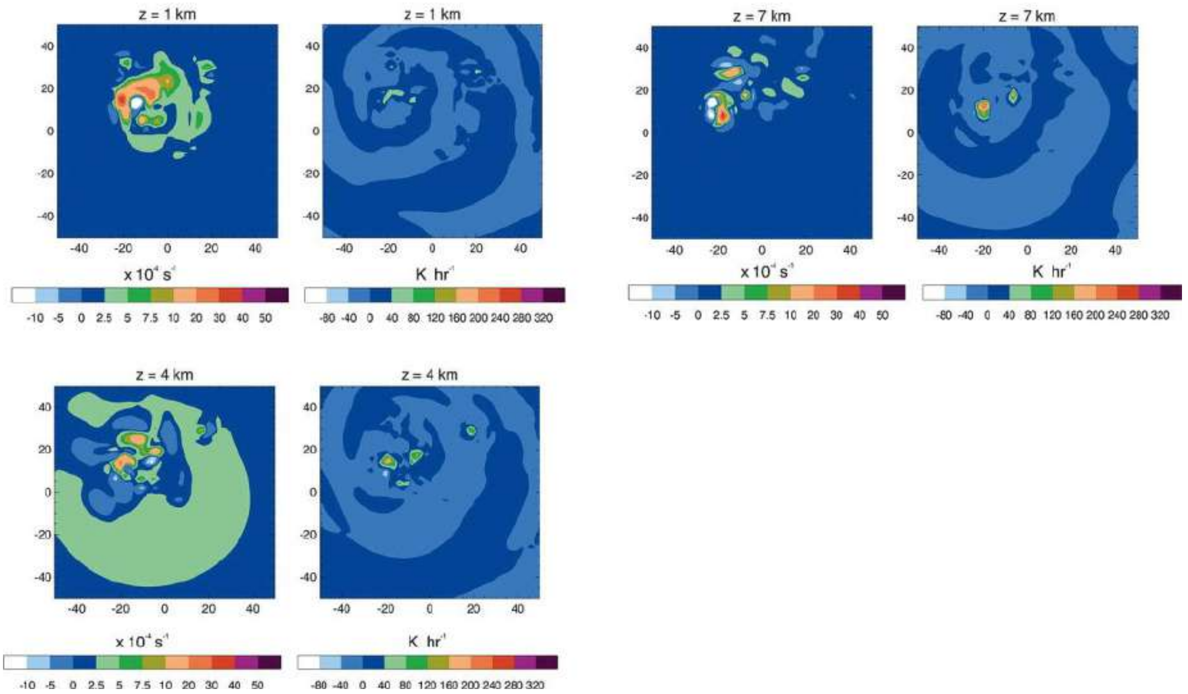

Figure 3: Model depiction of bottom-up Vortex Merger Theory (Left) Absolute vorticity (in 10^{-4} s^{-1}) and (Right) diabatic heating rate (in K h^{-1}) corresponding to the horizontal surfaces z = 1, 4, and 7 km (Source: Montgomery et al. 2006)

4.4 Marsupial Pouch Theory

The '*Marsupial Pouch Theory*' was hypothesized based on an observational study by Dunkerton et al. (2009) that initiation of tropical cyclone is based on the trough intersection of westward moving large- scale disturbance and critical latitude of the parent easterly waves over Atlantic and Pacific ocean basins. The latitude at which the wave speed matches with background flow speed is determined as the '*critical latitude*'. The point of intersection referred as '*sweet spot*' initiates tropical cyclone formation, and the surrounding region encompassing the sweet spot is a conducive environment to develop and maintain a closed region of low-level cyclonic vorticity. This envelope of closed region is known as '*pouch*'. The '*Marsupial Paradigm*' is a recent theory (Figure 4) that explains as to why some of the cloud clusters develop into tropical cyclones while others fail. According to this paradigm, the conducive environment is located where the mean wind speed and phase speed of tropical wave match. The resulting trajectory of air parcel moving with the tropical wave have closed isobars isolated from outside entrainment. Under this condition, development of the vortex further advances through sustained moisture influx and release of latent heat at the vortex location. Further, with advance in time when the vortex is strong enough to sustain on its own, it breaks apart from the parent wave. The convection within the wave trough and vortex interaction results in a deep rotating convection. The Marsupial Paradigm represents the bottom-up development of tropical cyclone formation. Another study using numerical simulation by Wang (2012) for bottom-up and top-down cases noted the co-existence of these cases. An important field experiment named PREDICT conducted during 2009 over the Atlantic Ocean (Wang et al., 2012) examined the vertical structure of the pouch, and postulated that moist and diabatic active wave pouch that extends from mid-troposphere (600-700 mb) to top of the boundary layer is a necessary and sufficient condition for tropical cyclone formation.

The above discussion on various cyclogenesis theories finally shed light and converge to the fact that the conceptual model of Marsupial Pouch Theory is quite promising as seen based on relevant studies carried over the Atlantic and Pacific Ocean basins (Dunkerton et al., 2009; Montgomery et al., 2012). Images of about 61 tropical storms and hurricanes that formed over the Atlantic and eastern Pacific basins during the period of August and September from 1998 to 2001 were analysed and this theory was successfully able to detect 55 of them (Doyle, 2008). The Marsupial Paradigm is quite innovative by itself and that can reckon a plausible clue on the favourable environment and necessary conditions for tropical cyclone formation. Hence there is

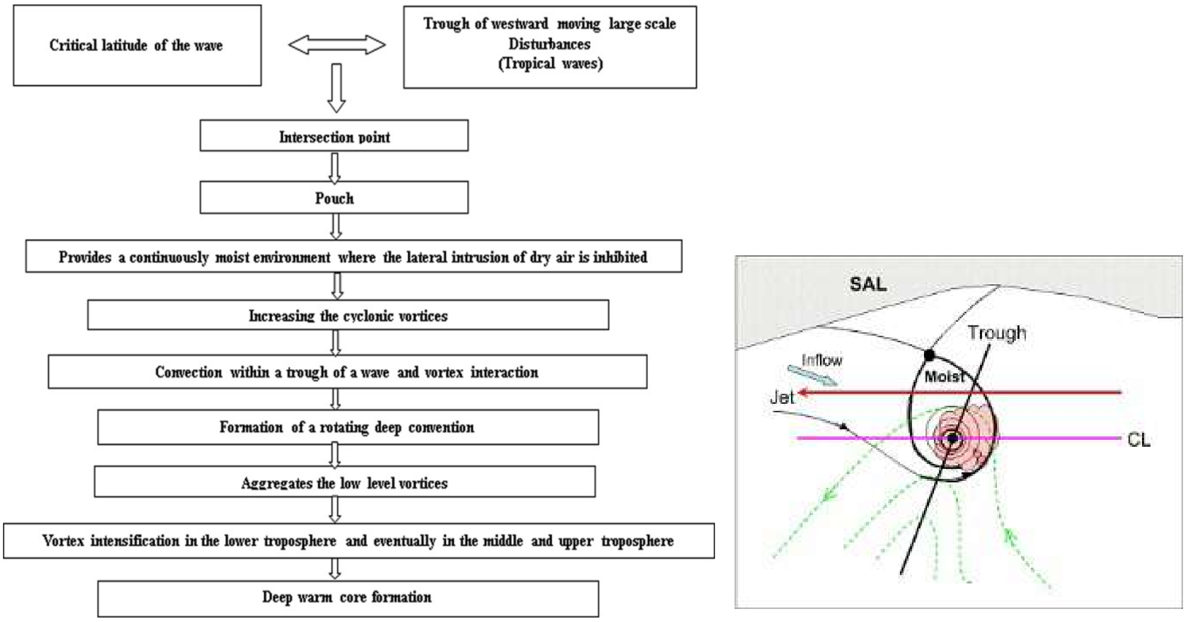

Figure 4: (Left) Sketch illustrating favourable conditions for tropical cyclone formation based on Marsupial Pouch Theory, (Right) Schematic of Marsupial Paradigm [Dashed: streamlines in ground-based frame of reference; Solid: streamlines in frame of reference moving at same speed with wave (wave pouch); Gray shading: deep convection sustained within the pouch] (Source: Michael Montgomery, Naval Postgraduate School)

a strong need in climate science studies for a detailed investigation of this paradigm in context to the Indian Ocean region to better understand the pouch formation environment and thereby improve the forecast skill of tropical cyclones.

5. Application of Marsupial Pouch Theory – real world examples for Tropical Cyclone formation

Development of tropical cyclones is indissolubly dependent on synoptic scale atmospheric disturbances and in context to Atlantic Ocean basin, the African easterly waves is one good example for synoptic scale disturbance (parent wave). Their period and wavelength can last typically from 3 to 5 days in scales ranging from 2000 to 3000 km (Reed et al., 1977). The Marsupial Paradigm is believed to provide a useful direction to explore synoptic linkages pertaining to tropical cyclogenesis. Wang et al. (2010 a, b) examined the formation of hurricane Felix during 2007 in the Atlantic Ocean basin. It was upgraded to a Category 5 hurricane on 3rd September, 2007 and made landfall just south of the border between Nicaragua and Honduras. The system sustained high wind speed of about 260 km/h sustaining as a Category 5 hurricane during the landfall time. The bulletin of National Hurricane Center identified the formation of hurricane Felix as having emerged from an easterly wave off the African coast on 24th August, 2007. Figure 5 illustrates the wave signal based on 2.5 day low-pass filtered 850 mb flow field from ECMWF analysis (Wang et al., 2010a). Sustained convective activity was evident as seen from the TRMM 3-h accumulated precipitation that occurred on the northern tip of the wave pattern. Thereafter, it was reported that a tropical depression had formed over the area of sustained convection around 21Z of 31st August, 2007 and as seen from Figure 5, the wave pouch is present at 850 mb at the time frame of nearly 2.5 days prior to the cyclogenesis. This clearly demonstrates the applicability of Marsupial Pouch theory in tracking genesis of real world cyclones.

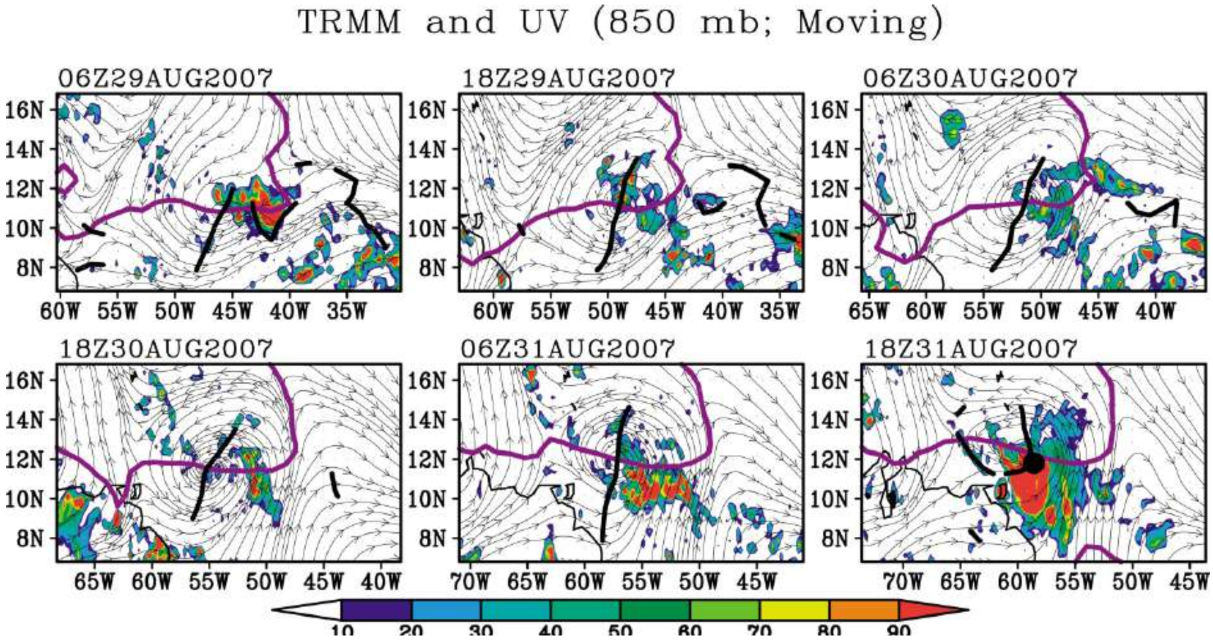

Figure 5: Streamlines corresponding to the 2.5-day low-pass filtered 850-hPa flow from ECMWF analyses valid from 0600 UTC 29 August to 1800 UTC 31 August, 2007. TRMM 3-h accumulated precipitation (mm/ day) is shown as shaded portion. The genesis location is indicated by the black dot in the final panel (adapted from Wang et al., 2010a)

The North Indian Ocean is an active basin for tropical cyclone formation, and in particular the frequency of cyclogenesis in the Bay of Bengal is much higher as compared to the Arabian Sea basin. The frequency ratio of occurrence in the Bay of Bengal is about five times higher compared to the Arabian Sea. There are hardly any studies pertaining to tropical cyclone formation over this basin. As a first study, Venkatesh and Mathew (2004) reported on the prediction of tropical cyclone genesis using a vortex merger index. A new method for detection using satellite Infra-Red images in near real-time was attempted for 2002 post-monsoon and 2003 pre-monsoon seasons. The method was successfully tested in the formation of tropical cyclones 04B (2002) and 01B (2003) about 48 hours after they attained storm strength. Very recently, Rajasree et al. (2016) using a modelling study attempted to investigate the recent theories for cyclogenesis pathways of tropical cyclone Madi that occurred during 6-13 December, 2013 (Figure 6). The Marsupial Paradigm was used to study the tropical cyclogenesis characteristics of Madi cyclone. It was for the first time over the North Indian Ocean basin that the validity of this theory was examined in detail in order to evaluate how a developing tropical convective system in the moving earth frame reference within the Inter-tropical Convergence Zone (ITCZ) serves as a parent wave for vortex development which initiated the occurrence of Madi cyclone over the Bay of Bengal region. The initiation of Madi originated on 6th December, 2013 as a depression, transforming into a deep-depression and cyclonic storm thereafter. It made landfall over Tamil Nadu coast. The study examined the initiation, underlying dynamics and thermodynamics using a high-resolution Weather Research and Forecasting (WRF) model and 3D-Var data assimilation technique.

Tracking of parent wave used the meridional averaged total precipitable water content and its propagation phase speed was estimated using vertically integrated moisture content (Rajasree et al., 2016). Estimated phase speed was used for the streamline analysis in a moving frame of reference, and the methodology proposed by Hendricks et al. (2004) and Montgomery et al. (2006) was used

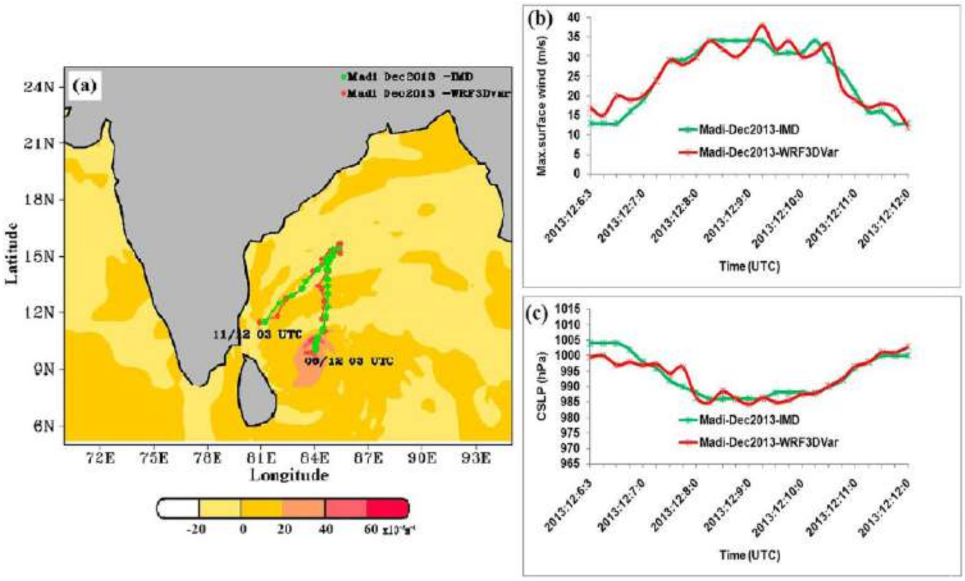

Figure 6: (a) Simulated track of Madi cyclone, (b) comparison of 10 m wind speed, and (c) mean sea level pressure using WRF-3D VAR modelling system compared against IMD observations (adapted from Rajasree et al., 2016).

for identification of vertical hot towers. Parameters such as distribution of vorticity and deformation aided to understand the stages of development pertaining to deep convection. Deep convective activity is directly related to increase in relative vorticity and inhibited by shear deformation. The dynamic state of balance between both these parameters is measured using the Okubo-Weiss (OW) parameter. As postulated by Gray (1968, 1975) the required large- scale features, favourable and sufficient conditions for tropical cyclogenesis remains quite popular and for Madi cyclone, the genesis environment had sea surface temperature greater than 26° C and tropical cyclone heat potential in excess of 100 KJ cm^{-2} (Rajasree et al., 2016). The other two important metrics in this context are the Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CIN). The CAPE is a measure representing the amount of work done for vertical acceleration of air parcel. In the genesis environment, large CAPE with low CIN values is essential to develop deep convective activity. Figure 7 illustrates the spatial distribution of CAPE and CIN Madi cyclone.

In order to identify rotational component in the genesis environment, the Okubo-Weiss parameter is very useful. As per the Marsupial Paradigm, the rotational

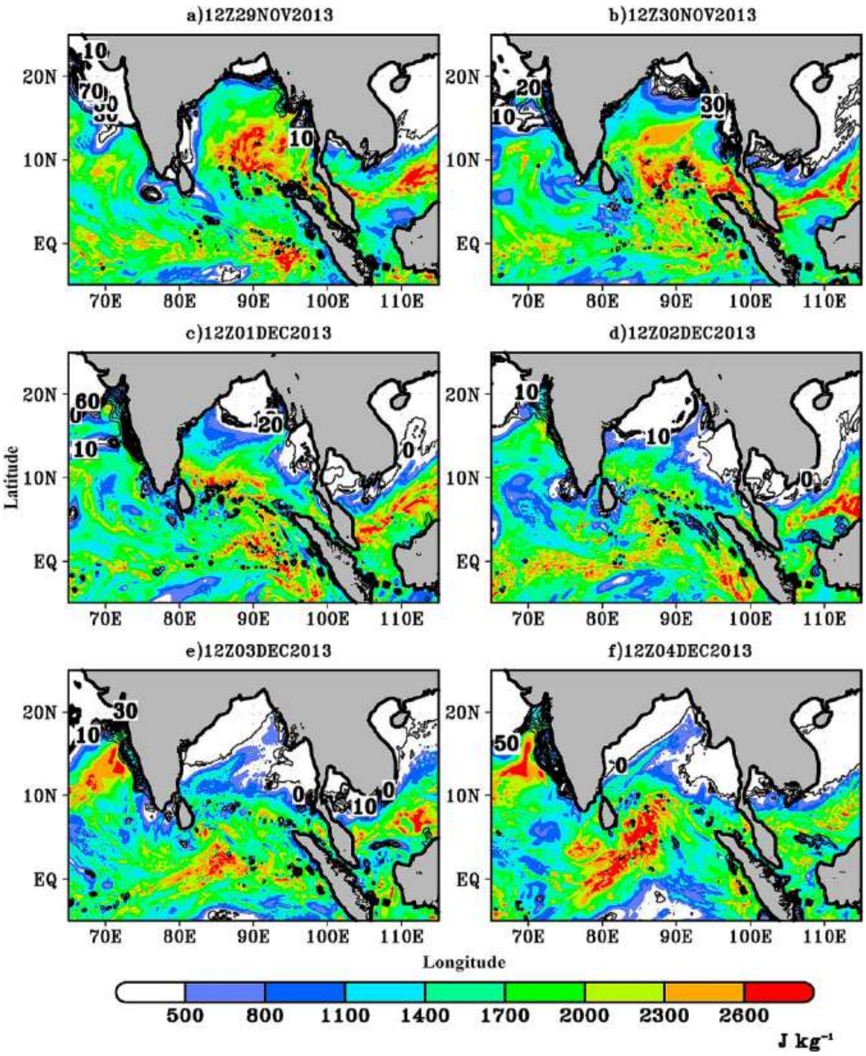

Figure 7: Spatial distribution of CAPE and CIN corresponding to the genesis environment of Madi cyclone (adapted from Rajasree et al., 2016).

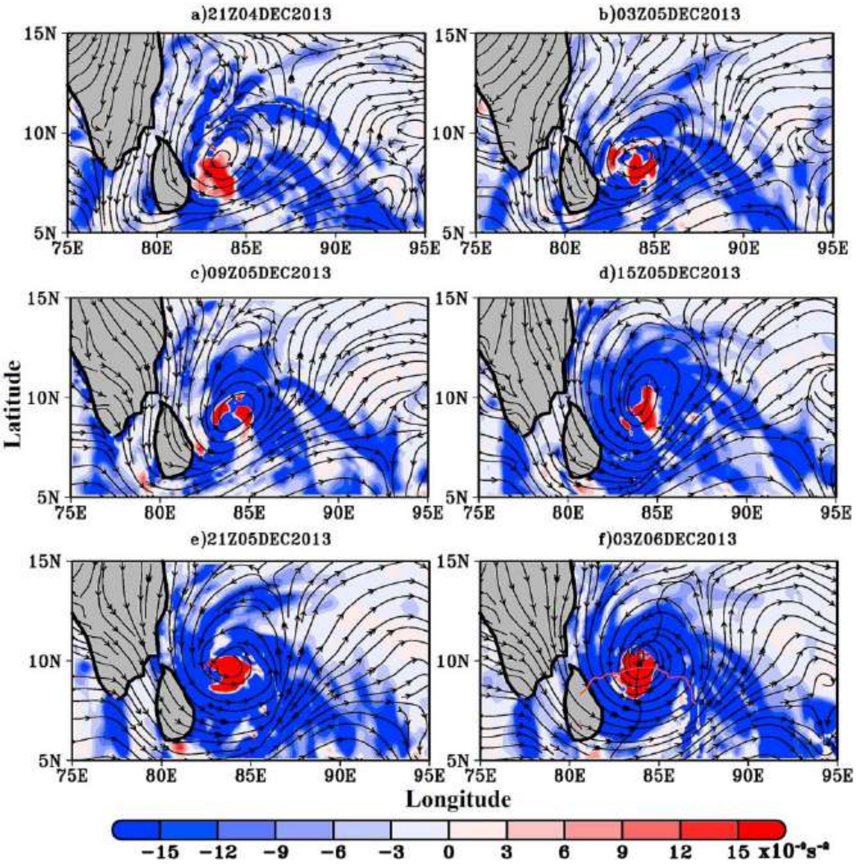

Figure 8: Spatial and temporal evolution of Okubo-Weiss parameter and corresponding wind streamlines at 850 mb in a moving reference frame during genesis of Madi cyclone (adapted from Rajasree et al., 2016).

signature associated with the parent wave using OW parameter can identify potential regions of maximum vorticity that are close to the genesis location. Figure 8 provides the estimated OW parameter at 850 mb level over laid against the wind streamlines (Rajasree et al., 2016). Surrounding the pouch region, the OW parameter is positive representing areas of enhanced vorticity and with progress of time; increased distribution of OW indicates convective intensification triggering a low-pressure system over the ocean. It is clearly illustrated in the panel of figures provided in Figure 8.

6. Historical perspective on Cyclogenesis over North Indian Ocean basin

The western sector of the North Pacific Ocean experiences the maximum number of global tropical cyclones, with an average of about 26 per year and followed by eastern North Pacific with an average of 17 per year. The South Indian Ocean and North Atlantic basin experience an average of almost 10 per year, while the number is about 10 per year for the North Indian Ocean region (Niyas et al., 2009). As compared to the global tropical cyclone activity, the North Indian Ocean basin alone accounts for about 7% and the frequency is about five times higher in Bay of Bengal compared to the Arabian Sea. The North Indian Ocean region experiences both pre and post-monsoon cyclones (March-May and October-December months respectively), and historical data signifies an increasing trend in the frequency of intense tropical cyclones (Singh et al., 2000, 2001; Srivastava et al., 2000). Tropical cyclones are classified as depression (D), deep depression (DD), cyclonic storm (CS), severe cyclonic storm (SCS), and Very super cyclonic storm (VSCS) based on the maximum sustained wind speed as per the classification by

India Meteorological Department. A study by Sahoo and Bhaskaran (2016) provides more details on a comprehensive assessment of historical cyclone tracks in the Bay of Bengal basin. Their study developed synthetic tracks or the most probabilistic cyclone tracks for all coastal states located in the East coast of India for risk based assessment studies. In addition, important energy metric parameters such as power dissipation index and accumulated cyclone energy for tropical cyclones during the past four decades were estimated, indicating that the power dissipation index in the present decade is about six times higher as compared to the past having wider socio-economic consequences.

A pioneering study by Kossin et al. (2014) postulated on a pole-ward trend in the location of tropical cyclone maximum intensity over global ocean basins. This trend is evident in global historical data for both the Northern and Southern hemispheres occurring at a rate of about 53 and 62 km per decade respectively. A recent study by Kossin et al. (2014) indicates an unclear trend observed for the North Indian Ocean basin. In this context, Sahoo and Bhaskaran (2016) analysed the locations of historical tropical cyclogenesis in the North Indian Ocean basin from records of India Meteorological Department cyclone E-Atlas and highlighted the absence of any pole-ward shift that occurs in the North Indian Ocean basin. Initially the study classified tropical cyclones based on the season as pre and post-monsoon cases. Figure 9 illustrates the density of cyclogenesis in the Bay of Bengal basin. The density of cyclogenesis can be correlated with higher SST (Sahoo and Bhaskaran, 2016).

The cluster diagram detailing post-monsoon cyclogenesis corresponding to cyclonic storms and very severe cyclonic storms are shown in the left panel and the overall cyclogenesis representation for depressions, cyclonic storms and severe cyclonic storms during the past five decades is shown on the right of Figure 9. As noticed from this figure, the head Bay of Bengal region is quite active in the formation of depressions. However, the water mass characteristics accounted due to high freshwater discharge and lower SST over this region is not conducive for the depressions to further intensity into cyclonic storms. A closer look into the cyclogenesis reveals a north-south oscillatory pattern that resembles the decadal SST scenario as reported by

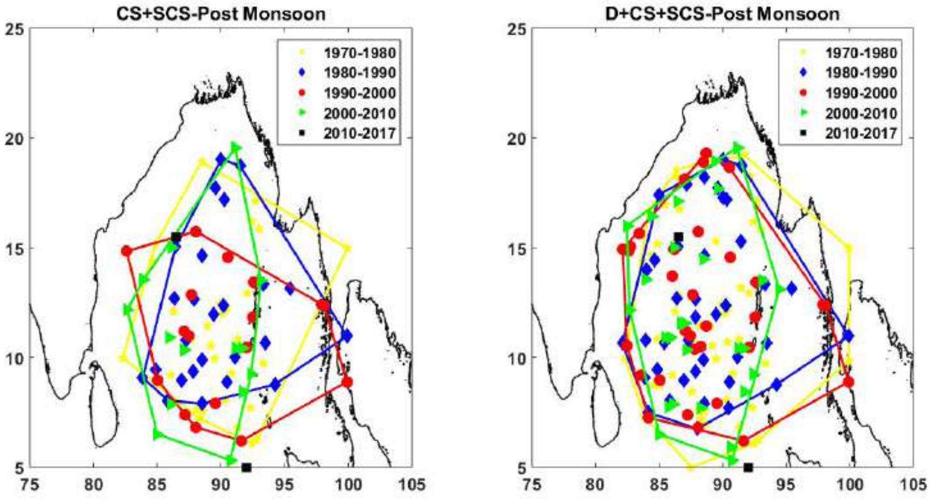

Figure 9: Cyclogenesis density in the Bay of Bengal basin during the post-monsoon season from 1970 to present (Sahoo and Bhaskaran, 2016)

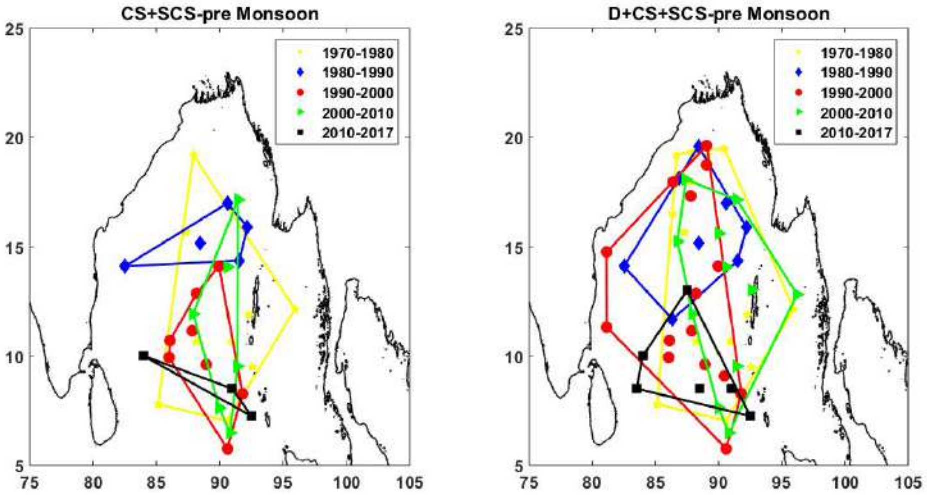

Figure 10: Cyclogenesis density in the Bay of Bengal basin during the pre-monsoon season from 1970 to present (Sahoo and Bhaskaran, 2016)

Sahoo and Bhaskaran (2016). Clusters corresponding to the decade 2000-2010 and for the period 2010-2017 indicate an increased frequency of cyclogenesis in the Andaman Sea location and that requires a separate detailed study.

Figure 10 illustrates the density of cyclogenesis over this basin for the pre-monsoon season. It is observed that cyclogenesis corresponding to cyclonic storms and severe cyclonic storms is relatively less as compared to the formation of depressions during this period. In general, the pre-monsoon cyclogenesis also exhibits a north-south decadal oscillatory pattern, whereas the genesis over the south-eastern sector is found to intensify as cyclonic storms and severe cyclonic storms. It is also seen that there is a tendency for depressions to form at higher latitudes in the basin as prevalent in the climatological high and low during the pre-monsoon period.

The inferences made from the above analysis pertain to the entire Bay of Bengal region. Keeping in view the differential water mass characteristics distribution over this region and for a better analysis, the study region was further divided into four segments beneath the 90° East Ridge and 15° North. Figure 11 shows the cyclogenesis clusters for the past five decades in these four segments. It is seen

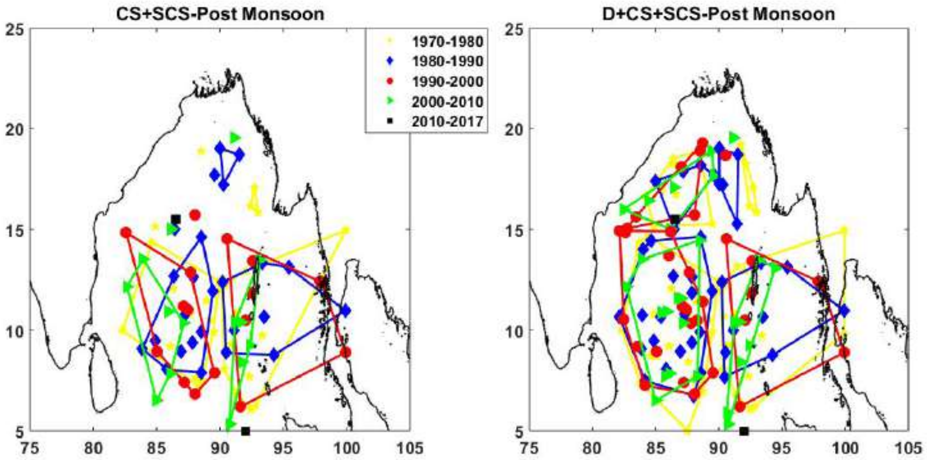

Figure 11: Cyclogenesis density in the Bay of Bengal basin during the post-monsoon season from 1970 to present based on water mass characteristics (Sahoo and Bhaskaran, 2016)

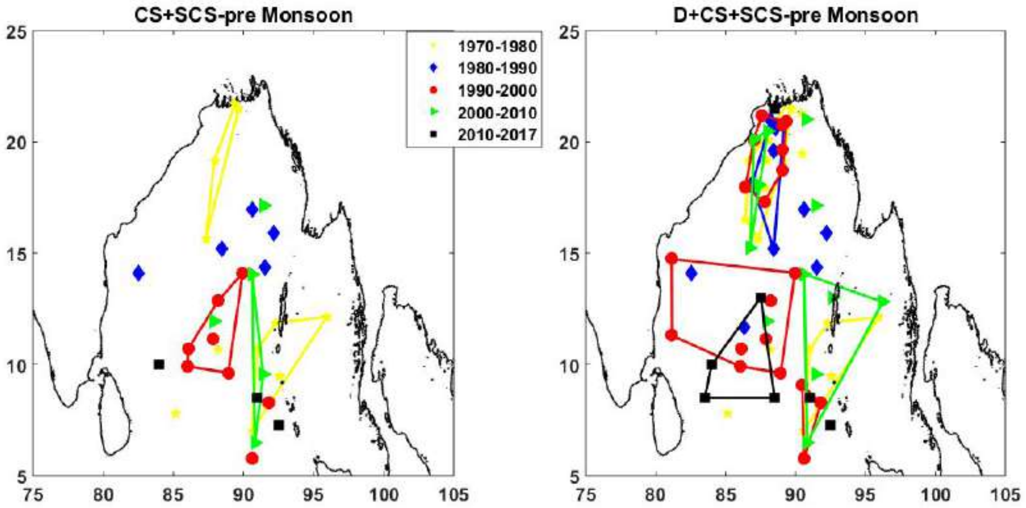

Figure 12: Cyclogenesis density in the Bay of Bengal basin during the pre-monsoon season from 1970 to present based on water mass characteristics (Sahoo and Bhaskaran, 2016)

that cyclogenesis exhibits an east-west oscillatory nature in the basin centring the 90° East ridge. Also the locations of cyclogenesis along the left and right panel of the ridge show opposing trend in a decadal scale. The study signifies that it is difficult to conclude any known trend for depressions in the head Bay of Bengal region and ascertain known patterns for cyclogenesis during the pre-monsoon season (Figure 12).

Cyclogenesis over the Arabian Sea is much less as compared to the Bay of Bengal basin. It is attributed to the atmosphere-ocean interactions controlling the intensity of tropical cyclones. In general, the Bay of Bengal is more stratified compared to the Arabian Sea as the upper ocean is much warmer and higher rainfall creates barrier layer in the near surface causing haline stratification. Hence, the cyclones in the Arabian Sea generally produce more surface cooling due to enhanced vertical mixing, and that limits cyclone intensification (Neetu et al., 2012). Similar to the Bay of Bengal region, the Arabian Sea also exhibits a decreasing trend of cyclogenesis frequency over the past five decades. Decadal cluster analysis for cyclogenesis of depression, cyclonic storm and severe cyclonic storms in the Arabian Sea show a marginal east-west oscillation in the basin during the post-monsoon period (top panel of Figure 13). During the pre-monsoon period, the north-south oscillatory trend is unclear considering depressions, cyclonic storms, and severe cyclonic storms for the Arabian Sea basin (bottom panel of Figure 13). However, there are indications of an increased frequency of cyclonic activity at present over the Arabian Sea basin.

7. Research areas and Knowledge gaps

Though several studies have been conducted to understand the structure and intensity of tropical cyclones, there are still many challenging issues that need special attention and focus in the future. A pertinent question and puzzle remain as to what are the factors that limit the intensity of tropical cyclones. There are observational supports which reveal that on an average only a few tropical cyclones attain 20% of theoretical Emanuel’s Maximum Potential Intensity (E-MPI) or using the SST determined MPI (Zeng et al., 2007, 2008). It is an indication that in reality other factors can limit tropical cyclone reaching its maximum intensity (Emanuel et al., 2004). One of the factors investigated over the recent times is on the internal dynamics focusing on the asymmetric structure of the eye-wall and spiral rain-bands. This could be one factor inhibiting tropical cyclones attaining maximum

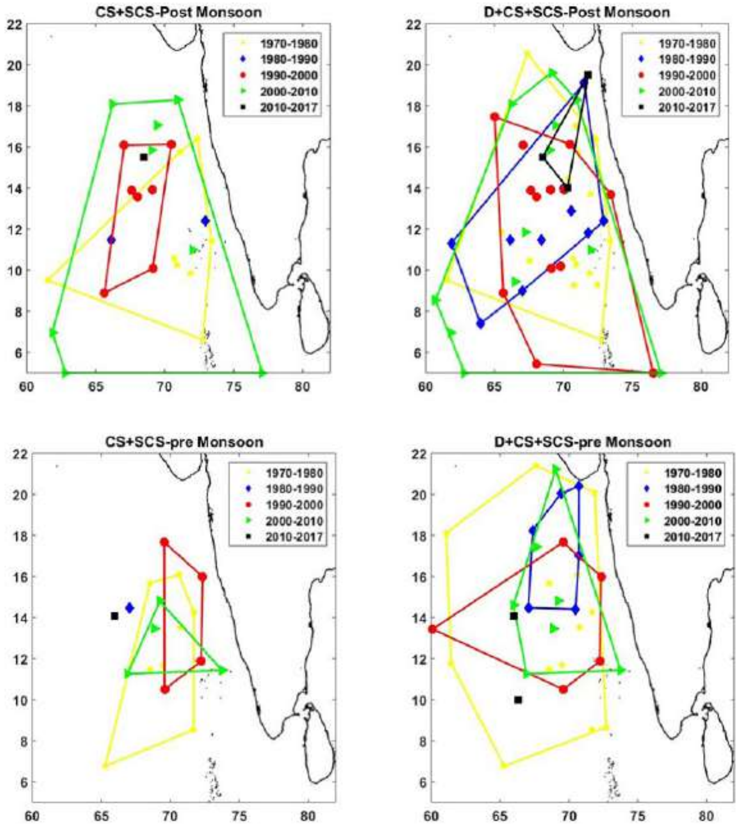

Figure 13: Cyclogenesis density in the Arabian Sea basin during the post- and pre-monsoon seasons from 1970 to present (Sahoo and Bhaskaran, 2016)

intensity as it can reduce the moisture and convergence of mass into the eye-wall region (Wang, 2009). The translational speed of a cyclone can also influence the maximum intensity. Observational studies have shown a high correlation between tropical cyclone intensity and translation speed (Zeng et al., 2007, 2008). For the western North Pacific and North Atlantic basins, translation speeds ranging between 3 and 6 m/s have produced very intense tropical cyclones (Zeng et al., 2007, 2008). Another interesting study by Kepert and Wang (2001) indicated that translational speed could also introduce asymmetric surface heat, moisture flux and friction to a progressing cyclone. Besides, the vertical shear of horizontal wind could limit intensification and intensity of tropical cyclones (the ventilation of warm core as proposed by Gray, 1968). There are other factors as well that inhibit tropical cyclone intensity. The upwelling effects from ocean and feedback mechanism is an area especially for the Bay of Bengal region that requires a detailed investigation. There are a few studies that document the feedback from oceans connecting translational speed, size, intensity and ocean mixed layer depth on tropical cyclone intensity such as studies by Zhu et al. (2004) and Wu et al. (2007).

What exactly determines the radius of maximum wind size is another puzzle that needs to be well understood. In the inflow boundary layer, the absolute angular momentum is lost to surface and therefore determination of the radius where the centrifugal force balances the radial pressure gradient force in addition to decreased radial wind needs a proper evaluation. Though Emanuel and Rotunno (2011) formulated an expression connecting radius of maximum winds for a steady state tropical cyclone, a detailed investigation is warranted to obtain a clear picture. Similarly, research pertaining to the decay rate for the outer core wind structure needs an elaborate work plan. In fact, very few studies such as by Holland and Merrill (1984) reported on the role of eddy momentum flux in the upper troposphere and thereafter, studies by Fudeyasu and Wang (2011) investigated diabatic heating outside the eye-wall region associated with spiral rain bands. How tropical cyclones form and a fundamental understanding of genesis remains elusive. Detailed studies are required on the recent vortex merger theories and establish its efficacy for the North Indian Ocean basin. What determines tropical cyclone activity for a given climate state is another area that requires a detailed investigation. Also, it is clear that tropical cyclones in recent years have increased in the North Indian Ocean basin. In this context, what controls the tropical cyclone size is another puzzle. There is no theoretical understanding of cyclone size in a changing climate scenario reported so far. More observational analysis and modeling efforts are required to further advance and improve knowledge on tropical cyclone formation and its intensification process.

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3

Vulnerability of coastal ecosystems and habitats due to erosion

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ABSTRACT

Coastal areas are vulnerable to sea-level rise (SLR) along which sensitive habitats and ecosystems are directly impacted. Coastal erosion caused by natural and/ or anthropogenic processes pose a major threat to these ecologically important areas. Assessment of vulnerability of ecologically sensitive areas such as mangroves and turtle nesting grounds was studied under the scenario of global mean sea level rise. Among the coastal resources, sandy beaches are highly susceptible to short-term changes due to storm surges. This in turn affects the marine turtle nesting sites and other unique intertidal fauna dependent on the beaches. Due to rapid coastal infrastructure developmental activities, mangroves that act as natural defence against extreme events are also under threat. Further, the role of coastal/ marine ecosystems as natural storm barriers has been assessed using the InVEST Model, with inputs from coastal hydrodynamic processes and geomorphology of the coast. From assessments, it was observed that North of Bitikola Nadi in Odisha experiences an average erosion of -449.67(m) as Net Shoreline Movement (NSM) at a rate of 17.33 (m/yr) among all the turtle nesting sites studied along the coast of India. For mangroves, maximum erosion was observed in Andhra Pradesh specifically in the Krishna Delta with an average erosion of -203.6 (m) NSM at -9 (m/yr) followed by Sundarbans -92.6 (m) NSM at -5.1 (m/yr) in West Bengal. Our results clearly indicate that some of the turtle nesting sites in India are highly vulnerable due to erosion and a few of the dense mangrove ecosystems along Krishna-Godavari Deltas are lost due to severe coastal erosion. At the same time, the model predicts high vulnerability to natural hazards in areas without natural habitat/ ecosystems.

1. Introduction

The process of long-term removal of sediment along the coastline, leading to loss of land and retreat of the coastline landward is defined as coastal erosion (Gibbs, 1978). The varied causative factors include natural processes such as waves, winds, tides or anthropogenic activities like construction of coastal engineering structures, sand mining etc. An added distress is the wide range of effects climate change can cause on the coast by decreased sediment supply, changes in sea level rise, increased frequency of extreme events, wave climate, etc. It is estimated that about 70% of the sandy beaches are impacted by coastal erosion (Bird, 1985).

1.1 Vulnerability of Coast

Coastal areas are vulnerable to sea-level rise (SLR) which also directly impacts the sensitive habitats and ecosystems. The effects of inundation and erosion in coastal areas may cause serious issues like creating uninhabitable small atoll islands over the next century (Kench et al., 2018). Coastal communities depend on natural resources for their livelihood and sustenance and thus, degradation of coastal ecosystems and habitats has direct bearing on their livelihood security. Besides, their vulnerability to exposure to natural hazards such as erosion, storm surges, cyclones etc. is higher. In order to understand the vulnerability of coast to extreme events, assessments through predictions are crucial. Coastal vulnerability assessments are directly related to the socio-economic conditions and are used in predicting the status of resource availability, livelihood impacts and loss of habitat or ecosystem. Such predictions would aid in the interpretation and selection of probable responses to Sea Level Rise (SLR) from a management perspective. Application of hydrodynamic models to determine the attenuation effect of vegetation and infrastructure also aids in prediction on wetland vulnerability to SLR along the coasts (Rodriguez et al., 2017).

1.2 Role of Coastal Ecosystem: Mangroves

Mangroves thrive in harsh coastal region and provide an indication of their ability to cope with natural hazards and also recover from these events, albeit at slower rates. They often modify the coastlines through their ability to attenuate waves, retention of fine sediments and shape soil texture ultimately helping in reducing the intensity of exposure and hazard on land-margins (Spalding et al., 2014). The shape of coastline and depth of near shore waters determine the pattern of waves reaching the coast. Winds and swell waves are drastically reduced as they traverse mangroves, thereby reducing wave damage during storms. The role of mangroves in protecting the coasts against coastal erosion and natural hazards such as storms, tsunamis and tidal waves has been widely upheld. Wider mangrove belts are more effective in reducing the flooding of surges occurring during major storm events by significantly shrinking the extent of flood in low lying areas (Verhagen and Loi, 2012).

In comparison, narrower mangrove belts are capable of reducing wind speed, the impact of waves of the surge and flood. It is also assumed that wide areas of mangroves can reduce tsunami heights, helping to reduce loss of life and damage to property in settlement areas falling behind mangrove belts. The dense roots of mangroves help to bind and build sediments. The above-ground (e.g. aerial roots, pneumatophores etc.) roots slows down water flows, encourage deposition of sediments and reduce erosion. They can actively build up sediments, increasing the thickness of the mangrove soil, which may be critical as sea level rise accelerates (Spalding et al., 2014). Nevertheless, mangroves cannot be a stand-alone solution; as need to be combined with other risk reduction measures to achieve a desired level of protection. If integrated appropriately, mangroves contribute in risk reduction along the entire coastline, from rural to urban and of heavily degraded landscapes (Verhagen and Loi, 2012). They also provide many associated benefits that can help reduce the vulnerability of coastal communities and support recovery following a hazard event by means of various services rendered as environmental, social and economic benefits (Spalding et al., 2014). Although frequency of storms has decreased, the intensity of storms over the Indian sub-continent has increased.

1.3 Importance of Sandy beaches

Sandy beaches, an important coastal resource, provide a rich habitat to unique species of vertebrates and invertebrates. They also support humans with crucial ecosystem goods and services and economic benefits (Lucrezi et al., 2009). Beaches are prone to constant changes in morphology and topography, reshaped by wind, storms and tidal action. The increased frequency of storms and sea-level rise due to climate change could result in beach loss, which apart from providing other benefits is also an important habitat for turtle nesting (Katselidis et al., 2014; Rivas et al., 2016) and many unique intertidal fauna. Beach scarping is a direct effect of erosion leading to loss of dunes and sediments (Figure 1).

The Sixth Assessment Report (6AR) by the Intergovernmental Panel on Climate Change (IPCC, 2013) projected a possible increasing of global mean sea level for different scenarios of Representative Concentration Pathway (RCPs) such as 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5 in 2100. However, the present study considered variation of sea level rise between 0.52 to 0.98 m of the RCP8.5 scenarios for 2100.

The IPCC has successfully raised awareness on the effect of climate change in the coastal areas at both the political and societal levels worldwide, which has resulted in many countries including sea-level rise as a major factor to be considered while devising shore protection measures in areas experiencing severe erosion. The estimation of possible alterations due to climate change is a major concern for future coastal management decisions.

Figure 1: Beach scarping at Tajpur, West Bengal

2. Habitat/ecosystem loss due to coastal erosion

2.1 Turtle Nesting Beaches

Marine turtles are vastly migratory as they cover a large stretch of the oceans between foraging and nesting grounds. The female turtles return to the beaches where they were once born, to lay eggs, breed and nest (Miller, 2017). Their dependability to natal nesting beaches often pose threat as the nesting beaches begin to disappear consequent to sea level rise or by erosion (Lutcavage et al., 2017). The site specific protection they are rightful of in areas such as the marine sanctuary, does not ensure their survival in a different locality (Hawkes et al., 2009).

Increase in sea level along with other coastal developmental activities has exacerbated coastal erosion in the past century. Over 70 percent of the world's beaches being recessional in nature (Feagin et al., 2005; Leatherman et al., 2000) and are eroding due to these phenomena. As a result, the sea level rise surges the range of wave action on land affecting areas that were relatively safer due to the higher elevation in the beach profile, and thus accelerating the movement of more sediment out to sea (Zhang et al., 2004). Erosion ultimately reduces the area of coastline, which is already highly vulnerable to coastal processes. Beaches being dynamic, dunes get flattened and replace the sandy beaches. As urbanization have hardened the shorelines by laying concrete structures and rock walls or built coastal highways, this shifting cycle cannot happen, resulting in the beach getting narrower.

Major threats for turtle nesting grounds due to climate change (After Fugazzotto, 2016)

- Loss of nesting beaches and coastal habitat through rising sea levels, an increase in storm surges, eroding shorelines, and coastal barrier projects
- Increased female gender bias in hatchlings
- Reduced hatching success from high temperatures and increased storm events
- Decreased or shifting food supply and
- Changing ocean currents impacting migration

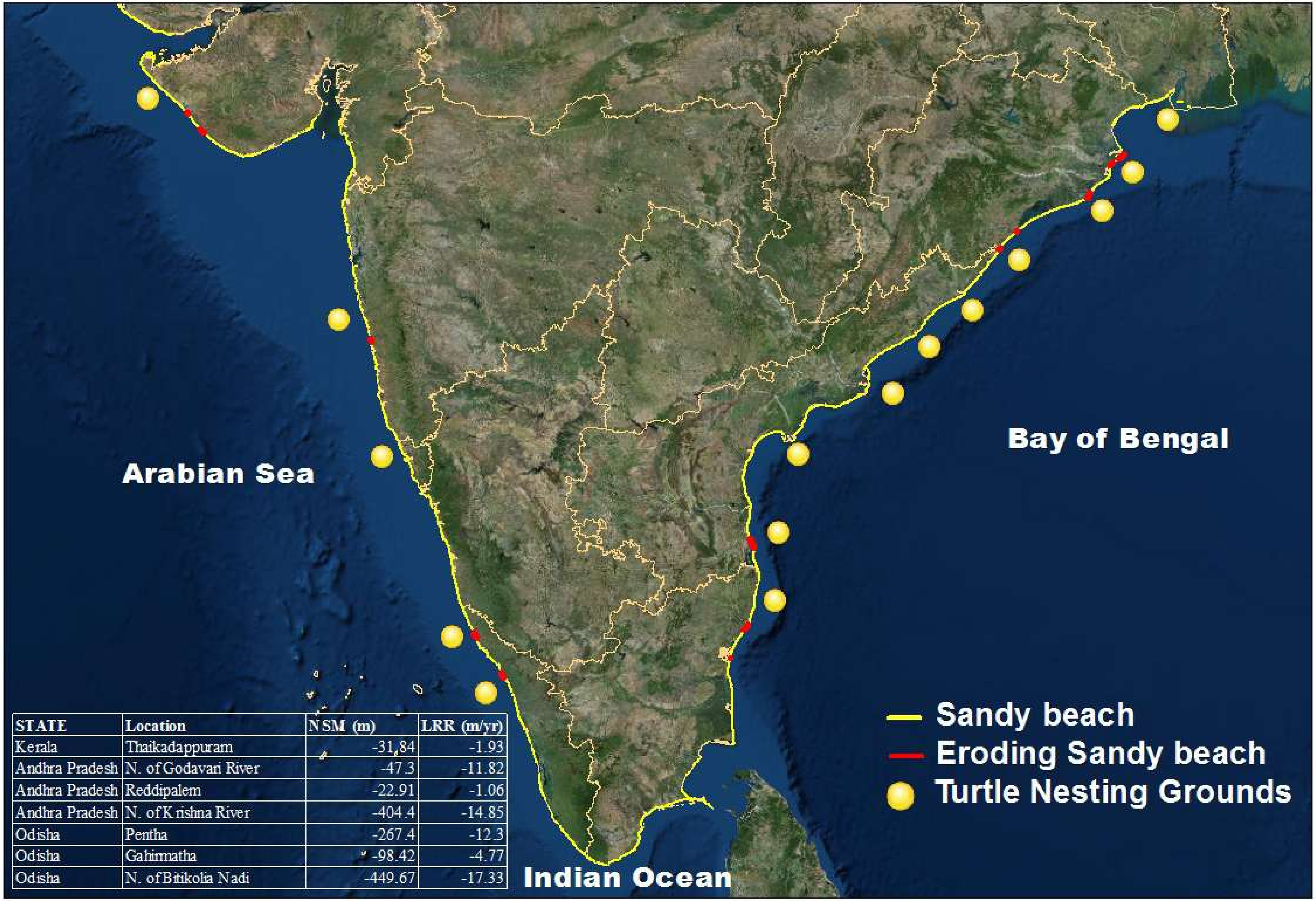
Beach nourishment is one of the significant interventions adopted which offers a buffer for the coast and helps temporary rebuilding of turtle nesting grounds. But most of the nourishment projects are expensive and must be repeated periodically (Landeck, 2017). This has made beach nourishment an unviable option in developing coastal nations.

2.2 Estimating the loss of Turtle Nesting Grounds

Robust estimation technique using historic shoreline position is a prerequisite for analysing long-term shoreline change rates. Different shoreline proxies such as High Water Line (HWL), berm line, swash line, wet-dry line, landward edge of artificial structures and seaward side mangroves were delineated to map the shoreline positions. This study presents a national assessment of shoreline dynamics along Indian coast for the turtle nesting sites for the past 36 years (1975-2011) using satellite images. A classification scheme (Saxena et al., 2013) was adopted based on Linear Regression Rate (LRR) analysis resulting into seven classes: high erosion, medium erosion, low erosion, high accretion, medium accretion, low accretion and stable coast. The eroding turtle nesting sites along the Indian coast is provided in Map.1.

Erosion along east coast is greater than west coast and West Bengal has the highest present (80%) erosion as can be seen in Figure 2 wherein the percentage of erosion and accretion patterns in eight coastal states are illustrated for 36 years..

The average NSM and LRR for the past 36 years along the coastal states is depicted in Table 1. It is clear that maximum shoreline recession and pro gradation is found in Andhra Pradesh, followed by Odisha and West Bengal while minimum is noticed in Gujarat and Goa. Similar scenario is true for highest rate of erosion and accretion in Andhra Pradesh, Odisha and West Bengal.



STATE	Location	NSM (m)	LRR (m/yr)
Kerala	Thaikadappuram	-31.84	-1.93
Andhra Pradesh	N. of Godavari River	-47.3	-11.82
Andhra Pradesh	Reddipalem	-22.91	-1.06
Andhra Pradesh	N. of Krishna River	-404.4	-14.85
Odisha	Pentha	-267.4	-12.3
Odisha	Gahirmatha	-98.42	-4.77
Odisha	N. of Bitikolia Nadi	-449.67	-17.33

Map 1: Eroding beaches (red) with turtle nesting grounds (yellow dots) along the Indian coast

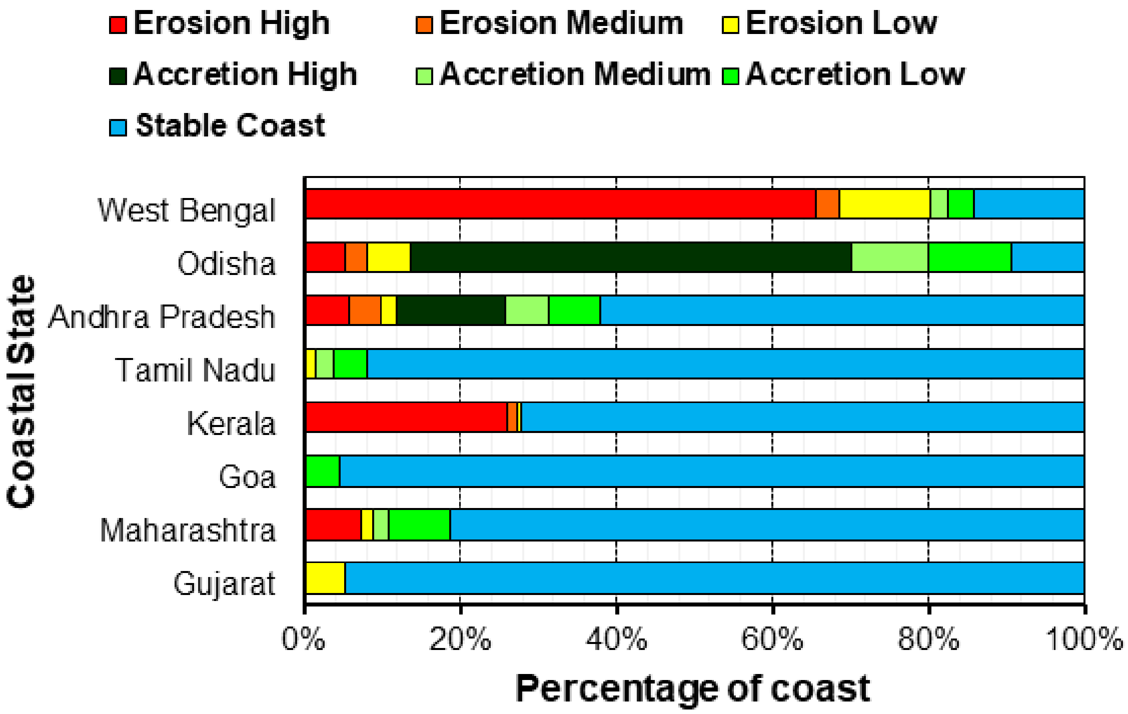


Figure 2: Status of shoreline change for the turtle nesting sites along the Indian coast

Table 1: Average erosion/accretion for Linear Regression Rate and Net Shoreline Movement during the years 1975 -2011 (1:10,000 scale)

State	No. of Turtle nesting sites	Length of the beaches (km)	Average NSM (m)		Average LRR (m/yr)	
			Erosion	Accretion	Erosion	Accretion
Gujarat	13	67.72	-3.23	2.65	-0.16	0.1
Maharashtra	14	3.46	-10.21	16.75	-0.5	0.8
Goa	6	3.91	-3.31	0	-0.09	0.77
Kerala	4	17.54	-32.81	3.97	-1.40	0.14
Tamil Nadu	8	36.25	-5.89	16.01	-0.23	0.61
Andhra Pradesh	12	49.61	**-158.24**	**283.97**	**-8.99**	**14.63**
Odisha	11	47.43	-122.76	72.67	-5.62	3.69
West Bengal	4	25.13	-48.60	170.89	-2.29	7.24






2.3 Causes of Shoreline Change

Along west coast, Kerala has the highest shoreline displacement towards the land primarily due to anthropogenic interventions such as seawalls, construction of groynes and breakwaters and sand mining along the beaches. In Maharashtra, shoreline recession is marginally less than progradation due to seasonal and bidirectional sediment movement causing seasonal accumulation and removal of sediment on the shore. The rate of erosion and accretion are almost same along the turtle nesting grounds of Saurashtra coast, Gujarat due to protection of the pocket beaches by rocky headlands and high slope. Minimal shoreline retreat is observed along North Goa coast, which is a seasonal cyclic process.

Erosion is also dominant near river mouths and deltaic regions along Andhra Pradesh and Odisha coasts due to sediment retention in the reservoirs which have decreased sediment supply to the coast. Construction of embankments at many locations along the coast of West Bengal has protected the coast temporarily from erosion but has moved erosion to non-eroding areas along the coast. Beaches along the coast of Tamil Nadu are stable owing to the seasonal littoral drift movement during South West and North East monsoons respectively.

From the assessments it was observed that North of Bitikola Nadi in Odisha experiences an average erosion of -449.67(m) NSM and 17.33 (m/yr) LRR among all the turtle nesting sites studied along the coast of India. Gahirmatha, famous for the mass nesting of Olive Ridley turtles (*Lepidochelys olivacea*) is undergoing erosion at a rate of -98.42 (m) NSM and -4.77 (m/yr) LRR, posing a serious threat to nesting grounds. It is also evident from the study that turtle nesting beaches especially on the east coast of India are undergoing high erosion. A suitable intervention to protect this loss is indeed imperative.

2.4 Estimation of loss of Mangrove Ecosystem

Mangrove ecosystem serve as the first line of defence along the coastline, with its intricate network of roots, capable of wave attenuation. Mangrove ecosystem provides a variety of ecological and societal goods and services. Mangroves enhance coastal fisheries, filter excess nutrients and pollutants, trap sediments, support tourism and protect coastlines and coastal communities from waves and extreme weather, among other values (Mukherjee et al., 2014). Climate change is one of the key drivers that can displace mangroves at greater levels along the coasts. Alongi et al. (2008) have predicted what may happen to mangroves as the planet warms, sea level rises, and the chemical composition of the atmosphere and oceans change. Their study reveals climate change as the ultimate anthropogenic disturbance factor resulting in a 10-15% loss of mangroves globally.

In their report Ward et al. (2016) have predicted the increase in frequency and intensity of storminess and these are likely to have a greater impact on North and Central America, Asia, Australia, and East Africa than West Africa and South America. The loss in mangroves adversely affects many species of fauna dependent on these nursery ecosystems for their food, shelter and reproduction (Figure 3).

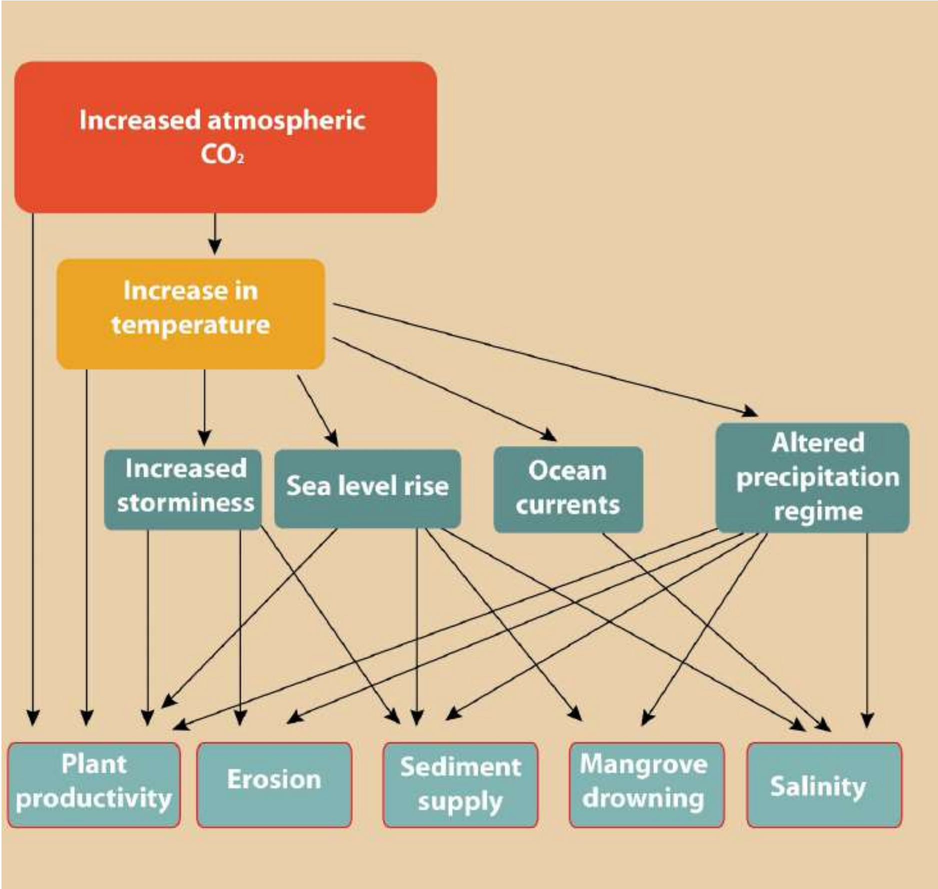


Figure 3: Conceptual framework: Principal impacting factors of climate change and how they are likely to negatively influence mangrove communities (Source: Ward et al., 2016)

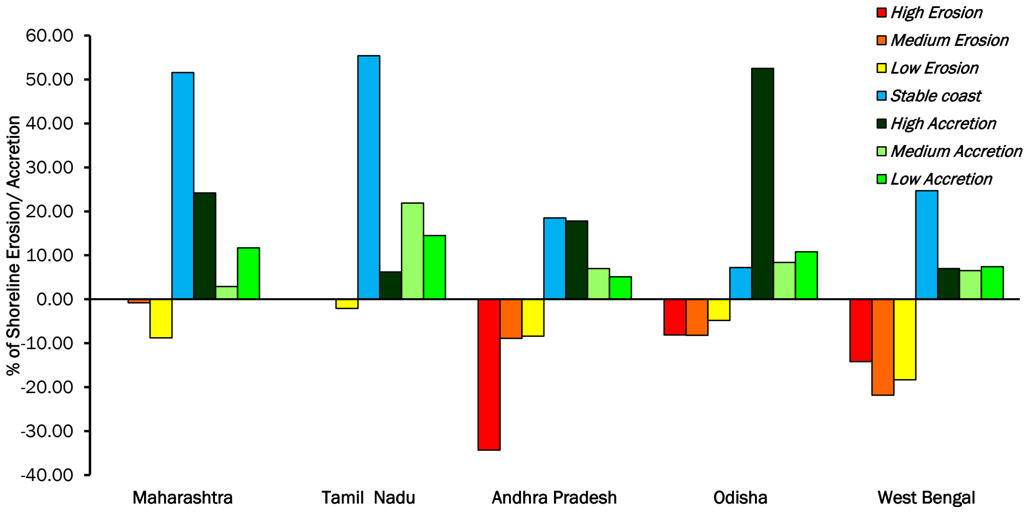
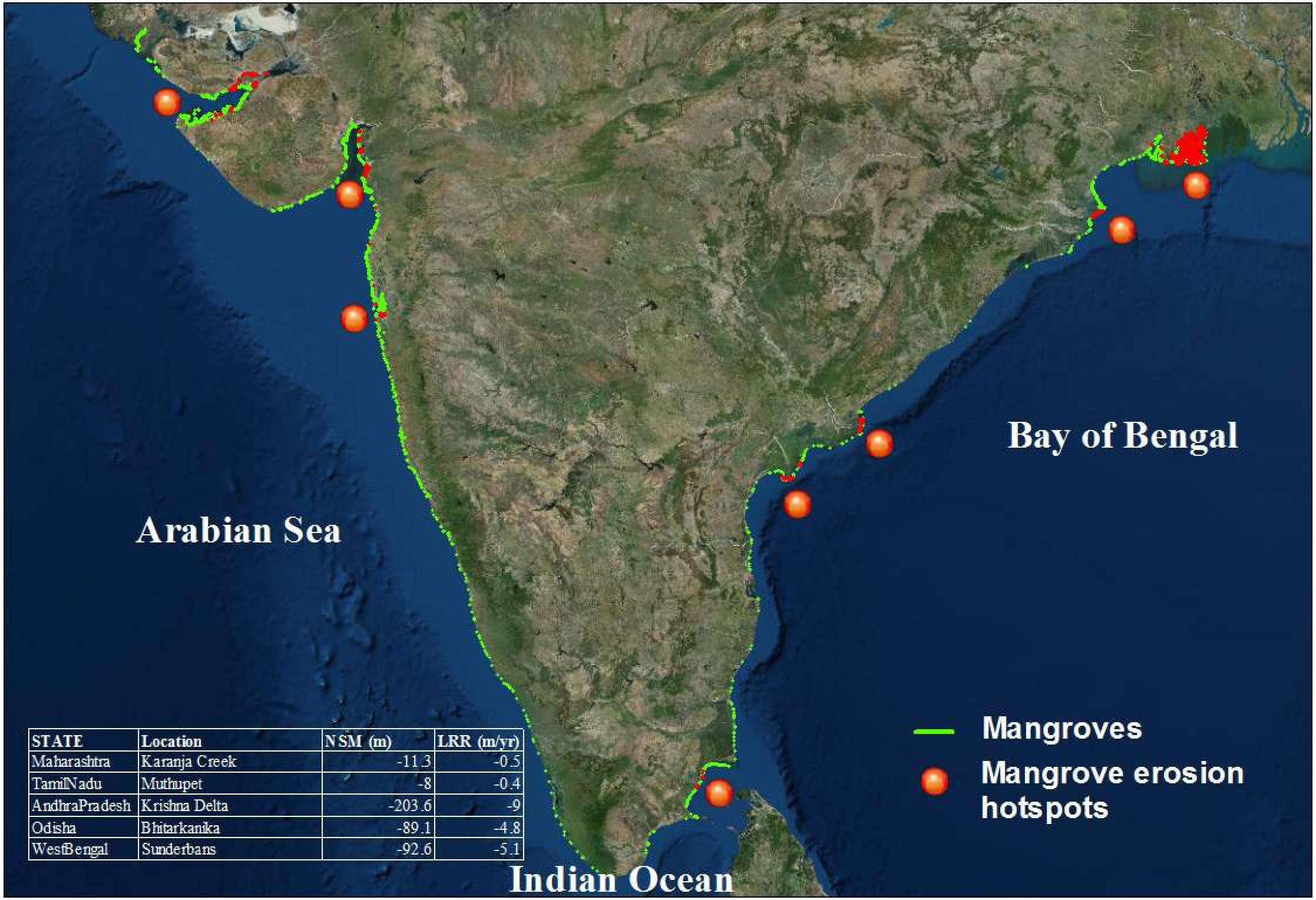


Figure 4: Status of shoreline change for the mangrove sites along the Indian coast

The status of shoreline changes for mangrove and the eroding mangrove along the coast of India is provided in Fig. 4 and Map.2. The Average Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) during the years 1975-2011 reveal high accretion of 291 m at Odisha; high erosion of -203.6 m along the mangroves of Andhra Pradesh (Tables 2 and 3).



STATE	Location	NSM (m)	LRR (m/yr)
Maharashtra	Karanja Creek	-11.3	-0.5
TamilNadu	Muthupet	-8	-0.4
AndhraPradesh	Krishna Delta	-203.6	-9
Odisha	Bhitarkanika	-89.1	-4.8
WestBengal	Sunderbans	-92.6	-5.1

Map 2: Eroding mangrove sites along the east and west coast of India

Table 2: Average Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) during the years 1975 -2011 along mangroves of India

States	Length of the shoreline (km)	Average NSM (m)		Average LRR (m/yr)	
		Erosion	Accretion	Erosion	Accretion
Maharashtra	30.0	-11.3	198.5	-0.5	8.7
Tamil Nadu	71.8	-8.0	52.4	-0.4	2.6
Andhra Pradesh	106.9	**-203.6**	170.7	**-9.0**	8.8
Odisha	96.2	-89.1	**291.0**	-4.8	**14.0**
West Bengal	1158.2	-92.6	102.6	-5.1	5.5

Table 3: Classification and levels of erosion and accretion (in %)

States	High Erosion	Medium Erosion	Low Erosion	Stable coast	High Accretion	Medium Accretion	Low Accretion
Maharashtra	--	0.8	8.8	51.6	24.2	2.9	11.7
Tamil Nadu	--	--	2.1	55.4	6.2	21.9	14.5
Andhra Pradesh	34.3	8.9	8.4	18.5	17.8	7.0	5.1
Odisha	8.1	8.2	4.8	7.2	52.5	8.4	10.8
West Bengal	14.2	21.8	18.3	24.7	7	6.5	7.4

The major mangrove ecosystems in India are undergoing erosion with maximum erosion in Andhra Pradesh specifically in the Krishna Delta with an average erosion of -203.6 (m) NSM and -9 (m/yr) LRR followed by Sundarbans -92.6 (m) NSM and -5.1 (m/yr) LRR in West Bengal. Other areas experiencing erosion at mangrove sites include Karanja creek in Maharashtra, Muthupet in Tamil Nadu and Bhitarkanika in Odisha. These mangrove areas are some of the best mangrove hotspots in the country supporting a wide diversity of flora and fauna and unique biodiversity.

3. Prediction of coastal vulnerability

Presence of natural coastal habitats is important in mitigating the forces responsible for coastal erosion and inundation so that management actions might best preserve the protective services provided by coastal ecosystems. Numerous models have estimated the vulnerability of coastal regions to long-term sea level rise, erosion and inundation based on geophysical and natural habitat characteristics.

3.1 InVEST Model

The study is an attempt to map the relative vulnerability of coastal areas to erosion and inundation using the Coastal Vulnerability module of Integrated Valuation of Ecosystem Services and Trade-off (InVEST) model by Sharp et al. (2015). The Coastal Vulnerability model produces a qualitative index of exposure of the coast to erosion and inundation and maps the location and size of human settlements (Arkema et. al., 2013). The model does not value directly any ecosystem service, but ranks sites as having a relatively 'low', 'moderate' or 'high' risk of erosion and inundation. It highlights the relative role of natural habitat at reducing exposure and showing areas where coastal populations are threatened. Thus, the model can be used in a simple way, to investigate how some management action or land use change can affect the exposure of human populations to erosion and inundation and suggest suitable management interventions.

The vulnerability of coast has been estimated (Arkema et. al., 2013) by deriving the Exposure Index (EI), based on parameters such as Mean Sea Level (MSL), Median Highest High Water (MHHW), Median Lowest Low Water (MLLW), global Digital Elevation Model (DEM), wind, wave, storm surge, coastal population and bathymetry of the continental shelf, geomorphology of the coast, characteristics of natural habitats, rate of sea level rise and structures on the coast (Fig. 4). The model estimates the coastal exposure with the cumulative ranking of geophysical and natural habitat parameters. Parameters such as the continental shelf, bathymetry, population from the global data sources, relief from SRTM data with a 30 m resolution, geomorphology, sea level rise, natural habitats [e.g. Mangrove, Reserved Forest, Seagrass, Salt marsh and Sand dune were obtained from various data sources and were incorporated in the model as initial parameters (NCSCM unpublished data). Physical parameters such as wind speed and wave model inputs have been generated from WAVEWATCH III model (Table 4). These parameters were assigned different orientations of 360 degrees as input to the model, since the direction of the wind is highly variable and the corresponding waves also vary.

In order to evaluate the role of coastal ecosystems in reducing exposure to sea-level rise, we developed two scenarios. (i) '*With habitat'* which includes nine habitats in the hazard index and. (ii) '*Without habitat'* assumes those habitats that no longer provide coastal protection. The 'with habitat' scenario is assumed to be the current state of the system. The 'without a habitat' scenario is not intended to be a plausible reflection of the future; instead, it is used to evaluate the extent natural habitats play in the loss of marine habitats. It also determines where their loss would give rise to risks from coastal hazards. On a pilot scale we have assessed the role of coastal habitats in reducing the relative vulnerability of the coast to erosion from sea-level rise (SLR) in 1 sq.km segment along the entire coast of Odisha, Andhra Pradesh, Maharashtra.

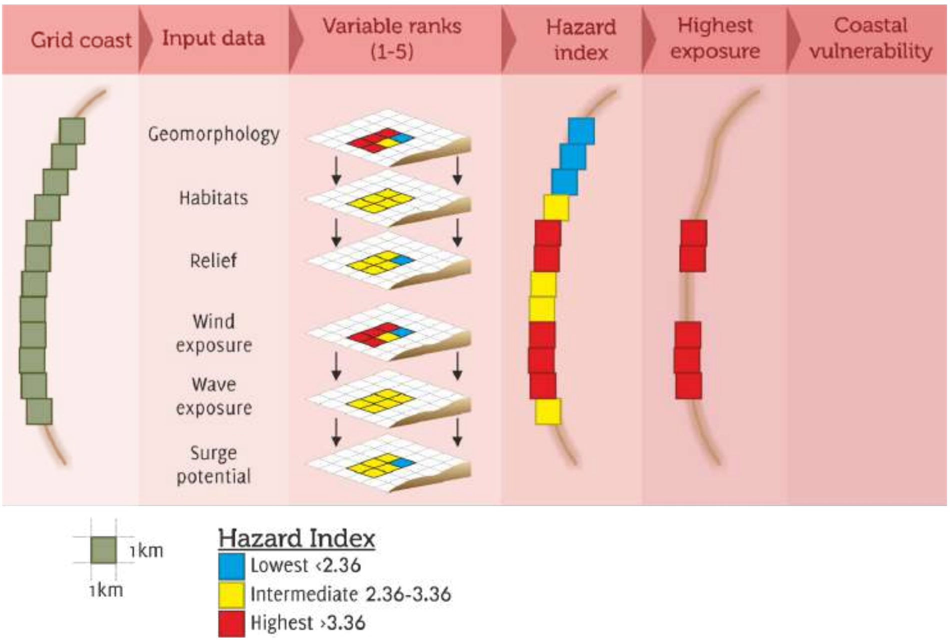


Figure 4: Schematic diagram of coastal vulnerability module of InVEST model

The coastal hazard index was calculated incorporating the seven physical and biological variables as mentioned above. The current wave and wind exposure was estimated based on six years of NOAA WAVEWATCH-III model hindcast reanalysis result for 2005-2010, to determine where habitats play an important role in providing protection from erosion and flooding with an SLR. In order to map hazard, the distribution index values were classified for all segments and scenarios ranging from 1-5 into quartiles to indicate areas of highest hazard (>3.36 = top 25% of the distribution), intermediate hazard (2.36-3.36 = central 50% of the distribution) and lowest hazard (<2.36 = bottom 25% of the distribution).

Table 4: Input parameters: wind speed (m/sec) and wave height (m) of InVEST model

LONG	LAT	Wind Speed	Wave height	Max. wind speed	Max. wave height
87.50	19.00	11.37	3.32	15.08	11.98
86.50	18.50	11.79	2.84	25.73	16.41
88.00	20.50	10.30	2.45	11.40	7.16
88.00	20.00	10.63	2.85	12.37	8.55
87.50	19.50	10.91	2.73	13.65	10.28
88.50	21.00	9.68	2.54	10.81	5.98
88.50	20.00	9.94	3.33	11.58	8.41
87.00	19.00	10.60	3.01	14.18	12.87
85.50	17.50	11.46	3.10	17.23	11.91
86.50	19.00	11.31	2.44	21.10	13.91
88.50	20.50	10.22	3.05	12.13	7.62
85.50	18.00	11.31	2.56	15.63	9.65
86.00	18.00	11.65	3.08	40.59	13.38
88.00	19.50	10.86	3.26	13.50	9.79

3.2 Increased vulnerability without habitat

In the context of storm surge vulnerability, entire Indian coast is categorized into four risk zones as (i) 'Very high risk' (Surge height > 5m), (ii) 'High risk' (Surge height between 3-5m), (iii) Moderate risk (Surge height between 1.5 to 3m) (iv) 'Minimal risk' (Surge height less than 1.5 m).

The Indian National Centre for Ocean Information Services (INCOIS), Ministry of Earth Sciences predicted storm surge along the coastline and indicated that the east coast of India between Paradip and Balasore in Odisha (i.e. 5-7m) and the Andhra coast between Bapatla and Kakinada with estuaries of two major rivers Krishna and Godavari (5-7 m) as Very High Risk Zones (VHRZ) The coastal areas and off-shore islands of Bengal are the most storm-surge prone about ~ 10-13m. Tamil Nadu coast between Pamban and Nagapattinam has about ~ 3-5m and is classified as High Risk Zone (HRZ), while Gujarat along the west coast of India has about ~ 2-3m and is classified as moderate risk zone (MRZ) areas. As per 2011 population census, the population of coastal districts in the coastal states is 200.37 million. Population distribution is also one of the parameters to assess coastal vulnerability.

Simulations were carried out to understand their vulnerability through the Exposure Index (EI) in the presence and absence of natural habitats. Maps of coastal ecosystems were overlaid on the vulnerability maps, which indicated that both attributes are inversely correlated. Areas covered with natural habitats along the coast have lower exposure index (EI) and thus, have lower vulnerability. Model predicted EI values were higher in the southern and northern parts of Odisha coast (high vulnerability), areas with natural habitats such as mangroves, seagrass and salt marshes have comparatively less vulnerability (Tables 9 & 10).

Table 8: Population of Coastal Districts of Coastal States

Region	State Name	Population of Coastal Districts (in million)	Area of Coastal Districts in Sq.km	Population Density of Coastal Districts (No/ Sq.km)
West Coast States	Gujarat	32.25	118929	271.14
	Maharashtra	27.81	35902	774.59
	Goa	1.46	3702	393.77
	Karnataka	4.70	18731	251.14
	Kerala	25.48	23049	1105.38
East Coast States	Tamil Nadu	34.68	49466	701.04
	Andhra Pradesh	34.19	92906	368.05
	Odisha	11.63	22308	521.43
	West Bengal	28.17	20257	1390.72

Table 9: Exposure Values for different districts in the states of Odisha, Andhra Pradesh and Maharashtra, where values ≥ 4 indicates Very High Risk Zones (VHRZ) and ≤2 are Low Risk Zones (LRZ)

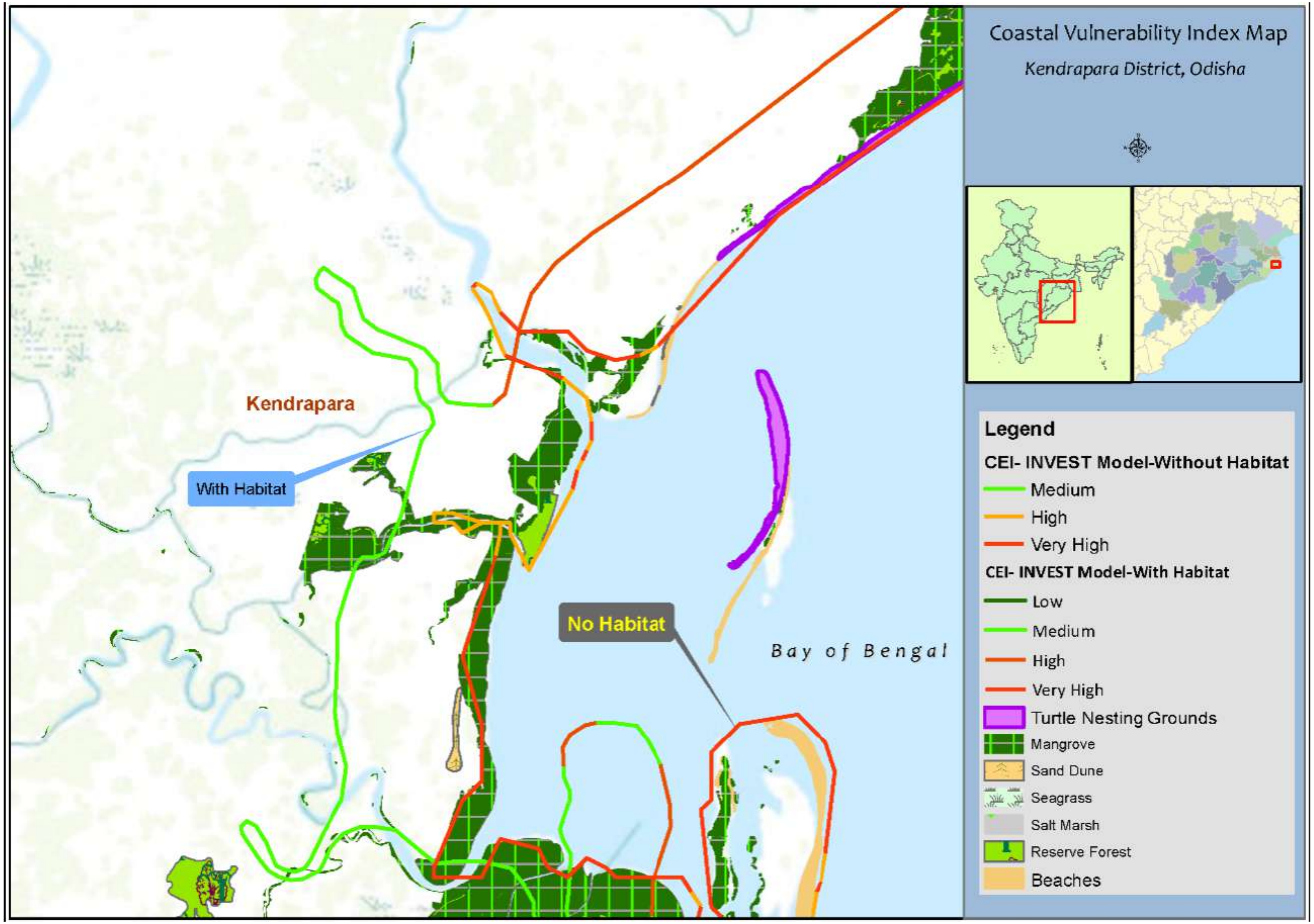
State	District	EI Values		
		High	Medium	Low
Odisha	Ganjam	4	-	-
	Puri	-	-	2
	Kendrapara	-	-	2
	Bhadrak	-	3	-
	Baleshwar	4	-	-
Andhra Pradesh	Nellore	-	3	-
	Prakasam	-	3	-
	Guntur	-	3	-
	Krishna	-	3	-
	West Godavari	4	-	-
	East Godavari	-	3	-
	Visakhapatnam	-	3	-
	Srikakulam	4	-	-

State	District	EI Values		
		High	Medium	Low
Maharashtra	Sindhudurg	-	3	-
	Ratnagiri	4	-	-
	Raigad	-	3	-
	Greater Mumbai	4	-	-
	Thane	4	-	-
	Palghar	4	-	-

Table 10: Coastal Vulnerability in turtle nesting grounds and mangroves

State	District	Type of Ecosystem/ Habitat	Coastal Vulnerability
Odisha	Ganjam	Mangroves & turtle nesting beaches	High
	Puri	Turtle nesting beaches	Low
	Kendrapara	Mangroves & turtle nesting beaches	Low
	Bhadrak	Mangroves	Medium
	Baleshwar	Mangroves	High
Andhra Pradesh	Nellore	Mangroves	Medium
	Prakasam	Mangroves	Medium
	Guntur	Mangroves	Medium
	Krishna	Mangroves	Medium
	West Godavari	Mangroves	High
	East Godavari	Mangroves	Medium
	Visakhapatnam	Turtle Nesting	Medium
	Srikakualm	Mangroves & turtle nesting beaches	High
Maharashtra	Sindhudurg	Mangroves & turtle nesting beaches	Medium
	Ratnagiri	Mangroves & turtle nesting beaches	High
	Raigad	Mangroves & turtle nesting beaches	Medium
	Greater Mumbai	Mangroves	High
	Thane	Mangroves	High
	Palghar	Mangroves	High

The predicted EI values along the coastal districts of Odisha were the highest in Baleshwar, followed by Ganjam, Jagatsinghpur, Kendrapara, Bhadrak and Puri (Map 3).



Map 3: Coastal Vulnerability Index (CVI) map of Kendrapara District, Odisha

In the case of Andhra Pradesh, EI values were high in the northern part of the coast than the south. High EI values were observed at Chirala, Narasapur and Tuni regions since these regions are highly exposed to the geomorphological changes, storm surges and sea level rise (Map 4).

Similarly, EI values were low and medium in the southern part of the Maharashtra coast (medium vulnerability), where the natural habitats such as mangroves and salt marshes are comparatively high in the southern part. The highest EI values were predicted along the Palghar coastal district followed by Thane, Greater Mumbai, Raigad, Ratnagiri and Sindhudurg coast of Maharashtra (Map 5).

3.3 Reduction in vulnerability with habitat/ecosystem

The InVEST model thus clearly highlights that areas without natural habitats/ ecosystems are prone to natural hazards and are highly vulnerable whereas, areas with natural habitats/ ecosystems would have protection from extreme events. The model also provides an opportunity to carry out plantation/ restoration of the degraded/ lost habitats/ ecosystems with high/ very high exposure index. The information generated from models as these can help coastal managers, planners and other stakeholders identify regions with greater risk to coastal hazards and subsequent intervention and implementation could be carried out.

3.4 Recommendations for Protection of Coastal Ecosystem/Habitat

Turtle nesting beaches

- Planting/ re-planting native vegetation on the dune to refortify the beach
- Avoiding structures on beaches (groynes, breakwaters etc.)
- Promoting enforcement of Coastal Regulation Zone (2011) notification
- Beach nourishment in degraded nesting sites (can cause a short term decline in nesting densities – at least 2 years or, an increase in nesting densities)

A success story from Florida, USA

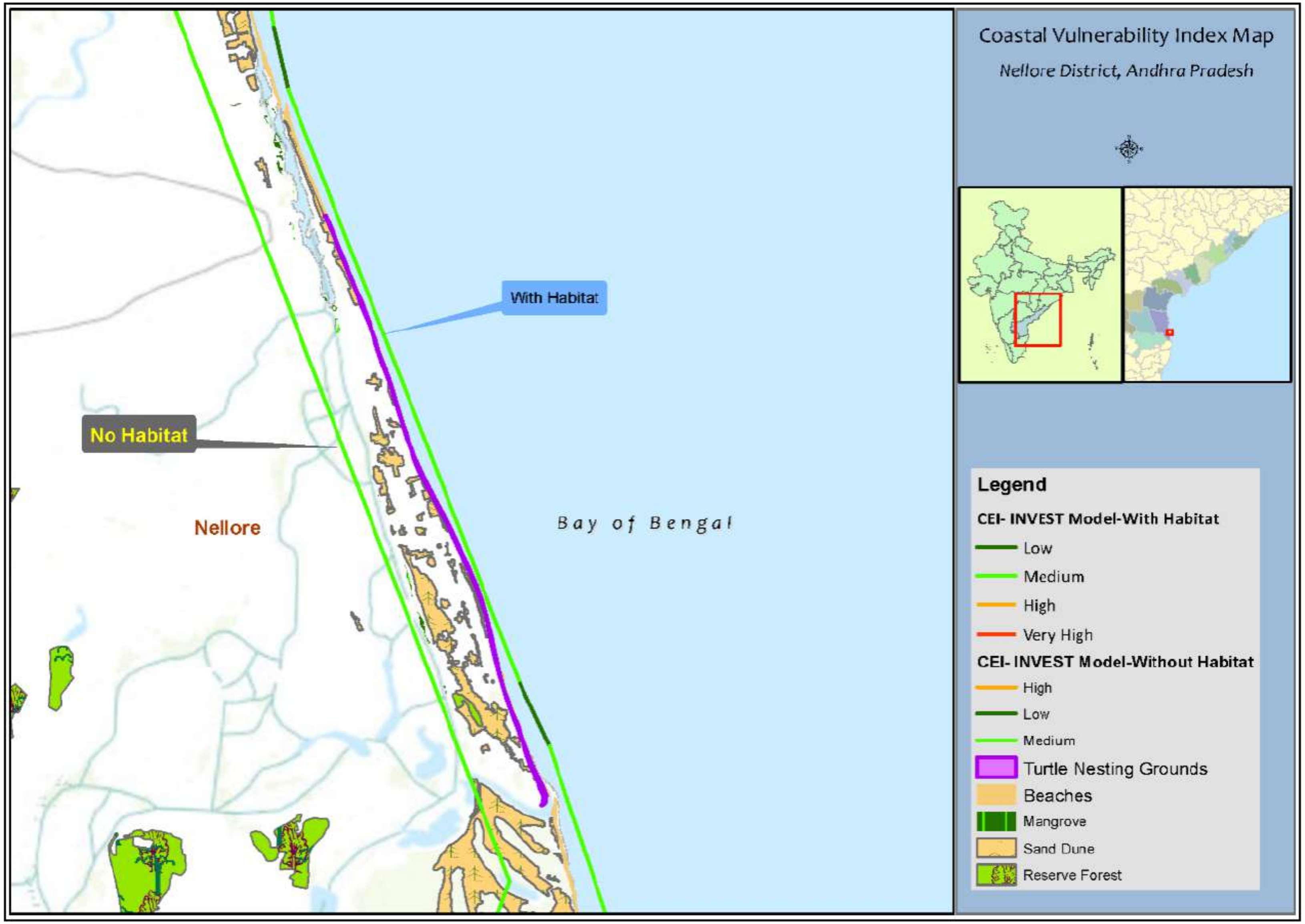
Effects of beach re-nourishment and nest relocation on the rate of emergence of Loggerhead sea turtle hatchlings was studied at the beaches of Pinellas County, Florida; the study period was five years, 2006 through 2010. Because beach re-nourishment can be environmentally detrimental for sessile organisms such as sponges and coral, a hypothesis that beach re-nourishment would negatively affect hatchling success of the Loggerhead sea turtles was attempted. Ironically, the study of ~53,700 Loggerhead sea turtle hatchlings showed that they are capable of surviving the interventions of humans to save them.

Lauren Dellert. 2012. The Effect of Nest Relocation and Beach Re-nourishment on the Loggerhead Sea Turtle (Caretta caretta) in Pinellas County, Florida. Honours thesis submitted to the University of South Florida, St. Petersburg.

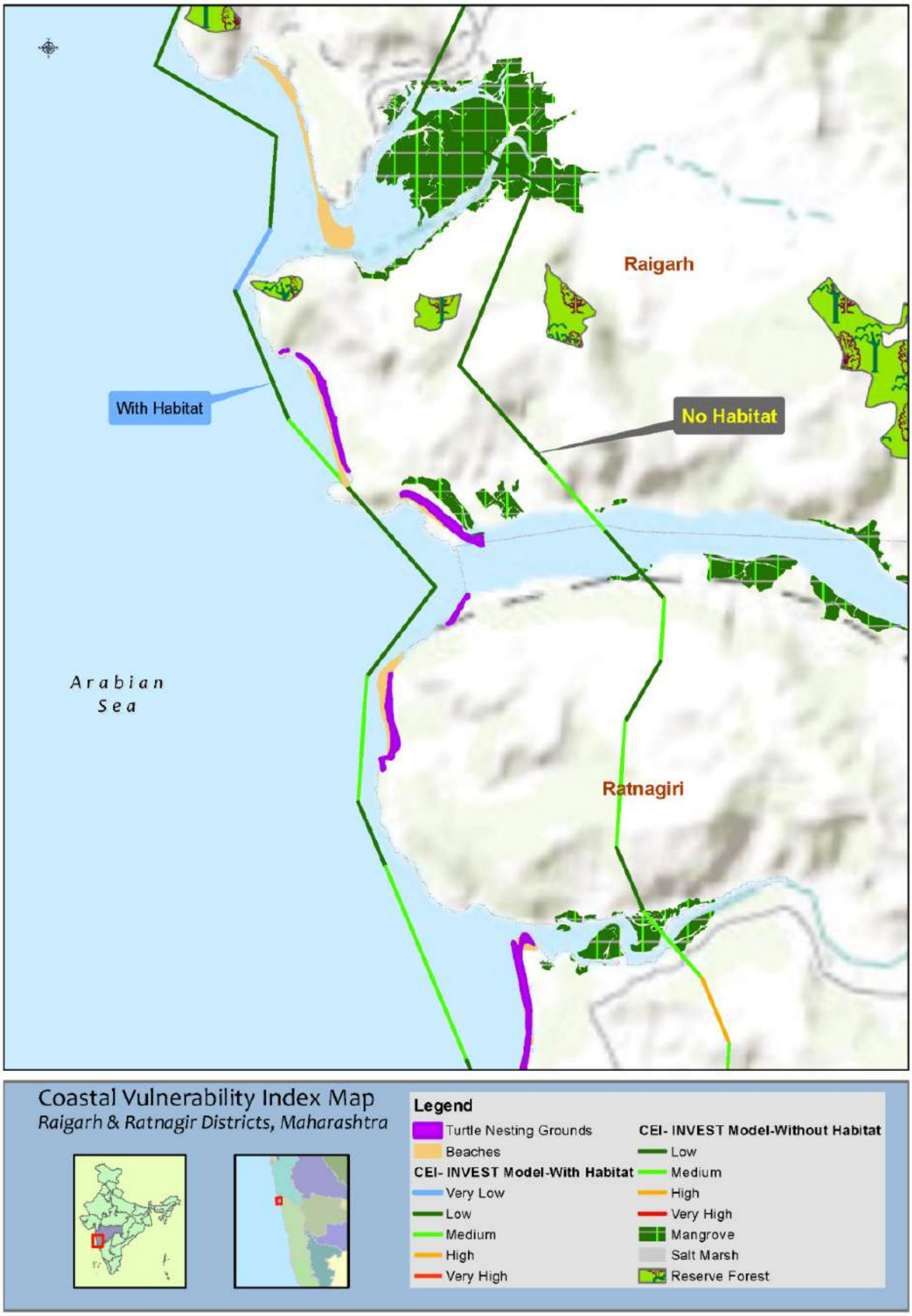
3.5 Recommendations for protection of Mangrove Ecosystems

Encouraging plantation of mangroves is a key factor especially in degraded areas. Some of the important interventions carried out globally to tackle climate change include:

- Identification of degraded mangrove areas using GIS tools (spatial and temporal changes)
- Undertaking mangrove restoration in the degraded areas
- Avoiding introducing mangrove plantation in areas that are salt marsh or mudflats, unless these were previously such ecosystems
- Identifying the local species from field surveys and prepare nursery for the same for future restoration work
- Avoiding clearing of mangroves for extended aquaculture activities
- Avoiding constructions obstructing natural tidal flow near mangrove ecosystems



Map 4: Coastal Vulnerability Index (CVI) map of Nellore District, Andhra Pradesh



Map 5: Coastal Vulnerability Index (CVI) map of Raigarh and Ratnagiri Districts, Maharashtra

Coastal erosion caused by natural and/or anthropogenic processes pose a major threat to coastal habitats and ecosystems. Under the scenario of global mean sea level rise predictions by the IPCC, vulnerability quotient of ecologically sensitive areas such as mangroves and turtle nesting grounds as coastal protection areas have been assessed. Among the coastal resources, sandy beaches are highly susceptible to storm surges and sea level rise subsequent to climate change. This would in turn affect the marine turtle nesting sites and other unique intertidal fauna dependent on this ecosystem. Further, urbanization, involving construction of coastal highways and concrete structures along the beaches, have resulted in the narrowing of beaches. In the given scenario, a significant positive approach is beach nourishment programs that can be initiated at highly vulnerable areas.

Further, mangrove ecosystems would face large scale displacement and landward migration as a consequence of climate change. This is supported by the expansion of mangroves even under direct anthropogenic pressure as a response to climate change in many parts of the world. The loss of mangroves along the coast would expose landward areas to natural catastrophes and also cause huge loss of biodiversity.

NCSCM has estimated the coastal vulnerability using the InVest model through the exposure index based on hydrodynamic and coastal parameters. Pilot scale studies were also undertaken in 1 sq.km segment along the entire coast of Odisha, Andhra Pradesh and Maharashtra to assess the role of coastal habitat/ecosystems in reducing the vulnerability of the coast. Based on these, the coastal hazard index was derived. The InVest model clearly highlights relatively higher vulnerability in areas without natural habitat/ecosystems to natural hazards than those with natural habitats/ ecosystems. Implementation of well-planned and proven intervention measures would help in conserving the unique habitats such as mangroves and turtle nesting grounds.

Application of InVest model thus provides the scope of better understanding data from past time periods on how landscape changes have influenced present vulnerability data. The model can be used to predict scenarios of any coastal ecosystem/ habitat for which data exist. Resource managers can thus effectively identify those areas where restoration or protection needs to be carried out.

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4

Who is vulnerable?

Evidence from districts on the east coast of India

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ABSTRACT

The most vulnerable villages due to extreme climatic events in three coastal districts of Kendrapada, Nellore, and Nagapattinam were identified based on a modification of socioeconomic vulnerability index adjusted at the village level. The index captures a comprehensive scale of vulnerability by including factors such as demographic, occupational, infrastructure and land use patterns. The analysis of vulnerability index is further mapped with application of GIS tools that serve to validate the robustness of the index. Areas of policy gaps in addressing issues of poverty and early engagement in informal job markets, lower levels of education, and higher dropout ratios in particular for the selected districts have a direct impact on vulnerability due to climate change. Higher dependency on agriculture as the primary source of income leads to higher vulnerability. Further, transport and communication facilities are weaker in the study areas which are bottlenecks in the context of both development and coping strategies. Based on the findings the government and other agencies can design more robust climate response, adaptation and vulnerability reduction policies and interventions.

1. Introduction

India is subject to a wide range of climatic conditions ranging from the Himalayan winters in the north, to the tropical climate of the southern neck of land; from moist, rainy climate in the north-east to the arid great Indian desert in the north-west; and from the marine climates of its vast coastline and islands to the dry continental climate in the interior. Climate along the Indian coast varies from that of true tropical region in the south to that of sub-tropical and arid environment in Kachchh in the northwest. Similarly, rainfall varies from only 300 mm in the semi-arid region of Kachchh in the western part of Gujarat to an average maximum of 3200 mm in the Andaman-Nicobar Islands in the south. On the eastern coast of India, there are gigantic deltas of the Ganges-Bramhaputra, Krishna-Godavari, and Mahanadi, which support large areas of river estuaries and excellent growth of tidal forests. The coastal zones are important and critical regions for India, which has a low lying densely populated coastline of over 7500 km with Arabian Sea on the west and Bay of Bengal on the east. It is inhabited by more than 10 million people in nine coastal states (that of West Bengal, Odisha, Andhra Pradesh and Tamil Nadu on the east coast; Kerala, Karnataka, Goa, Maharashtra and Gujarat on the west coast); two union territories (Puducherry and Daman & Diu) and two groups of islands (Andaman & Nicobar and Lakshadweep). There are about 65 coastal districts in the 9 states. The total area occupied by coastal districts is around 3,79,610 kilometer, with an average population density of 455 persons per kilometer; which is 1.5 times the national average of 324 (Census, 2011).

The Indian coastal zone exhibits a number of geomorphologic features, including shorelines with coastal cliffs, dune and beach ecosystems, mangroves, coastal wetlands and estuaries. The pressure on coastal areas has been growing due to migration from inland to the coastal zone and making its population vulnerable to the increased frequency and intensity of natural and human induced hazards. There are a number of reasons for this increased pressure; these regions are more developed with greater employment opportunities as some of the major urban centers (Chennai, Kolkata and Mumbai) are located in these regions. Moreover, out of the 35 urban agglomerations with a million plus population identified for India in the Census of 2011, 18 are situated in the coastal states. From among these 18 urban agglomerations, 8 lie on the coastline. The activities in many of these areas are tending to exceed the capacity of the natural coastal ecosystem to absorb them, making these regions more exposed and vulnerable to increased frequency and intensity of natural and human induced hazards.

Vulnerability varies widely across communities, sectors and regions. This diversity of the "*real world*" is the starting place for a vulnerability assessment. International comparisons of vulnerability tend to focus on national indicators; to group less developed countries or to compare progress in human development among countries with similar economic conditions. At a national level, vulnerability assessments contribute to setting development priorities and monitoring progress. Sectoral assessments provide more detail and targets for strategic development plans. At a local or community level, vulnerable groups can be identified and coping strategies implemented, often employing participatory methods. Although vulnerability assessments are often carried out at a particular scale, there are significant cross-scale interactions, due to the interconnectedness of economic, social and climate systems (Parthasarathy et al., 2019).

In the development economics literature, the term vulnerability is mostly used in the context of poverty. The World Bank (World Bank, 2001) defined vulnerability as a measure of resilience against shock. Conceptual papers in economics dealing with the notion of vulnerability have emerged in recent years (Dercon, 2001; Prowse, 2003). Over the same period, vulnerability has become a familiar term in the climate change literature, which has produced its own conceptual literature (Jones, 2001; Brooks, 2003; O'Brien et al., 2004; Fussel and Klein, 2006). The literature on vulnerability has grown enormously over the past few years. Key articles from a development and sectoral perspective include Bohle and Watts (1993) and Chambers (1989). Extensions related to natural hazards are Blaikie et *al*. (1994), Clark et al. (1998), and Stephen and Downing (2001). Climate change explorations include Adger and Kelly (1999), Bohle et al. (1994), Downing et al. (2001), Handmer et al. (1999), Kasperson et *al*. (2002), and Leichenko and O'Brien (2002). The IPCC has significantly contributed to the reframing of vulnerability combining problems of exposure, sensitivity, and adaptation (Parry et al. 2007).

Agarwala et al. (2003) presented the integrated case study for Bangladesh with reference to development and climate change. The report focuses on three issues: first, recent climatic trends and climate change scenarios for Bangladesh are assessed and key sectoral impacts are identified and ranked along multiple indicators to establish priorities for adaptation; second, donor portfolios in Bangladesh to examine the proportion of development assistance activities affected by climate risks; and third, an in-depth analysis for coastal zones, particularly the coastal mangroves in the Sundarbans, which have been identified as areas particularly vulnerable to impacts of climate change (Agarwala, 2003).

Dang et al. (2003) explored the possible contradictions and synergies between adaptation and mitigation strategies and the implications for developing countries and sustainable development targets. Dixit reviewed the nature of flood disaster in the Himalaya-Ganga by focusing on the plains of Nepal and argues that conventional approaches have not been able to provide the security envisaged and also suggests that vulnerability of people in risk prone areas must be addressed by enhancing resilience capacity (Dixit, 2003). Adger developed theoretical perspective on institutional adaptation to social vulnerability to environmental risks and evaluated in Nam Dinh Province in northern Vietnam (Adger, 2000). In this case, the author defines the term '*social resilience*' and shows a link between social and ecological resilience, particularly for the social groups or communities dependent on ecological and environmental resources for their livelihoods. Further, the study also explores potential links between social and ecological resilience in the context of coastal community in Vietnam (Adger, 2000).

Dowlatabadi provided an overview of integrated assessment with a special focus on policy motivated integrated assessments of climate change. The paper also discusses the taxonomy of policy motivated models (Dowlatabadi, 1995). Chichilnisky et al. (1993) discuss the risks in the context of climate change and its remedial measures such as mitigation and insurance. Four key issues are incorporated in the analysis: the difficulty in assessing risks; endogeneity of risk; the correlation of risks; and the irreversibility of risks (Chichilnisky et al., 1993). With such ample evidence of literature and the growing concerns of climate risks and adaptation (Narayanan and Sahu, 2016), it is important to categorize the most vulnerable areas in the eastern coast of India which caters to the densely populated settlements. Therefore, this study is an attempt to answer "who is vulnerable?" in these areas. This work intends to categorize vulnerability using an index of socioeconomic vulnerability coupled with ecological indicators. Further, analysis is also carried out using GIS techniques to identify the vulnerable areas and map using an index based approach. The second section describes data sources and methods employed in this study. It also discusses the details of vulnerability index computation and GIS techniques used. Section three explains the patterns of cyclone incidence and identification of vulnerable areas. Section four identifies and explains implications of this study while section five concludes with identification of policy gaps in addressing vulnerability of these regions.

2. Data sources and methods

Vulnerability can be broadly defined as "The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of natural or man-made hazards" (Blaike et al., 1994). The definition of vulnerability suggests that it cannot be described without reference to a specific hazard or shock. So, the question that must always be asked is, "Vulnerability to what?" People living along coastal areas or rivers may be vulnerable to seasonal storms and flooding, while the inhabitants of countries with social, political and economic problems may face difficulties in achieving a satisfactory and sustainable quality of life. This section attempts to analyze the relative vulnerability pattern across the villages of the three study areas namely Kendrapara, Nellore and Nagapattinam in the Indian states of Odisha, Andhra Pradesh and Tamil Nadu respectively. Vulnerability is often reflected in the condition of the economic system as well as the socioeconomic, infrastructure, ecological, and governance characteristics of the population living in that system. Vulnerability is derived by focusing on indicators that measure both the state of development of the region as well as its capacity to progress further. The first aspect is reflected through demographic setup and climatic variations, while the second is reflected through agricultural development. In other words, the climate change impacts are examined from agriculture, employment and demographic and infrastructure characteristics for the select areas of the eastern coast of India.

The method adopted in this paper is based on a modification of socioeconomic vulnerability index formulated by Patnaik and Narayanan in 2005. This modified version of the index seeks to capture socioeconomic vulnerability at the village level of each of the study districts. The index tries to capture a comprehensive scale of vulnerability by including many indicators that serve as proxies. Specifically, the section looks at four different sources of vulnerability: viz., demographic factors, and occupational factors, infrastructure factors and land use patterns. Once the index is calculated based on the socioeconomic characteristics of the study areas, the discussion moves ahead to address climate-related characteristics and tries to map the results with the applications of the GIS tools.

2.1 The vulnerability index

The exercise tries to capture comprehensive scale of vulnerability at village levels. It is assumed that vulnerability can arise out of demographic factors, occupational factors, land use factors and infrastructure factors. The demographical features play an important role in measuring socioeconomic vulnerability. Here, three components to define demographic vulnerability are considered namely: density of population, literacy rate and agriculture pattern as higher the population density larger the number of people who might be vulnerable. The level of education is defined by the literacy rate (representation of informed population). The pattern of land use serves as a proxy for agricultural vulnerability. Four components have been considered to determine this indicator, namely: irrigated land, un-irrigated land, forest land and land under no cultivation. Further, we have used the number of schools, hospitals, communication facilities and number of banks to assess the infrastructure vulnerability. To define the occupational vulnerability the numbers of total workers, agricultural workers, cultivators, household workers and the non-workers as the nearest proxies were considered. These represents the labour force components. For the construction of the index, data was derived from the Census of India, 2011 household electronic data set. The approach is adopted from the basic approach of Anand and Sen (1994) for calculation of the human development index (HDI). Chart-1 shows the framework undertaken to estimate the vulnerability index.

For the calculation of the index, these steps were followed- first the dimension index of each of the indicators (represented in chart-1) for a district (X_I) is calculated -

$$\frac{(\text{Actual } X_I - \text{Minimum } X_I)}{(\text{Maximum } X_I - \text{Minimum } X_I)} \quad (1)$$

Further, an average index for each of the four sources of vulnerability viz. demographic, climatic, agricultural and occupational vulnerability is calculated-

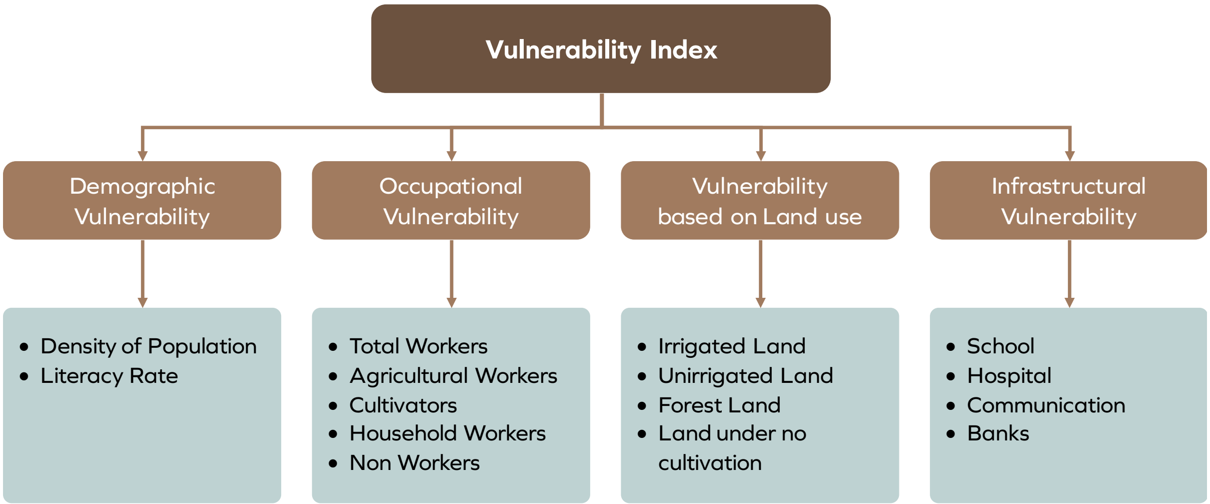
$$\text{Average Index}_i = \frac{[Indicator_1 + Indicator_2 + \ldots + Indicator_J]}{J} \qquad (2)$$

Finally, the aggregate index of vulnerability across all the sources of vulnerability sources is arrived at -

$$\text{Vulnerability Index} = \frac{\left[\sum_{i=1}^{n} (\text{Average Index}_i)^{\alpha}\right]^{\frac{1}{\alpha}}}{n} \qquad (3)$$

Where, J represents number of indicators in each source of vulnerability and n represents number of sources of vulnerability (in the present case n = **α** = 4)

Chart 1: Vulnerability from different sources



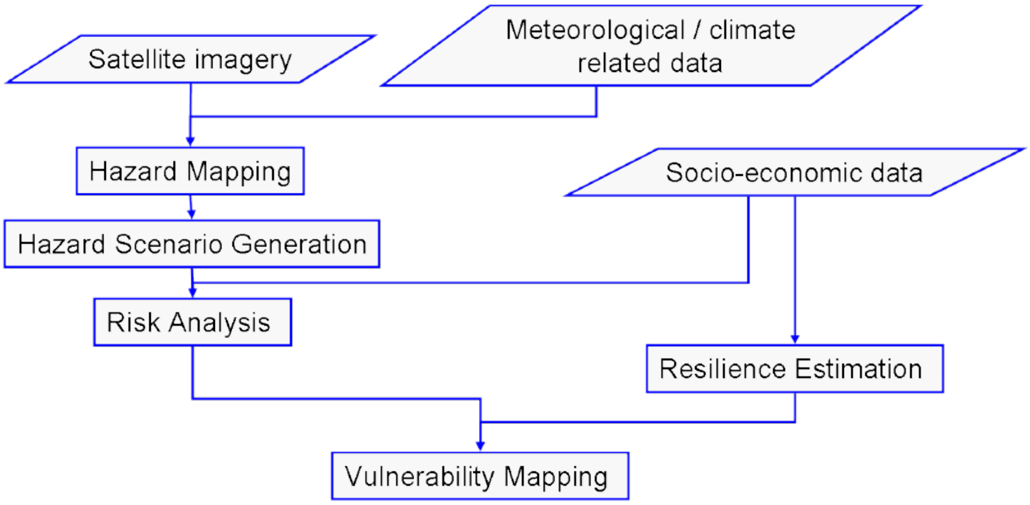
Further, we also used the GIS approach for linking the results of vulnerability index with the GIS approach. In this approach, vulnerability mapping is divided into three phases, namely, hazard mapping, risk analysis and vulnerability mapping. The inundation maps presented are mainly prepared based on elevation and sea level rise information. We have created three scenarios for the inundation maps. For the scenario-I only sea level rise information is used, whereas, scenario-II is generated with sea level rise and rainfall data (forecasted rainfall for 2021) from Indian Institute of Tropical Meteorology (IITM).

The forecasted information of rainfall is superimposed on scenario-I to arrive at scenario-II. This gives idea about increase in inundation level, if rainfall coincides the sea level rise along with the highest high tide of the area(s). Similarly, scenario-III uses forecasted rainfall information for the year 2071 from IITM. Please note that these maps are primary outputs as they are not considering the contiguity of terrain. Characteristics of inundation maps are presented in Table 1 and the snapshot of overall methodology of GIS approach is presented in Chart 2.

Table 1: Different scenario for inundation maps

Scenarios	Characteristics
I	Probable inundation maps are generated with the help of digital elevation model (DEM) and considering half meter inundation level from mean sea level.
II	Probable inundation maps are generated with the help of DEM and considering half meter inundation level from mean sea level along with rainfall information for year 2021 (simulated by IITM using PRECIS).
III	Probable inundation maps are generated with the help of DEM and considering one meter inundation level from mean sea level along with rainfall information for year 2071 (simulated by IITM using PRECIS) and highest high tide difference from mean sea level (MSL).

Chart 2: The Conceptual framework followed for GIS approach



3. Patterns of cyclone incidences and identification of vulnerable areas

For the Indian region, data on cyclonic events is available from 1877 to 1991. The source of data is the '*Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea*', a 1996 publication of Indian Meteorological Department. This data has been put in the GIS format. This data classifies the intensity of cyclones into three categories: Depression, Storm and Severe Storm. From 1971 to 1990, there were 261 cyclonic events in the Bay of Bengal and Arabian Sea. Of these 261 events, the number of cyclones that crossed the Indian coastline was 147. The rest of them either didn't cross the land or crossed foreign coastlines such as Bangladesh, Myanmar and Pakistan. Therefore they have been excluded from our dataset. Also, among those not included in our dataset (out of the 261 that are shown in the '*Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea*') are those depressions which formed on land and dissipated on land. Overall 7.5 cyclones pass yearly. From the data we can observe that the number of cyclones is highest for the state of Odisha compared to Andhra Pradesh and Tamil Nadu. When we look into the distribution of the three types of cyclones in three districts under study, we can see that from 1971-1990 there are ten cyclones that affected Kendrapara and Nellore whereas, Nagapattinam was affected by only one such event.

As mentioned earlier data from the census of India, 2011 is used for the calculation of the index. Computation of the index is one of the key strategies to arrive at the most vulnerable villages for each districts. As we can see, for Nagapattinam district, Tamil Nadu, most of the villages (around 212) fall in the range of 0.15-0.20. There are very few villages that fall that in the first category i.e. less than 0.05. Except for two villages, most of the villages in this district are identified as vulnerable. There are nine blocks in the district, and for each of the nine blocks, index is calculated and presented in a frequency distribution (Figure 1).

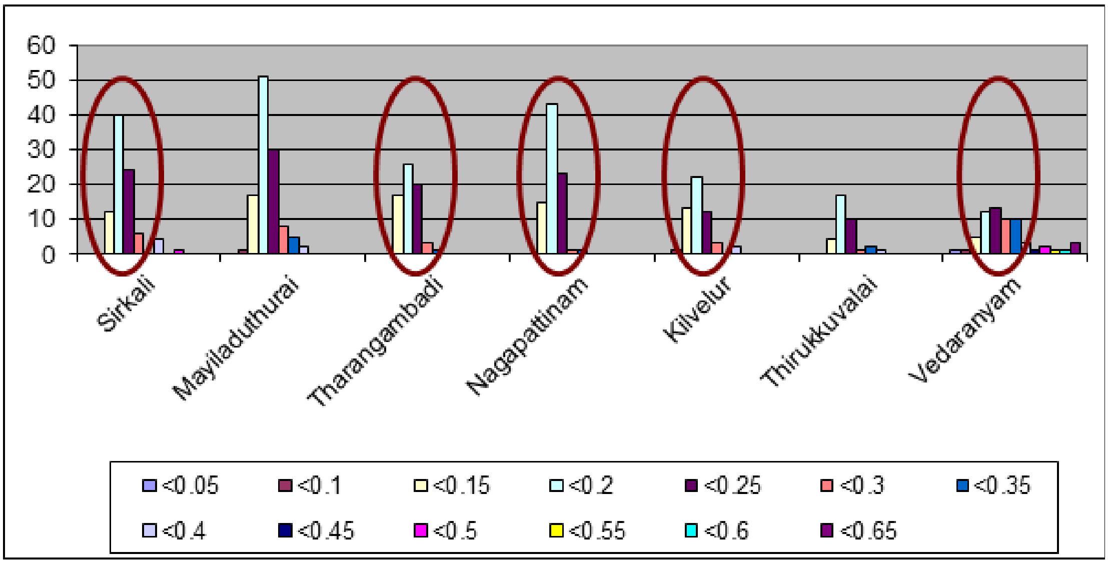


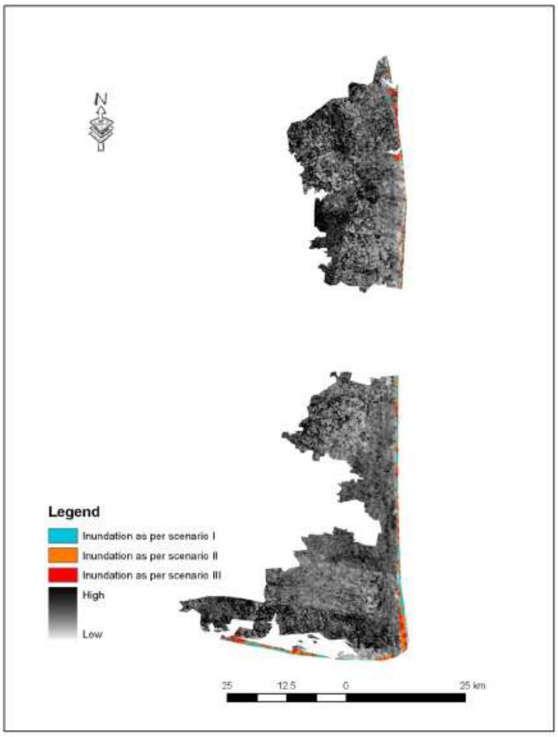
Figure 1: Socioeconomic Vulnerability – an inter block comparison in Nagapattinam District

Of the seven sub-divisions, five of them are on the coast - Sirkali, Tharangambadi, Nagapattinam, Kilvelur, and Vedaranayam. The inundation map prepared for Nagapattinam district (Map 1) is based on elevation information and information on increase in sea level. The vulnerability index and the elevation information go hand in hand and we arrive at the same block identified as most vulnerable ones.

Similarly, for the Nellore district in Andhra Pradesh, data set has information on 1110 villages. The villages were classified into three major revenue divisions following the classification given in the official district website. The inundation map for Nellore district is given in Map 2 and analysis of index is also carried out and presented in Figure 2.

The census has information of 1407 villages for Kendrapada district, Odisha. Identified vulnerable pockets are presented in Figure 3 and inundation map for Kendrapara district is given in Map 3.

Map 1: Scenario base on inundation for Nagapattinam district



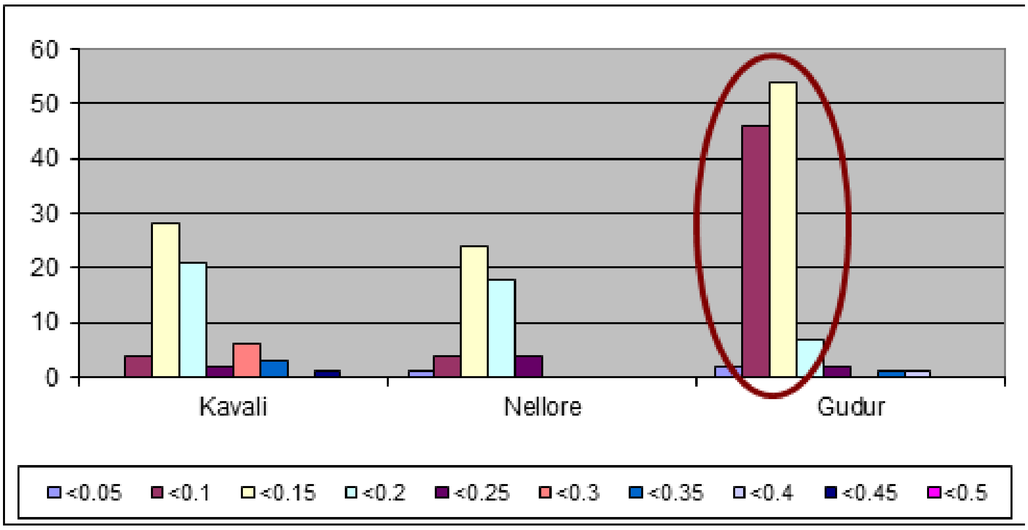
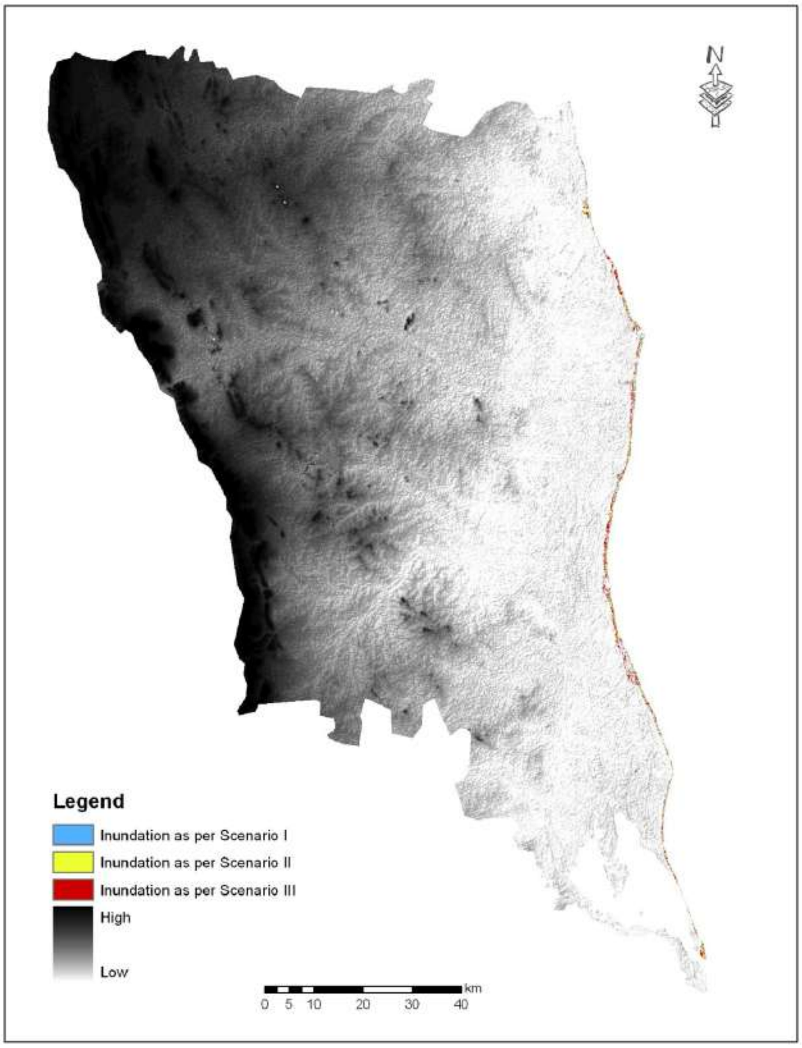


Figure 2: Socioeconomic Vulnerability: an inter block comparison in Nellore District

Map 2: Inundation map for Nellore



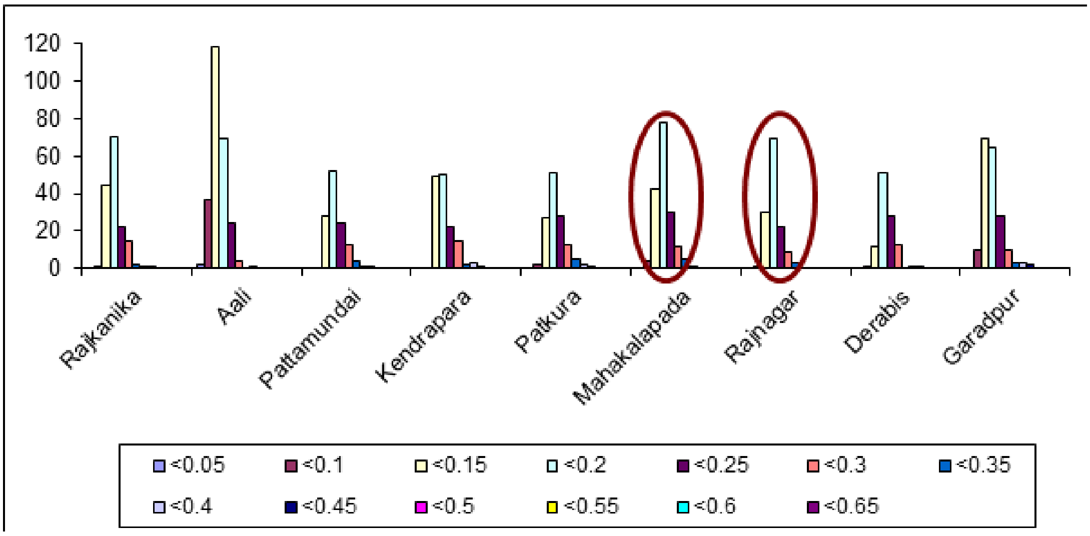
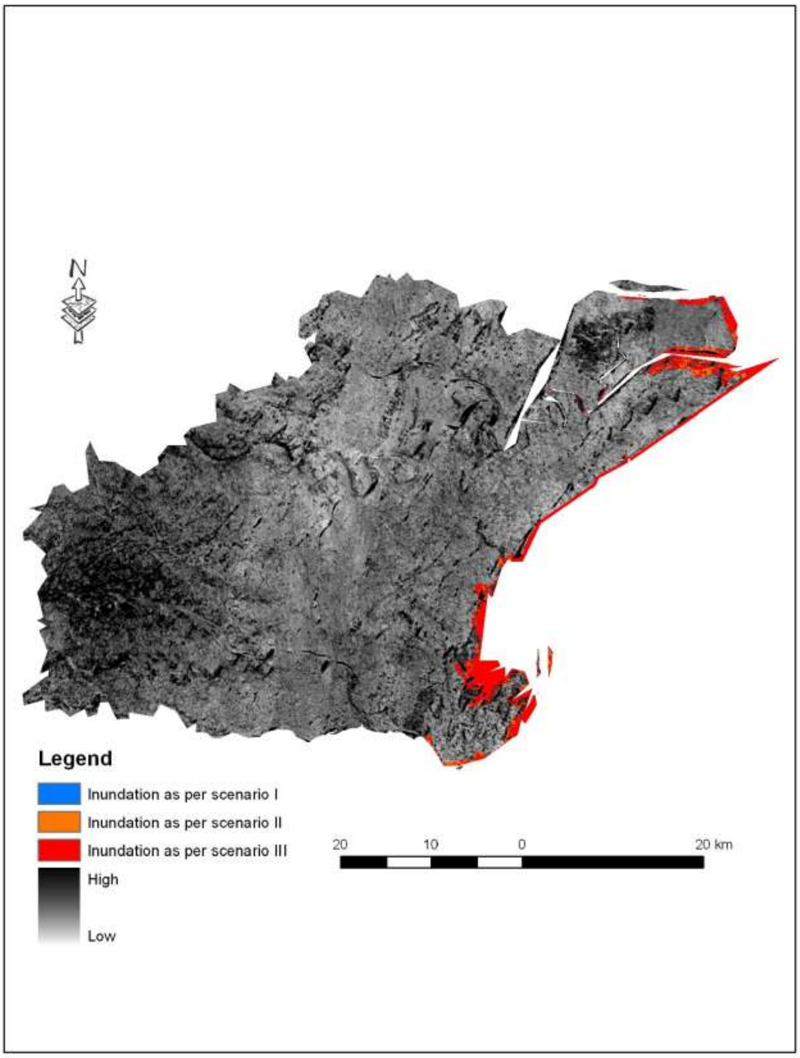


Figure 3: Socioeconomic Vulnerability: an inter block comparison Kendrapara District

Map 3: Inundation map for Kendrapara district



4. Issues and implications

Once the vulnerable villages are identified both from vulnerable index and from the GIS technique, the next step is to come up with relevant policy instruments for these regions. This research has linked statistical and GIS techniques in identifying who is vulnerable in the context of eastern coast of India. In attempting policy suggestions, information from focus group discussions, pilot and field surveys and discussions with the government officials and think tanks are used. The most important factors explaining the adaptive capacity and coping strategies for the vulnerable areas, and hence populations, are as follows:

1. Poverty has a direct link to vulnerability due to climate related hazards. From the primary data analysis it is concluded that in these regions the socioeconomic profile of the population is directly related to vulnerability both from income and climatic risks. Early engagement in informal job markets, lesser education, higher dropout ratios are highly related to the severity of vulnerability.

2. The major coping strategies of the inhabitants are found to be the help and support from relatives/friends. Given the fact that the people are poor and fight for the daily livelihood, they have no savings to cope such shocks. In many villages, the institutional support seems to be weak.

3. Transport and communication facilities are found to be weak in those villages under study, which has a compound effect on education, evacuation, and health related issues. Waterborne diseases, snakebites and skin diseases are found to be common during and after a disaster, often compounded due to lack of proper medical facilities after a disaster.

4. Dependency on agricultural land is one of the most important income generating activities of people residing in the sample villages. However, due to both income and wealth inequalities, most of the people depend on agriculture on sharing basis. As agriculture land is most sensitive to any climatic risks, it has direct influence on the household income that makes these regions and population more vulnerable to climate change.

5. The other economic activity in these regions are income from livestock and poultry. From the focussed group discussions it was observed that the population of livestock and poultry have reduced from last few years due to extreme climatic conditions. Hence, dependency on these economic activity has come down, which in turns make household worst-off economically and vulnerable to climate change.

6. Female headed households, illiterate households and below poverty level (BPL) households, are at higher risk compared to others. Conforming to well-accepted theoretical and empirical research (Blaikie et al., 1994), the current work too reveals that vulnerability to climate change cannot be separated from everyday vulnerabilities of populations deriving from a range of socio-economic, political, and cultural contexts and factors. Further as the IPCC assessment reports also emphasize (Oppenheimer et al., 2014), climate change poses not just key risks in the form of direct impacts, but are contributing to “emergent risks” as well, as outlined in the seven points above.

The study has identified various issues and urgent areas of interventions related to the eastern coast of India in connection with climate change impacts and vulnerability of population. Given the range of issues including identification of “who is vulnerable”, the Government of India and international agencies can use this information in designing more robust climate response, adaptation and vulnerability reduction policies.

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Impact of coastline changes on archaeological sites of India

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ABSTRACT

Archaeological and historical records indicate that several port cities, settlements along the Indian coasts have existed during its five millennia-old history, their prosperity supported by overseas trade and commerce. Ancient Indian literature has information on the destruction of coastal settlements, often expressed in religious beliefs and literature. Due to change in the coastline and sea level fluctuations, several ancient ports and settlements have either submerged in the sea like Bet Dwarka, Pindara, Poompuhar and Mahabalipuram or pushed far in the hinterland such as Harappan sites along the Gujarat coast. This study is an attempt to trace the ancient coastline of India based on archaeological and historical accounts. Such records indicate fluctuations in the coastal environment over periods of human history.

1. Introduction

The dawn and evolution of human society in the past, present and future is directly connected with ocean systems. Studies on marine prehistoric Archaeology have provided ample information on how early man lived on the continental shelf during the various ice ages in Pleistocene period as the eustatic sea level was over 100 metres lower compared to the present times. Research in these areas have yielded the remnants of stone tools, bones, fireplaces, food remains and cut timber from 5000 to 1 million years BP off the coasts of South Africa, Japan, Australia, North America and many European countries (Flemming, 2004). The spread of humanity throughout the globe has been influenced by the exploitation of the continental shelf during glacial phases, by the use of coastal food resources, and by the effect of changed migration routes, connected land masses, or channels which were easier to cross. The coastal habitations have been severely affected due to change in the coastal environment which include long term changes and some extreme events like cyclones and tsunamis.

Coastal areas of the continents have been the focal points of the emergence of civilisation. For instance, the Indian Ocean witnessed the rise of three major Bronze Age Civilisations around it, during the mid-Holocene period. Oceans have played a crucial role by providing food security and water routes for overseas trade and commerce. However, historic sea level fluctuations have played a significant role in the coastal settlements. Various studies have indicated that the shoreline and sea level have never been static. Several researchers in India too have studied sea-level fluctuations along the west coast of India (Agrawal, et al., 1973; Nair, 1974; Gupta, 1977; Bruckner, 1989; Gaur and Vora, 1999; Rao, et al., 2003). There are well-defined observational data on quaternary sea level oscillations. However, these researches are based on geological proxies such as study of corals, limestone, foraminifera and other marine organisms. Also, these studies focus on a large time frame and consequently have high degree of error bar due to paucity of data, with different methods in measurement of date due to various factors.

It is now generally agreed that glaceo-eustatic sea-level stood higher than the present in and around 6000 yrs BCE (Katupotha and Fujiwara, 1988; Erinc, 1978; Pirazzoli, 1991). During the mid-Holocene, the Indian Ocean witnessed the rise and full-scale development of three major civilisations- Mesopotamian, Egyptian and Indus Valley.

Many archaeological sites with evidence on maritime activities either from excavations or from literary references were important port towns during their heyday (Figure 1). Over time, they either got submerged or are now land-locked due primarily to siltation, though sea level change and tectonic activity also may be important at times. Such sites provide vital clues with dates to infer the shoreline changes in the recent past.

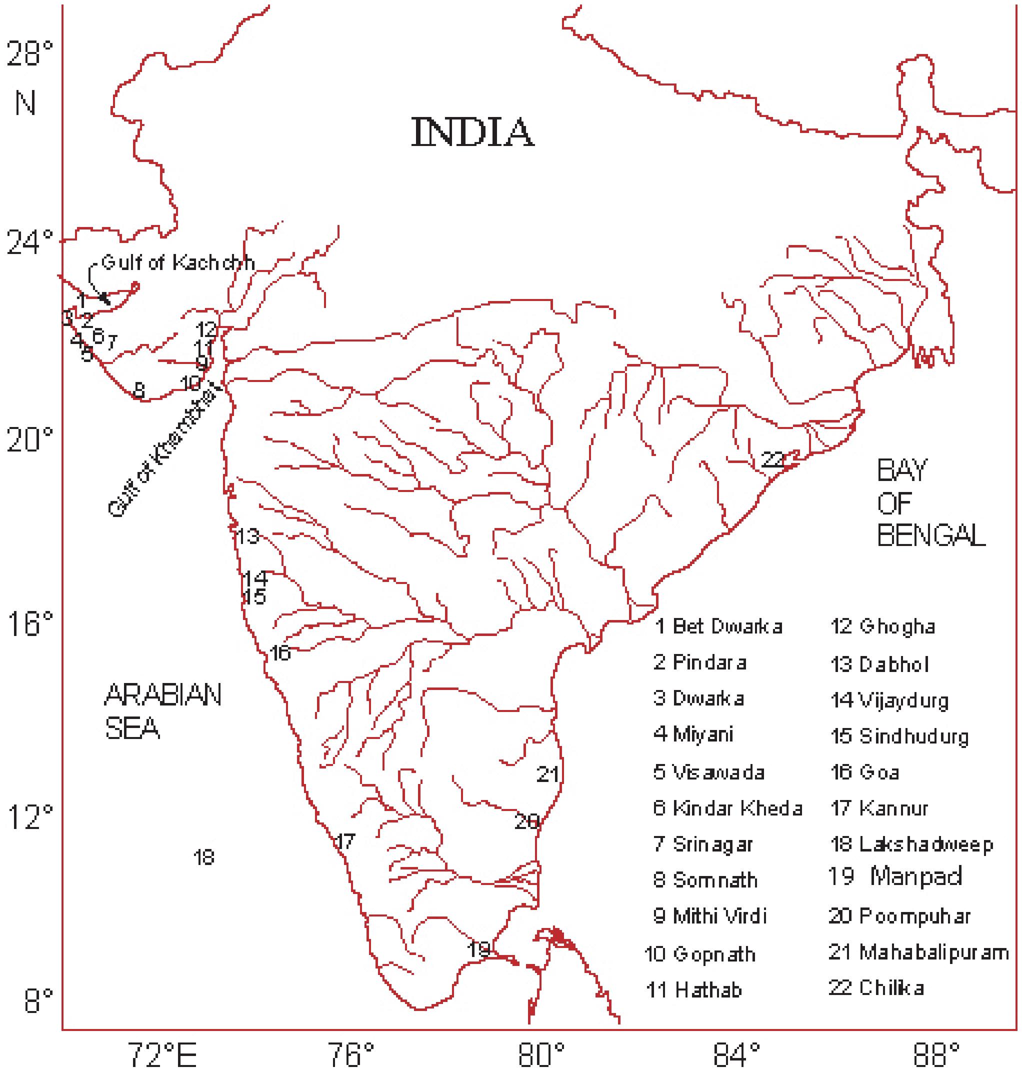

Figure 1: Major archaeological sites along the coast of India

2. West coast of India

The ancient coastlines particularly of the Pleistocene and Holocene of Gujarat have been well recorded on the basis of geological formations and at least two higher strandlines were recorded +20 m and +6 to +10 m dating back to the Pleistocene and Holocene respectively (Patel, 1991; Merh, 1992). The changes in the coastline of Gujarat have also been studied earlier on the basis of archaeological findings (Gaur and Vora, 1999). It suggests that the sea level was higher during the mid Holocene period. On the east of Pindara there are 3 small port towns of Harappan period (Rao, 1991a), namely Amra, Lakhabawel and Vasai. These are located along the backwater region. However, at present tidal water is not reaching up to the site. This indicates a higher sea level during the Harappan times (Gaur and Vora, 1999).

Archaeological evidence such as settlements on the islands and exploitation of marine resources from Kachchh suggest that maritime activities began a little earlier than the Harappan civilisation. A group of people migrated from the Sind area called Amri culture, to Kachchh around 3000 BC and settled in northern Kachchh area. Several sites of Indus Valley Civilisation are within 20 km from the present shoreline. These are believed to be the ancient ports or centres busy in exploiting the marine resources and suggest migration of shoreline. Several studies have reported changes in sea-levels and shoreline migration with particular reference to the Gujarat and Maharashtra coasts (Merh, 1992; Patel, 1991; Agrawal et al., 1973), and suggested a sea level during mid-Holocene Period between 2 and 6 m which is higher than the present. Much of the evidence has been based on ^{14}C dating and morphological features and lithologies.

Archaeological data suggesting maritime practices are used as an indication for palaeo-shoreline of Gujarat. Examples from archaeological sites belonging to the Harappan period such as Lothal, Padri, Bet Dwarka (Figure 2) and others have been cited to indicate shoreline movement in the last 4500 years. Excavations at Lothal have brought to light a Persian Gulf seal, terracotta models of an African mummy, guerrilla and boat model, demonstrating the maritime practices and relations with Mesopotamia and Egypt between 5000 and 4000 yrs BP. There is a massive brick structure identified as dockyard by the excavator (though others dispute the claim) and some pursed stones (suggested as anchors) found in the vicinity suggesting that Lothal was an important maritime Harappan trading centre. Lothal, therefore, can be considered a clear evidence of offshore- ward movement of shoreline. Indications from other archaeological sites are also discussed to configure shoreline movements during the last 4000 years.

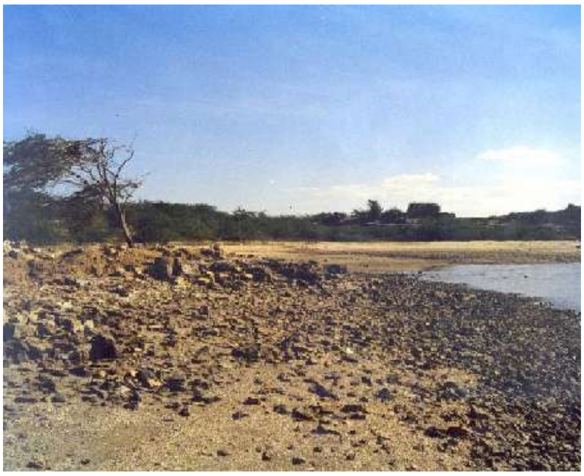

Figure 2: An archaeological site, exposed during Low tide in Bet Dwarka Island

2.1 Rann of Kachchh

The Great Rann and Little Rann are unique examples of Holocene sedimentation. The two Ranns represent filled-up gulf and mark the site of accumulation in an estuarine delta environment that was marked by a fluctuating strandline since the advent of Holocene. According to Gupta (1977), the Holocene sedimentation of the Little Rann and Nal Lake were contemporaneous. The lowermost sandy clay horizon extends from about 9000 yrs BP to about 4200 yrs BP overlain by the silty clay horizon dating from 4200 to 1500 BP and then again by the most recent silty clay horizon. He further suggested that even as late as 2000 yrs ago, Little Rann was about 4 m deep and thus was inundated throughout the year. Another important factor of shifting of the shoreline may be due to tectonic effect. Recent studies on sea-level changes suggest that neo-tectonic activity had also played a vital role in sea level fluctuations, particularly in Saurashtra and Kachchh region, during the Late Pleistocene/ Holocene. Studies on sea-level along the Mumbai coast (Rao, 1996) suggest that until 8300 yrs BP, shallow sea-level conditions prevailed on the carbonate platform located at about 80-90 m depth off Mumbai. This is in contrast with the glacial eustatic sea-level position which was at about 22 m at 8300 yrs BP.

The British explorers during the late 18th and 19th century vividly described the features of the Rann of Kachchh. They have also recorded various traditions indicating the Rann as an extended sea in the past and mentioned names of a few villages on both sides (north and south banks) of the Rann as prosperous port towns. There are three prominent hypotheses regarding the palaeo-morphological conditions especially during the Harappan times, namely: a) a former arm of the sea which has been raised due to a series of tectonic activities (Frere, 1870, Platt, 1962, Krishnan, 1968, Wadia, 1975; Roy & Merh, 1977), b) Rann as a delta region of the Indus and other rivers and present change in morphology is due to tectonic disturbance of 1819 (Wynne, 1812), and c) similar conditions are prevailing at least since the 3rd millennium BC (Joshi, 1990).

Archaeological investigations in Kachchh demonstrate the existence of a prosperous dynamic society during the Harappan times. Though the Harappan civilisation was supposed to be an agrarian society, Kachchh does not offer good cultivating land for an advanced society like Harappan; thus the colonisation of Kachchh by Harappans could have been for other reasons than the agrarian. Bisht (1989) observed "Kutch does not fulfil requisite qualifications to be an advanced agrarian state. It becomes, therefore, all the more imperative to comprehend the palaeo-climate as well as an ergonomic mechanism so that the palaeoenvironmental conditions and land-man relationship existing in the Indus times are understood better." Regarding the agricultural products during the early 19th century, Macmurdo (1920) mentions "Cutch does not produce (grain) one-half sufficient for its consumption. Grains of all kind imported, some from Hullar or the Peninsula Guzarat and others from Malabar or from Sindh" Thus it is very clear that Kachchh has never been an attraction for the agrarian society; instead they have been considered as great mariners and successful businessmen. The recent study on the source of various kinds of stones and metal by Law (2008) indicated that Gujarat and Kachchh region has been the major source centre of limestone, agate, lead etc. The large-sized limestone rings discovered at Harappa and many other sites might have transported from Khadir or Pachchham islands in the Rann of Kachchh. Sometimes the weight of these stone is as high as 100 kg; thus there is a possibility that the sea and riverine route might have been easier for such transportation which could have been approached by crossing the Rann.

There is an interesting tradition recorded by Frere (1870) about Verawow as an ancient port which says "more than 800 years ago, at that time sea-going ships came with ease to the immediate vicinity of the present town (Verawow), and they still show the stone posts to which the ships were moored, when the present edge of the sand-hills was washed at every tide by the waters of the sea. They (local merchants) add, that in consequence of the progressive shoaling of the water, a great portion of their community migrated 300 of 400 years ago to Mandavee (Mandovi), in Cutch as a more convenient spot for sea-borne commerce, and that since that time the water near Verawow has gone on shoaling, till now it is several generations since any sea-borne ships have been near their ancient port."

Morphological changes in lower Sind has been so significant that the river Indus has moved several kilometres westward (Flam, 1999) which affected the dynamics of the Rann of Kachchh during historical times. Earlier studies of coastal Harappan sites along the Saurashtra region indicated significant change in coastline in the Gulf of Khambhat region (Gaur and Vora, 1999). There are two very important factors responsible for morphological changes of the Rann of Kachchh: tectonic activity and sea level fluctuation. Kachchh is well-known area as seismically highly active zone and many severe earthquakes recorded recently. From archaeological records, at least three earthquakes have been recorded in the past during the Harappan times (Bisht, 2011).The final earthquake led the abandonment of the Harappan settlement sometime around 2100 BCE, and it was reoccupied after a few decades by the late Harappans. However, there are very few late Harappan sites noticed in the Kachchh area which also indicates that people might have shifted towards Saurashtra region (comparatively safer from earthquakes) and perhaps because of this reason, a large number of late Harappan settlements have been observed in Saurashtra region.

The study of digital elevation map suggests that in case of rise of sea level of about 5 metres, both Ranns get a water depth 3-5 metres whereas Little Rann and Gulf of Khambhat come closer to each other. As mentioned earlier, the area is a highly sensitive zone concerning tectonic activities, thus elevation and subsidence of land is expected to have happened in the past and based on archaeological evidence, it may be postulated that both Ranns were navigable in the past (Gaur et al., 2013).

3. East coast of India

The east coast of India is punctuated with several rivers which mostly originate from the Himalayas or the Western Ghats. This coast also witnessed the rise of several ports in the past such as Tamralipti (Tamluk), Dosarne (Dhauli), Kainapara (Konark, Palura (Gopalpura), Kalingapatnam, Vengipura (Peddavegi), Maisolia (Machilipatnam), Kadal Mallai (Mahabalipuram), Mylapore, Poduke (Arikamedu), Kaberis (Kaveripatnam), Colchi (Korkai) and Comari (Kanyakumari). However, our fieldwork is limited to Tamil Nadu coast and the focus remained at following two locations.

3.1 Poompuhar and Tranquebar

Silapathikaram an ancient Tamil text of Sangam literature vividly describes the port town of Poompuhar (Pillai, 1989). It says that Poompuhar (Kaveripatnam) covered an area of 4 Kavatham (approximately 30 sq miles) and its boundaries extended up to Karuvendanathapuram and Kadarankondan on the west, Thiru Kadavur on the south, Kalikamur on the north and sea on the east. It encompassed 30 villages and could boast of 60,000 families (Rao, 1991b).

The legend of Kovalan, the merchant, and his devoted wife Kannagi, who was enraged by the most unjust beheading of Kovalan by the Pandyan king at Madurai, has given rise to the Kannagi Cult and Poompuhar has became a place of pilgrimage. The tragic events form the main story of the epic Manimekhalai. According to Manimekhalai the port city was submerged by the sea as a sequel to the wrath of Indra whose festival the inhabitants failed to celebrate (Nandkumar, 1989).

The archaeological explorations at Poompuhar and Tranquebar demonstrate that the sea has gradually encroached into the land to a great extent since the last 2000 yrs (Sundaresh, et al., 1997). It is worth mentioning here that, the Kannagi statue installed in 1973 on the shore of Poompuhar about 200 m away from the high water line was shifted about 150 m landward in 1994 because the base structure was destroyed by the sea showing the extensive coastal erosion. Similarly, other monuments at Poompuhar were also destroyed by the sea (Figure 3). The factors responsible for land erosion may include construction of several dams along the course of River Kaveri since 1900 AD for irrigation and hydro-electricity. Rivers usually discharge a significant amount of land-driven detritus, especially sediments, into the sea, thus maintaining a dynamic balance between the coastline and the sea. Today, the influx of sediment into the sea by Kaveri has been reduced to negligible amounts due to the dams, resulting in a disturbed natural balance. The human-induced disturbance appears to have withdrawn the natural resistance to the waves. Subsequently, the sea began to erode the coastine, leading to submergence of several ancient coastal structures of Poompuhar.

Figure 3: Brick structure in inter tidal zone of Poompuhar

At Tranquebar, which is situated 15 km south of Poompuhar, there is a clear indication of coastal erosion from the last 300 yrs. The remains of Dutch fort found in the inter-tidal zone and location of southern bastion of the fort was protecting the present Dansborg museum, but there is no barrier protecting the temple, causing great destruction. Thus, ancient habitation sites are being damaged by the wave action because there is no proper protection for them. While the immediate cause of coastal erosion is the removal of sand from the beaches that results in destabilisation and destruction of coastal structures (Figure 4), the ultimate cause needs to be addressed.

Figure 4: Evidence of coastal destruction along the Tranquebar coast

Bay of Bengal, whose western boundary is formed by the east coast of India, is a rather unusual sea. The Bay of Bengal is subject to a large number of high-intensity cyclones compared to the Arabian Sea. Cyclones are short-lived phenomena, capable of causing immense amount of destruction when they cross the sea and make landfall. The destructive power of cyclones at present and in the past along the coast of Chennai, Andhra, Odisha and Bangladesh is sufficiently well documented.

The next geological peculiarity that can contribute to coastal erosion is the narrowness of the eastern continental shelf. This shelf is less than 50 km in width, in contrast to the western shelf which is a few hundred km wide. Wave propagation over a narrow shelf results in low frictional loss of energy and thus expends much energy on the coastline, causing a great degree of coastal erosion.

Superimposed on these factors is the net rise in global sea level. Recent evidence from the west coast of India and widely scattered regions such as Florida on the Atlantic coast of the U.S. indicate episodic and rapid rise and fall of the sea level. The rates reported are about a metre per century over a time period of 500 to 1000 yrs. These findings have now dispelled the notion that sea level is a stable and unchanging datum. The inference drawn from the above is that during a period of rising sea level, the zone of erosion shifts landward (submergence), and during a fall in sea level, the zone of erosion shifts seaward, resulting in seaward progradation of land. An example of this is the location of the ancient port cities at Korkai and Algankulam in south Tamil Nadu coast which are far inland now, but which were patently designed and located to be on the shoreline.

4. Catastrophic Events

4.1 Ancient Tsunamis

Tsunami is a Japanese word meaning “harbour waves”. Tsunamis are shallow-water waves, and therefore, like tides, they move in the open sea at very high speeds. Tsunamis are caused by a large-scale perturbation of the ocean floor. Tsunamis are rare in the Indian Ocean: only 0.8% of Tsunamis are recorded in the Bay of Bengal. Most tsunamis have been recorded in the Pacific and submarine earthquakes are the major cause. Recently, on 26 December, 2004, an earthquake of magnitude 9.3 (Richter scale) occurred off the coast of Sumatra, Indonesia. This triggered the devastating tsunami that killed over 300,000 people in Indonesia, Sri Lanka, India, Thailand, Myanmar and Somalia, making it the biggest killer Tsunami on record. Signatures of the tsunami were recorded by tide gauges in India and in several other countries.

Coastlines in the Indian subcontinent region are sometimes subject to rapid change. Conventional geological features available along the coastal areas are used to understand the causes and recurrence intervals of rapid coastal changes, but many times these features have not always proved adequate to identify such incidences as the evidence for these is obscured by later coastal changes, making it difficult to understand how it has impacted coastal societies and ecosystems at particular times.

The historically known sources of Tsunamis off the coast of the Bay of Bengal are the Andaman–Sumatra subduction zone and off the Arakan coast of Myanmar (Rajendran et al., 2007). The former is known to have generated a few large earthquakes during recent and historic times. Among the earlier earthquakes, only those in 1881 and 1941 are significant (Bilham et al., 2005; Rajendran et al., 2007). The 1881 earthquake caused a tsunami surge that reports say did not exceed 0.75cm at Car Nicobar (Rogers, 1883). Another large earthquake is reported from the middle or north Andamans, which occurred on January 28, 1679 and also appears to have been non-tsunamigenic (Iyengar, et al., 1999). An earthquake also occurred off the Arakan coast of Myanmar (Burma) on April 2, 1762 (Oldham, 1883; Chhibber, 1934). During this earthquake, the Arakan coastal tract was elevated by 3 to 6 m, and the rupture resulted in a tsunami that affected the coast of Bengal, including the cities of Kolkata (formerly Calcutta) and Chittagong. The 1883 eruption of Krakatau also generated a tsunami that registered nominally on tide gauges in Tamil Nadu (Ortiz & Bilham, 2003; Pelinovsky et al., 2005). The available historical records, therefore, show that the December 26, 2004, event had no known historical precedent in the region in terms of its magnitude, rupture length, or tsunamigenic potential. Geological studies from the Sumatran and the western Thailand coasts, however, suggest palaeo-tsunamis in the Indian Ocean during A.D. 780–990 and A.D. 1290–1450 (Jankaew et al., 2008; Monecke et al., 2008).

The impact of 2004 Tsunami on the Tamil Nadu coast prompted geophysicists to investigate some of the known historical sites namely Kaveripoompattinam (Rajendran, et al., 2011) and Mahabalipuram (Rajendran et al., 2006). The findings are summarized here to help understand the role of Tsunami in destruction of ancient coastal habitations.

During the excavation at Saluvankuppam near Mahabalipuram (Mamallapuram), two anomalous layers were observed. Both layers occur as discontinuous patches of varying thickness (Rajendran et al., 2006) and their laminated structure with embedded brickbats, suggests deposition under turbulent conditions. The date of the upper layer is between AD 1019-1161, whereas that of the lower level is AD 321-427. The researchers (Rajendran et al., 2011) concluded that at least two large events of vast coastal flooding at this site must have occurred around AD 320-560 and AD 950. The 2004 tsunami inundation data suggests that a previous tsunami of similar size could have reached 800 m inland and damaged many of the man-made, near-sea structures of weak foundations located on a previously extended coast. That the 2004 tsunami exposed the older temple sites along the Mamallapuram beach implies that a similar size tsunami in the past could have scoured the temple foundations. Like the one at Saluvankuppam, temples built on sand are more vulnerable to the scouring action of the tsunami than those built on rock outcrops.

Similarly, the investigation by the scientists around Poompuhar coast yielded the remains of a palaeo-Tsunami. Rajendran et al. (2011) state that 'a tsunami event layer at Kaveripattinam has been identified on the basis of sedimentary characteristics whose age has been constrained by OSL (1091±66 yr) and TL methods (993 ±73 yr). The OSL date of the inferred tsunami sand and the TL date of embedded pottery sherds along with the archaeological context of the event layer support our contention on the Chola-period tsunami on the Indian coast. Our studies suggest that this implicated event is a high-intensity tsunami that inundated deep into the then-existing coast'.

4.2 Cyclones

The Bay of Bengal is one of the major centres of the world for breeding of tropical storms. Cyclones over the Bay of Bengal usually move westward, northwestward, or northward and cross the east coast of India or Bangladesh. They bring strong winds and high rainfall to the coastal region, causing loss of life and damage to property.

Compounding the damage is the occurrence of a "storm surge" that often accompanies a storm. The surge is primarily piling up of water due to the strong winds. This raises the mean water level in the coastal zone, whose magnitude is dependent on the strength of the winds. It is not unusual for this rise to be a metre for many cyclones, and 2-3 metres for major cyclones. With mean water levels elevated, and with strong winds generating high waves, storm surges lead to immense loss of life and property. The supercyclone of October 1999 caused a loss of over 10,000 lives and huge property loss in Odisha. Of the 34 reported storm surges with loss of life of 5000 or more around the world, 26 have occurred in the Bay of Bengal. A storm surge in 1970 in Bangladesh caused 500,000 deaths. The rather flat topography of Bangladesh makes it particularly vulnerable to storm surges.

The oldest tropical cyclone – also the first palaeo-event in the catalogue – is derived from geological data and dates to approximately AD 1000, and affected the North Cinque Island located south of the Andaman Islands (Kunz et al., 2010). The oldest historical tropical cyclone (also the second oldest event listed) dates to AD 1484 and is reported to have affected the Chittagong coast (Hasan, 1999). The large time gap between these events is significant because it hints at the probability that many more tropical cyclones remain to be identified within the region's historical and geological records. Even though India has a long civilisation and history, its historical records are poorly preserved (Majumdar, 1877; Hoxie, 1988; Murthy, 2011).

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Alam and Howes (2015) in a review article presented a new tropical cyclone catalogue containing 304 events occurring between AD 1000 and AD 2009 in the northern Bay of Bengal. They opined that the temporal extent of the events listed goes well beyond the existing local (i.e. BMD, SPARSO) and regional tropical cyclone catalogues (i.e. IMD). This hints that more tropical cyclones can be retrieved from the region's archive records. In collecting and reviewing tropical cyclone data contained within the documents and sources, significant challenges were noted and discussed. From the multiple sources of documents, they could report only 28 and 127 tropical cyclones prior to AD 1800 and AD 1900, respectively. However, after AD 1900, 277 tropical cyclones were recorded. According to the authors, 'the lack of tropical cyclone data prior to AD 1000 and the few records between AD 1000 and AD 1900 cannot be used to infer non-occurrence or low frequency during this period'. The destructive nature of cyclones and storm surges on archaeological sites is yet to be studied though it is well known that storm surges can increase erosion.

Conclusions

We know that ocean is continuously changing its vertical level and horizontal expansion. Any change in environmental condition of the coastal areas directly impacted the development of human society. There has been remarkable awareness due to recent extreme events such as Tsunami and cyclones. During the 2004 Tsunami, over 2 to 3 million people were affected and over half a million lives were lost along with loss of billions worth of property. Archaeological investigations at two archaeological sites on the east coast (namely Mahabalipuram and Poompuhar) brought to light the remains of ancient Tsunamis/ floods which might have destroyed ancient settlements and the vivid description of one such event is found in an ancient text, Manimekhalai. Similarly, cyclones too might have caused destruction of many coastal settlements in the past.

During the Harappan period, the Rann of Kachchh was the extension of the Arabian Sea and was navigable. The environmental conditions around it must have been different than those prevailing today. Otherwise, it is very difficult to explain the existence of so many mature Harappan fortified towns along the Rann of Kachchh which is the least populated place in the subcontinent. The exact reasons for changes of this type are debatable. Many of them are attributed to the series of tectonic events which uplifted the base of the Rann resulting in preventing the Arabian Sea from being able to encroach into it. Other important aspects responsible for sea dynamics in the recent times are human driven such as construction of dams on the rivers and several developmental constructions along the coastal area. From a situation where rivers discharged millions of tons of sediments annually into the sea, today there is very little sediment discharge into the sea which has resulted in the sea starting to encroach into land wherever possible.. Past global sea level fluctuations have been natural processes and have been associated with global temperature fluctuations which might not be associated with human disturbances. However, the growth of the human society was affected largely due to change in sea level. Thus, any development that is planned along the coastal area must take into account the dynamics of the coast.

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Coastal **Sensitivity**


SBE

6

Monitoring and assessment of coastal water quality along the Indian Coast

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ABSTRACT

Coastal areas have been centres of human activity for millennia. Though coastal regions contain some of the most vulnerable and fragile ecosystems, they are the sink and often the dumping grounds for a wide range of contaminants. Like most coastal regions of the world, coastal areas of India are densely populated, and ~30% of its human population is dependent on coastal and marine resources. Monitoring programmes for protection and management of coastal resources have not explicitly included consequences of climate change. This chapter looks at the 25- year- old coastal monitoring programme in India and suggests new approaches for monitoring the coastal waters has been proposed in the light of the rapidly changing climate.

1. Introduction

Coastal regions are unique and dynamic ecosystems as they are at the interface of atmosphere, terrestrial and aquatic systems. This interaction creates a wide variety of complex habitats which host a rich biodiversity, energy and mineral resources. Although coastal ocean covers only ~10% of the total area of the ocean, it accounts for 30% of the primary production, half of the carbonate burial and most of the burial of organic carbon (e.g. Gattuso et al., 1998; Liu et al., 2000; Muller-Karger et al., 2005). Coastal ecosystems also recycle nutrients, filter pollutants, and help to protect shorelines from erosion and storms (Burke et al., 2001). It is estimated that coastal systems provide important ecological and economic services (Costanza et al., 2014) in the form of coastal protection, fisheries and other living and non-living resources. This has made the coastal areas centres of human activity for millennia. It is not by chance that virtually all of the world's major cities are located on coasts and an estimated ≈50% of the world's population lives within the coastal regions (Sharpe, 2005).

Unfortunately, though coastal regions contain some of the most vulnerable and fragile ecosystems, they are sinks and often the dumping grounds for a wide range of contaminants. The world population is estimated to increase to 11.2 billion by 2100 (www.un.org). The rapid industrialisation along the coastal regions to meet the needs of the increasing human population are stressing the earth's ecosystems; as a result, no area remains unaffected by humans and, a large fraction of the ocean ecosystem (41%) is strongly affected by multiple drivers (Halpern et al., 2008). Therefore, the gradual deterioration of various ecosystems across the globe and the failure of several marine ecosystems to recover even after the cessation of disturbances have resulted in a growing demand for comprehensive and comprehensible ecological assessment.

Like most coastal regions of the world, coastal areas of India are densely populated and, ~30% of its human population is dependent on the coastal and marine resources. Due to the rapidly growing population and subsequent industrialisation, most parts of the coastal waters of India have become modified to some degree so that there are unlikely to be many pristine sites along the coast. In addition, climate change may interact with others stressors resulting in either positive or negative consequences on different coastal habitats. Therefore, human disturbances coupled with rapid climate change may result in biodiversity decline affecting the ecosystem services.

It has been long recognised that long-term research, which includes monitoring programmes, are critical for understanding and managing the complex ecosystem (Lindenmayer & Likens 2009). The increasing degradation, as well as depletion of various resources, has prompted for an integrated approach towards sustainable management of these ecosystems. As a result, many countries initiated monitoring of their coastal water quality for protection and management of these resources. Historically, ecosystem monitoring programmes have been based on the presumption of stable climate. Since most monitoring programmes were initiated several decades ago, climate-change was not explicitly included in most monitoring programmes. Although, the reasons, and consequences of climate change have been debated over the last two decades, there is now scientific evidence and consensus that climate change is largely man-made. However, much remains to be understood of the Earth's complex climate. As a result of the growing recognition of the potential threat of climate change to the ecosystem, it is necessary to understand these changes and include this aspect in monitoring programmes.

In view of this, this Chapter briefly outlines the complexity of the Indian coastal system and likely threats to the coast, followed by some results of the coastal monitoring programme in India. Based on the experiences gained in the last 25 years in coordinating the monitoring programme, new approaches for monitoring the coastal waters is proposed in the context of rapid climate change

2. Sources of Pollution to the Coastal System

India is the world's tenth most industrialized nation and with a population of more than one billion people, is one of the fastest developing regions of the world. Three of the four megacities (Mumbai, Chennai and Kolkata) and several industrial cities are located on or near the coast (e.g. Jamnagar, Kochi, Visakhapatnam, Paradip, Haldia). Contaminants in the coastal and marine environment are mostly directly from the land-based sources. Pollution caused from disposal of sewage, industrial wastes and agricultural runoff are the major environmental concerns in the Indian coastal waters. There are about 490 large and medium scale industries located along the coast. In addition, a number of small scale industries are located in most coastal towns and cities. Nearly 8000 industries release their effluents into the coastal waters either directly or indirectly. Further, it is estimated that about 390 million tonnes of industrial effluents are discharged into the coastal waters. Additionally, 1600 million tonnes sediments end into the coastal waters from various sources.

The population of India increased from 870.610 million in 1990 to 1.311 billion today. India's present population accounts for 17.84% of the world population and a UN study predicts that India will surpass China by 2022 to become the most populous nation. The country will have to further increase its production to meet its present and future needs. Rapid industrial growth can further increase the pressure on the environment. During 2015, the estimated sewage generated from domestic sources was about 61754 Million Litres per Day (MLD) of which only 38% was treated (CPCB, 2016). Moreover, the use of pesticides to enhance agricultural productivity appears to be increasing every year which is ultimately washed through runoff into the coastal regions. Coastal structures, solid waste dumps, salt pans, coconut husk retting, aquaculture, tourism and disposal of wastes from fishing industries, trawlers and small ships are other sources of pollutants to the coastal system. It is estimated that aquaculture ponds discharge 3 million litres of waste water per year into the coastal waters.

The maritime route remains the most important mode of transport for intercontinental trade and a large number of countries, including India, are increasingly dependent on the Indian Ocean for their foreign trade. Maritime traffic has increased drastically in the last two decades, thus increasing the risk of pollution associated with these activities. A study shows that about ~70% of the total sea transport is ferried through the Indian coastal waters (Anon, 2003). Oil pollution is major threat to the Indian coastlines as two main oil tanker routes pass through the Arabian Sea and Alang, the largest ship breaking yard, is also located along the Gujarat coast. In addition, residual oil in the coastal and marine waters forms tar balls due to the physical, chemical and biological processes. During monsoon, these tar balls are deposited on the shore, making beaches unusable, affecting tourism. Further, cleaning of tar balls is difficult as mechanical cleaning can affect the intertidal organisms. Unplanned industrial growth to meet demands of growing populations will further increase pressure on environment. In most coastal regions, waste management strategies have failed to keep pace with rapid industrial growth and urbanisation. Therefore, pollution through both domestic and industrial wastes, either as point or extended sources, along with poor management plans is affecting the quality of coastal waters.

3. SWQM Programme: Monitoring Coastal Waters of India

3.1 Background

In view of the increasing pressure on the coastal system, the Ministry of Earth Sciences (MoES) formerly, Department of Ocean Development (DOD), initiated a nationally co-ordinated monitoring programme, "Coastal Ocean Monitoring and Prediction System (COMAPS)" in 1990. The primary objectives of the programme was to (i) monitor water quality parameters periodically in selected locations in the coastal waters of India and (ii) develop possible prediction of sea water quality in these selected locations to assess the state of marine environment and to take remedial measures for minimizing the adverse impacts of the pollutants on the marine ecosystem and its resources.

The monitoring component of COMAPS program was renamed as "Seawater Quality Monitoring (SWQM) during the XII Five Year Plan period (2012 –17). Presently, the National Centre for Coastal Research (NCCR) (formerly Integrated Coastal and Marine Area Management Project Directorate, ICMAM PD) is implementing this multi-institutional programme with the active participation of seven national R&D laboratories and Academia.

3.2 Sampling Strategy

Initially, 76 – 81 locations covering all the coastal regions were monitored for >25 parameters (physico-chemical, biology and microbiology). The sites were selected based on the potential sources of contaminants and samples were collected at a frequency of 3 or 4 seasons per year or once a year (Madeswaran et al., 2018). During the XII Five Year Plan (2012-17), the number of monitoring locations was reduced to 24 (Figure 1).Further, the number of stations in each location was also reduced from 7 (distance from shore 0, 1, 2, 3, 4, 5, 10, 25/30 km) to 3 (0/0.5, 2/3 and 5 km). The collected samples were processed using standard protocols (Burkwall& Hartman 1964; Gledriech et al., 1965; Strickland & Parsons 1972; Grasshoff et al., 1999; JGOFS protocols). Periodical inter-laboratory calibration (ILC) exercises were conducted for selected parameters and project staff of the participating organisations were regularly trained.

3.3 Status of the Coastal Waters: 25 years

Based on the data collected in the last 25 years, a consolidated report was prepared to provide insights into the status of coastal waters of India (Madeswaran et al., 2018). Parameters considered for the report were dissolved oxygen (DO), nutrients (nitrate, ammonia, phosphate and silicate), phytoplankton abundance and biomass (Chl-a), zooplankton (abundance and biomass), macrofauna (abundance and biomass) and Total Viable Count (TVC) and health indicator bacteria such as *Escherichia coli* (*E. coli*) and *Streptococcus faecalis* (*S. faecalis*) as they are the primary water quality indicators of coastal systems.

The result of the 25 years data indicates that the concentrations of all the nutrients (NO_3, NH_4, PO_4 and SiO_4) showed an increase in most of the monitored locations. The high concentration of ammonia along with phosphate indicates discharge of untreated sewage in the coastal water (Xu et al., 2008). During 2015, of the 61754 Million Litres per Day (MLD) sewage generated from domestic sources, only 38% (22963 MLD) were treated, while 38791 MLD of untreated sewage was released into the aquatic system (CPCB, 2016). The coastal states of Maharashtra, Tamil Nadu and Gujarat (Figure 2) along with Delhi and Uttar Pradesh account for about 50% of the total sewage generated in the country (CPCB, 2016).

Despite the awareness of the importance of coastal systems, waste management strategies have failed to keep pace with the rapid industrial growth and urbanisation. The condition is further worsened due to the lack of proper sewer systems and discharge of untreated/semi-treated sewage and effluents from many coastal towns/cities into the coastal environment. The Ministry of Environment, Forest and Climate Change (MoEFCC) have initiated measures to control discharge of untreated sewage into the coastal waters and increase the reuse of sewage water. A new standard for sewage treatment plants has been drafted and will be notified after receiving the recommendation of the stakeholders. In addition to sewage, land runoff carrying excess fertilisers from agro ecosystems is also an important source of nutrients to the coastal waters (Pradhan et al., 2014; Krishna et al., 2016). The use of nitrogen based fertilisers increased from 7997 tonnes in 1990-91 to 16,735 tonnes in 2016-17 indicating a twofold increase in the last twenty years (www.faidelhi.org/statistical-database.htm).

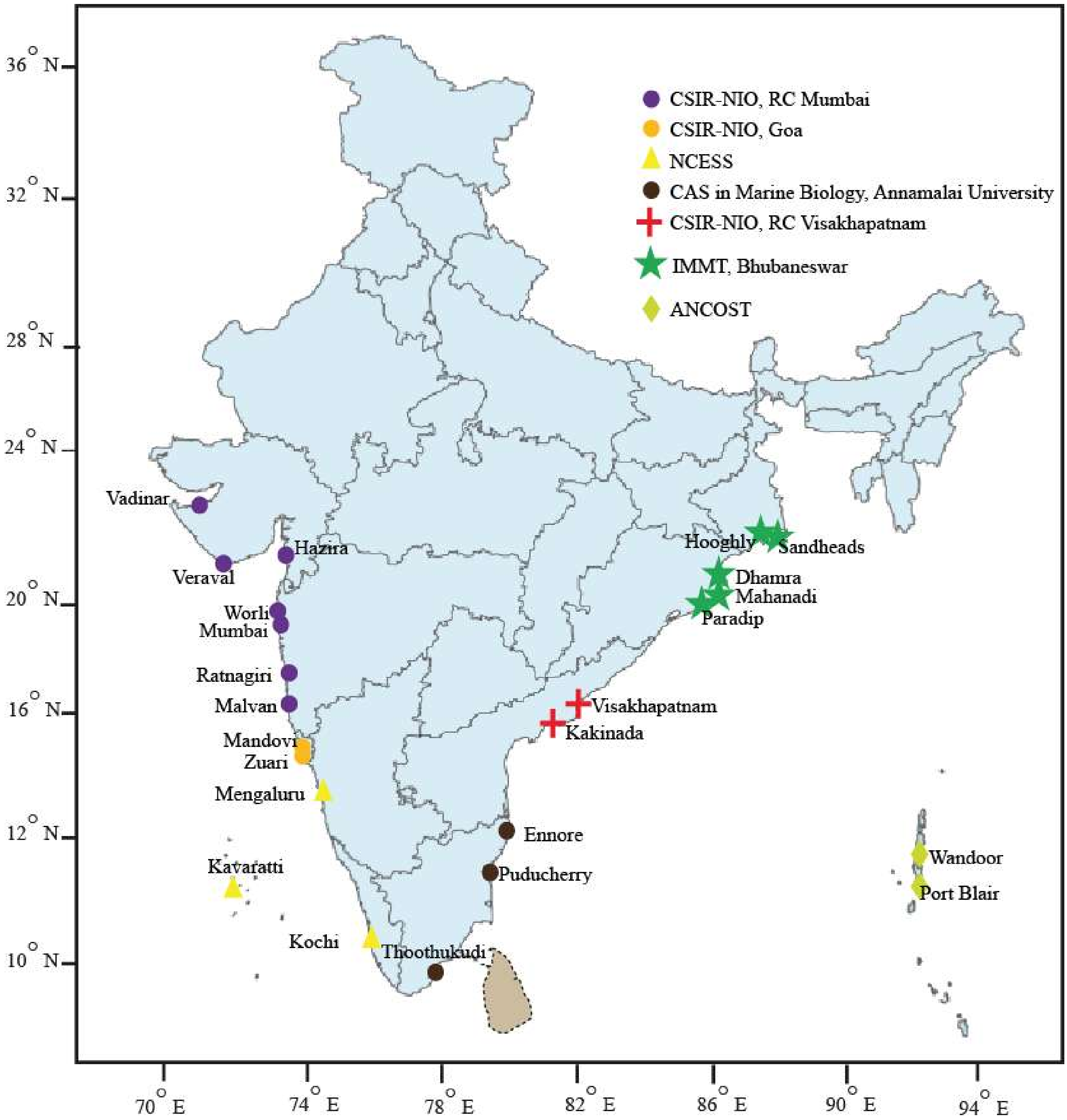

Figure 1: Map showing the monitoring locations and participating organisations. Participating organisations: CSIR-National Institute of Oceanography, Goa (CSIR-NIO); National Centre for Earth Science Studies, Thiruvananthapuram (NCESS); Centre of Advanced Study in Marine Biology (CASMB), Annamalai University; Institute for Minerals and Materials Technology (IMMT), Bhubaneswar; Andaman Nicobar Centre for Ocean Science and Technology (ANCOST), NIOT, Port Blair.

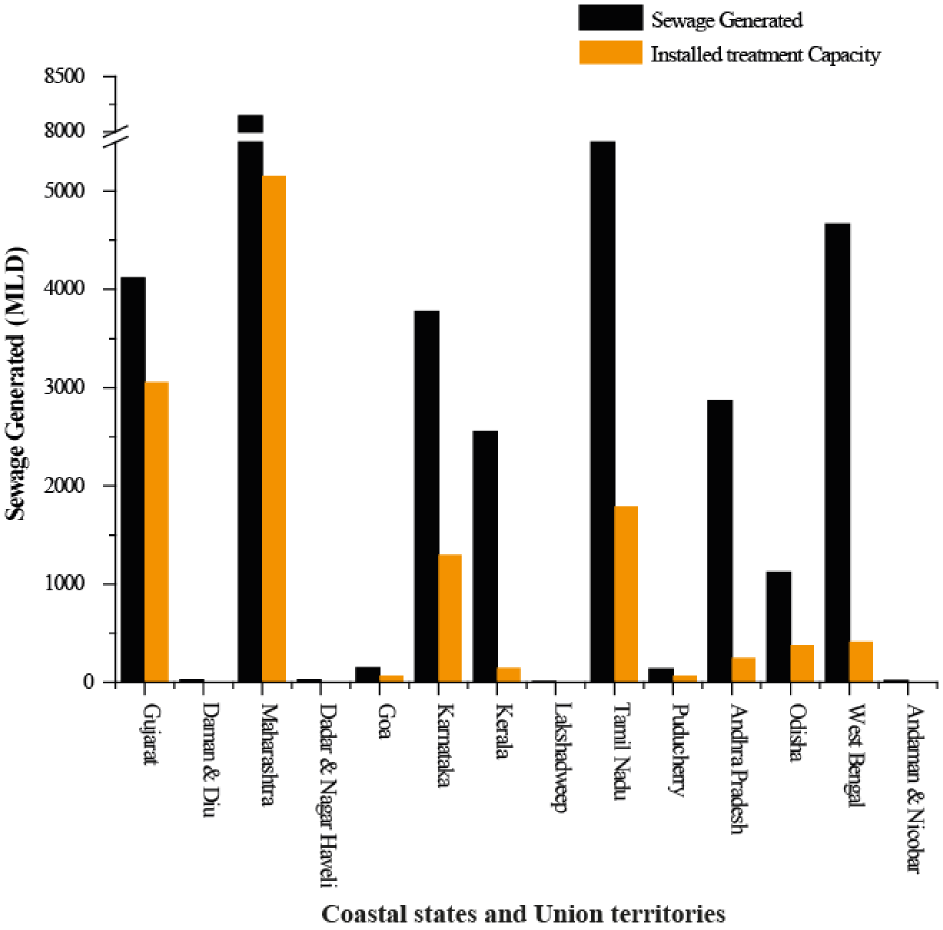

Figure 2: Annual sewage discharged and treatment capacity in the coastal regions of India. Source data: CPCB, 2016.

The increase of nutrients in coastal waters is of concern as it may lead to increased incidences of eutrophication that has the potential to cause algal blooms. Although the nutrients have increased in the coastal waters, it was not reflected in the plankton abundance or biomass. The reason for this could be that the inorganic nitrogen was predominantly composed of ammonia which is known to inhibit the uptake of NO_3 by coastal phytoplankton community (Dugdale et al., 2012). Another possible reason could be the increased suspended solids preventing the phytoplankton production in the coastal waters. However, the unusually high abundance of phytoplankton recorded during certain years of the monitoring period at some locations (Madeswaran et al., 2018) and the increased incidences of algal blooms along the Indian coast indicates the harmful effect of increased nutrients on the coasts (Padmakumar et al., 2012; Sathish Kumar et al., 2018). Increasing algal blooms along the Indian waters is a major concern as most blooms reported had direct or indirect effect on the coastal organisms, fishery and humans (D'Silva et al., 2012). There is clear evidence that nutrient loading has greatly increased due to anthropogenic activities over the last few decades in the coastal waters of India. Although high nitrogen and phosphorus are the basic requirements for eutrophication and subsequently algal blooms, the mechanisms for the formation of blooms is not fully understood. Based on various studies, the presence of influencing factors such as excessive nitrogen and phosphorus, slow current velocity, favourable temperature and other environmental factors and microbial activity and biodiversity triggers eutrophication and algal blooms (e.g. Li & Liao 2002; Howarth & Marino 2006; Rabalais et al., 2009).

The increased nutrients in the coastal waters also affect the benthic system by increasing the organic matter influx. This was evident from the increased sediment organic matter in many of the monitored locations. The clearing of coastal vegetation for construction, direct discharge of sewage and industrial effluents and land runoff may have also contributed to the increasing organic load in the coastal sediment. Moreover, most of these monitored locations (shore to offshore) were dominated by fine sediment that allowed the accumulation and retention of the organic matter. The increase in organic load can shift the benthic community to *r*-selected (small-size and fast reproducer) species (Pearson & Rosenberg, 1978). The macrofaunal community of most of the monitored locations were dominated by polychaete families Spionidae, Pilargidae, Nepythidae and Capitellidae that are known opportunistic species. The microbial community also confirmed that the nutrient load has increased in the monitored coastal locations. The increase in faecal bacteria is often associated with increasing nutrient load (e.g. Nogales et al., 2010; Paerl et al., 2003).Therefore, increasing input of contaminants in the coastal waters may cause a shift in the plankton and benthic communities, consequently causing cascading changes in the coastal food web and ultimately affecting the ecosystem services.

A general trend that was observed in most locations is that the water quality parameters (nutrients and bacterial population) decreased towards the offshore locations (5 km from coast) i.e., the effect of disturbances was mostly observed up to 2 km from the shore. The complex hydrodynamic conditions at the monitored locations could be responsible for the mixing, dispersal and distribution of pollutants. Therefore, studies using numerical models are needed to investigate the transport of pollutants from the point sources at the monitored locations.

3.4 Benefits of the Coastal Water Quality Monitoring Programme

The SWQM programme has made some contributions to ensure availability of quality data and its usage for monitoring of the country's coast. A major contribution of the SWQM programme is the baseline data. Data of >25 parameters collected from 1990 onwards is available at the Indian National Centre for Ocean Information Services (INCOIS) website (www.incois.gov.in/portal/comaps/home.jsp). In addition, actions were taken by the Central and State Pollution control boards based on the information provided by the SWQM. Oil spill trajectory modelling, sensitivity mapping, and collection, development and testing of local hydrodynamic models at a few coastal locations were also carried out under the programme. Under capacity building, a Marine Microbial Reference Facility (MMRF) was established at CSIR- National Institute of Oceanography, RC Kochi.
At presently the library contains 1055 isolates, of which 556 are health indicators. Additionally, training project staff, student thesis (graduate, post-graduate and PhD) and publications are also some of the important contribution under the SWQM programme.

4. Repercussion of climate-change on coastal monitoring programme

Climate change, without doubt, is becoming one of the major challenges for the society and environment. Earth's climate and weather are primarily caused by differential radiative heating and, the dynamic movement of the resultant energy between the atmosphere and ocean. Perturbation of this dynamic energy balance of the Earth's system, caused mostly by human activity, is driving the present global warming. As oceans take >90% of the heat, analysing the long-term trends in Sea Surface Temperature (SST) is a critical parameter to understand global warming. In addition, trends in sea level, wind, precipitation, carbon dioxide, ocean heat, snow and ice are also important for measuring global climate.
Anthropogenic climate change is exerting great influence on the Earth's ecosystem through increasing temperatures (air and ocean) and associated changes in the precipitation pattern, sea level, glacier melting and increase in the frequency and severity of extreme weather events

(e.g. Levitus et al., 2005; Timmermann et al.. 1999; Cobb et al.. 2003). Economic development and industrialisation accompanying the growing world population that begun in the last century has transformed several habitats around the world, as discussed. Although slow, most ecosystems are also known to naturally change with time. Therefore, delineating the relative role of anthropogenic forcing, natural variability, and climate change and how they will interact presents a significant challenge for researchers, policy makers and environmental managers. Sustained observations around the world along with models on biogeochemistry, carbon cycle, and atmospheric inversions have been critical in improving our knowledge and understanding of climate change, and untangling the natural variability from anthropogenic disturbances and climate change.

Long-term studies, including monitoring programmes, provide essential background information to researchers, policy makers and managers to assess the status and trends of the ecosystem. The SWQM data can be highly useful in climate change research, as it provides long-term data of number of parameters collected at large spatial scales. Further, long-term data can be crucial to identify if the changes are natural, unusual or anthropogenically forced. As discussed earlier, temperature is a key parameter in climate change research. Although dynamic, the SWQM data also confirms the increase in atmospheric and sea water temperature. Temperature fluctuation is known to alter species' distribution range, physiology and prey-predator relationship. Warming temperature may affect the phytoplankton and zooplankton distribution, abundance and biomass (e.g. Chust et al., 2014; Kvile et al., 2016). Moreover, nutrient influx and higher levels of ultraviolet radiation due to the effect of climate change will further affect the plankton species distribution and composition (e.g. Häder et al., 2014; Carillo et al., 2015). Nutrients showed increasing trend have crossed the permissible limits in many of the monitored locations. Consequently, this will affect the plankton biomass, which in turn affects fishery resources. Nicolas et al. (2014) reported that the increase in SST resulted in the reduction of cod fishery, despite decrease in fishery pressure in the southern North Sea. In tropical regions like India, major recruitment of most marine organisms occurs during the monsoon period as food is abundant, influenced by upwelling. Temperature also plays an important cue for spawning of tropical communities. The high temperature, just before the onset of monsoon triggers spawning event. However, early high temperature could affect this natural cycle of many marine organisms. Moreover, climate change is also affecting the Indian monsoon cycle, which will further affect the benthic communities (Gaonkar et al., 2013), including the fish. Warming ocean can induce decline/increase or lead to migration of species. Therefore, monitoring programme needs to consider the 'Shifting baselines' and 'unbounded boundaries' caused by climate-change (Elliot et al., 2015).

Future monitoring programmes should address this problem and help identify and improve resilience to climate change impacts. Numerous marine and coastal monitoring programmes around the world have developed and are in the process of developing strategies for climate change adaptation. Till date, the coastal monitoring data and approaches have traditionally been limited to water quality of the coastal waters (shore to off shore). Now, there is need to link between the coastal and riverine and estuarine system as they greatly influence the coastal environment. Changes in the land use arising from climate change could modify the runoff patterns that may increase the input of various components including contaminants. This knowledge gap in the present programme may form a barrier to identify the causative links to the sources of pressures and subsequently may affect the monitoring objectives. These links need to made, initially at small scale, and could be upscaled if it provides useful data.

5. New approaches in coastal monitoring

As the Indian coastal and marine ecosystems are highly complex, they require systematic and integrated climate change research. Although considerable progress has been made during the last few decades under various National programmes to understand the Indian coastal system, knowledge gaps exist. As most monitoring programmes covers a wide spatial and temporal range, they can, if well-conceived and well-executed, provide important insights in the ecosystem processes. Lindenmayer & Likens (2009) in their review also highlight the several benefits of long-term studies including the monitoring programmes and argue the need for new approaches in such long-term studies. From a practical perspective, successful management of coastal area requires (1) continuous application of new approaches and tools for monitoring programmes and (2) a stringent coastal policy. The following section discusses the first aspect.

5.1 Application of new approaches and tools in monitoring

The future monitoring programmes need a dynamic multidisciplinary scientific strategy to provide an understanding of the impact of climate change on the coastal systems for prediction and developing appropriate responses. The SWQM strategy should include (1) use of the existing data to provide the necessary information for identifying and developing appropriate strategies and (2) collection and synthesis of data using new and integrated approaches.

Application of new approaches and tools in monitoring should allow rapid quantitative assessments, be simple to use and must be cost-effective. A number of approaches have been identified that can be considered under the coastal monitoring programme:

- *Geospatial information technology*: Remote sensing, geographic information systems (GIS) and *in situ* observatory platforms have emerged as a powerful tool to provide an invaluable complementary source of data at local to global scales and continuous frequency.
- *Long-term time series observations:* Although SWQM monitors the coastal waters, they only measure basic parameters and have limited spatial coverage. Geospatial information technologies allow the long-term time series observations of the coastal at multiple scales. In general, there is a clear need to strengthen the routine monitoring under the SWQM programme and long-term time series observations for various parameters from climate to pollutants and covering watershed to the offshore region by using advanced technology. Geospatial information technology has improved our understanding of the coastal system and can significantly contribute to develop models, design management plans for the sustainable development of the coastal zone (Nayak, 2017).
- *Ecosystem- based approach*: Allows better understanding of the ecological process and how any disturbance will alter these processes.
- *Climate manipulation experiments:* Along with routine monitoring, manipulation studies (microcosm and mesocosm experiments) can be carried out to explore the link between the ecosystem components, and their response to projected climate change scenarios. Experimental studies have become popular in climate change research as they form a link between the experimentally controlled experiments and complex natural system.
- *Improving taxonomy*: Accurate species identification is critical for biodiversity study. The use of integrated approach (molecular and classical) will significantly benefit various biological disciplines, as the result will be based on relatively stable species data and library.
- *Molecular techniques:* Molecular tools have improved the processing time and accuracy of data that has considerably improved the management of environmental resources. Molecular characterization of the bacterial community could lead to more robust health risk indication at a lower cost than conventional approaches (Stewart et al., 2008; Bourlat et al., 2013; Ininbergs et al., 2015).
- *Integrated data management system*: To maximise the value of the data for science and decision making, there is a need to develop a systematic system that integrates data from various sources, data management and data sharing.

- *Developing Models*: Using field data, experimental data and geospatial information, local and regional models can be developed to stimulate how the coastal system may respond to changes (natural or human-induced) thus guiding management strategies.
- *National and international networking*: Increased interaction and networking amongst various institutions, academic and environmental managers for sharing knowledge and experiences.

Conclusion

SWQM is a collaborative programme that collects environmental and biological data to study coastal water quality at selected locations along the Indian coast. Although nutrients and microbial parameters showed an increasing trend, significant increase was noticed at a few monitored locations. Further, increase in the measured parameters was restricted up to near shore. The major accomplishment of the SWQM programme has been the generation of long-term data from selected locations along the Indian coast which is available from the INCOIS website. Data collected from a large spatial area and over long-term can provided important insights in the ecosystem processes and hence can be very useful for climate change research.

Climate change is identified as one of the most profound future drivers of changes in the coastal system. However, this system is known for its natural variability and subjected to disturbances due to anthropogenic activities. Like many countries, India will seriously be affected by climate changes, so climate change research is necessary for the environmental, economic and societal development of the country. The SWQM programme has a long-term and large-scale data that can be useful for planning future research strategy. Even though the SWQM programme is largely successful to a level, it can be improved upon. Building on the available data, application of new approaches and increasing networking with national international organisations for monitoring the coastal system will help to address the triple issue of climate change, anthropogenic stressors and natural variability. New approaches include the use of integrated approach (molecular and traditional methods) for biodiversity, coupling experimental studies with real-world observations, and geospatial information technology that will provide data at local to global scales and, at continuous frequency. Models developed from data derived from different methods can help to understand the complex coastal system and predict its response to any disturbances. Hence, application of an integrated approach will provide valuable information on the coastal system to fill the knowledge gap, predict and mitigate the effects of climate change. To sum up, the SWQM future programme aims to facilitate innovative, integrated and impactful science for the sustainable management of the coastal system.

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Impacts of climate change on coral reefs of India

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ABSTRACT

Climate change has made a significant impact on all marine ecosystems, in particular, to coral reefs, associated biodiversity, and dependent human livelihood. Most of the warmest years of have occurred since 1998. Climate-driven coral bleaching has occurred in 1998, 2010 and during 2014-2017, affecting large areas of the world's pristine reefs with high levels of coral mortality. In India major reef areas like Gulf of Mannar and Palk Bay, Gulf of Kachchh, Andaman and Nicobar Islands and Lakshadweep Islands have witnessed such events and consequent mortalities. Various modeling projections have predicted bleaching and mortality in corals with more frequent and intense bleaching events. Thus, there is a need to undertake continuous monitoring of all reef areas towards appropriate management actions. The existing warning system can be strengthened and make bleaching alerts readily available to reef researchers and managers. Degraded reef areas should be restored with resilient and resistant native coral species to assist the recovery process. A coordinated response plan involving both the scientific and the coastal community would help to manage the coral reef ecosystems of India, and to mitigate the effects of coral bleaching and disease outbreak.

1. Introduction

Coral reefs are considered to be the most dynamic and productive marine ecosystems. They are home to thousands of ecologically and economically important marine species. Apart from supporting a wide array of organisms, coral reefs also protect the shorelines and act as carbon sinks. The economic benefits such as fisheries, tourism and coastal protection derived from coral reefs amount to between USD 30 and 375 billion per year (Costanza et al., 1997; Cesar et al., 2003). In spite of their intrinsic value, since the past few decades, coral reefs around the world continue to face an unprecedented decline due to various human-induced factors. This is in addition to natural causes such as climate change. Because of the unique position of their occurrence near the junction of land, sea, and atmosphere, coral reefs and their natural habitats have to suffer from both marine and terrestrial impacts of any climatic change and thus they are rendered all the more vulnerable to the ill-effects of human activities (Hughes and Connell 1999).

Global climate change has wrought significant alterations in all ecosystems. In particular, temperature anomalies driven by climate change have caused remarkable impacts on all living organisms in the last few decades. The year 2016 was the hottest year in the history of the earth breaking the previous records of 2014 and subsequently of 2015 (NASA, 2017). All of the ten warmest years of the planet have occurred between 1998 and 2015 (Steffen and Fenwick, 2016). Further, the six warmest years on record have occurred since 2010 (NOAA, 2018). 2017 was the 41st consecutive year since 1977 with temperatures above the 20th century average. More such temperature anomalies are likely to occur in the near future.

Corals are sensitive animals that respond even to slight deviations in the environmental parameters and more so to temperature anomalies. Coral bleaching is a general response of corals to increased sea surface temperature. It refers to the loss of the symbiotic unicellular algae called zooxanthellae which are vital for the survival of coral colonies. Zooxanthellae are primary producers and they provide energy to the corals through a symbiotic relationship. The loss of zooxanthellae for a longer period would make the corals starve to death. Incidentally, it is the zooxanthellae that give the corals their colour and thus the absence of zooxanthellae makes the corals look white or bleached. Bleaching can happen when corals experience increased sea surface temperatures even of 1 to °C. Corals would recover from bleaching if the normal temperature returns within a short period but, if the temperature stress continues over a long- term, corals will eventually die (Hughes et al., 2016).

The significant temperature elevation of the year 1998 destroyed an estimated 16% of coral communities around the world (Hoegh-Guldberg, 1999; Wilkinson, 2008). Since then many more widespread coral bleaching events and the consequent mortalities have damaged the global coral reefs (Hoegh-Guldberg et al., 2014; Wilkinson, 2008; Hoegh-Guldberg et al., 2015). The second global coral bleaching event took place during 2010 causing widespread damage (Wake, 2016; NOAA, 2018). The third and longest global coral bleaching driven by climate change happened in many reef regions between 2014 and 2017, and it surpassed the previous two global coral bleaching events in the magnitude of damage it caused to coral reefs (NOAA, 2018). By October 2015, the phenomenon was witnessed in all the three ocean basins, the Indian, the Pacific, and the Atlantic. The first report of bleaching was during June 2014 from Guam. It soon spread to Hawaii, Florida, Marshall Islands, Papua New Guinea, Solomon Islands, Fiji, American Samoa, Chagos Archipelago, Maldives, Indonesia, Red Sea, Panama, Kiribati, Cuba, Bahamas, Turks & Caicos, Cayman Islands, Dominican Republic, Haiti, Bonaire, Tanzania, New Caledonia and the Great Barrier Reef (Heron et al., 2016; Eakin et al., 2016). This bleaching event made a severe and irreversible impact on the world's biggest reef, the Great Barrier Reef (NOAA, 2018).

2. Impacts of climate change on coral reef ecosystems, biodiversity and livelihood

As the changing climate directly damages biodiversity and thus affects the dependent human populations, impacts of climate change are felt more than ever in all the ecosystems. In many cases, climate change has emerged as a serious threat—serious more in causing a decline at the species level than in the destruction of their natural habitats (Thomas et al., 2004). It is a general perception that reef communities are well-adapted to disturbances (Connell, 1997; Hughes and Connell, 1999) because of their ability to survive in a stressful environment but in recent years it is realized that this adaptive capacity of coral reefs is no match to the intensity and frequency of climate change and temperature anomalies (Buddemeier et al., 2004). Coral reefs can tolerate chronic stresses and recover from acute stresses, but chronically stressed reefs are far less likely to recover from acute stress (Kinsey, 1988; Buddemeier et al., 2004). Coral reefs could migrate to higher latitudes in response to global warming, but this is no compensation to the ecological and economic losses caused by the destruction of tropical reefs (Buddemeier et al., 2004).

Coral bleaching and the consequent mass mortality not only have negative impacts on coral communities, but also affect the fish and human communities that depend on coral reefs. Reduced growth rates, decreased reproductive capacity, increased susceptibility to diseases and elevated mortality rates are some of the likely repercussions that bleached corals have to face. Changes in the composition of coral community structure can occur when bleaching events kill more susceptible species. Changes in coral community structure also affect those species that depend on corals, such as fishes and invertebrates. Coral death due to coral bleaching would bring about changes in the abundance and composition of reef-fish assemblages. It might also trigger declines in genetic variability and species diversity (Source: Reef Resilience Network, 2018).

Degraded coral reefs are unlikely to provide any ecosystem services on which the local human communities depend for their survival. For example, degraded reefs are less productive and may not be able to sustain accretion rates necessary to ensure their continuous ability to protect the shorelines. Reefs damaged by coral bleaching can quickly lose many of the features that underpin the aesthetic appeal that is fundamental to reef tourism. The loss of revenue from reduced tourist activity might jeopardise the livelihoods of the local communities. Coral bleaching events giving rise to significant coral mortality can drive large shifts in fish communities. This can translate into reduced catches for fishers targeting reef fish species, which in turn can result in reduced food supply and associated economic activities. The cultural values of many tropical island communities depend on healthy coral reef ecosystems, and they can be adversely affected by coral bleaching. Coral reefs are valuable sources of several pharmaceutical compounds. Degraded and dead reefs are less likely to offer any important medicinal resources (Source: Reef Resilience Network, 2018).

About 40 percent of people live within 100 km of coastlines, and their lives and livelihoods depend mainly on coastal ecosystems. When these ecosystems are impaired by climate change, they will turn their attention to coral reefs and other adjacent fragile environments which will then bear the brunt of more interference and disturbance from humans (Cesar et al., 2003; Buddemeier et al., 2004). The 1998 global coral bleaching event effectively destroyed 16% of the global reef with the whole of Indian Ocean and the Western Pacific sustaining most of the damage (Wilkinson, 2004). This bleaching event naturally caused significant impacts on the economies of many regions. For example, in the Maldives, coral bleaching in 1998-1999 resulted in an estimated loss of about US$ 0.5–3.0 million from tourism-related revenues. In Palau, coral mortality was about 50% during the 1997–98 bleaching event and the consequence was a 5–10 percent drop in tourism in the following years (Westmacott et al., 2001; Graham et al., 2001; Buddemeier et al., 2004).






Coral mortality during the third global bleaching event between 2014 and 2017 has been termed the worst ever, including at World Heritage reefs (Heron et al., 2017). About 70% of the world's reefs suffered bleaching during this period (NOAA, 2018). In the Great Barrier Reef, the world's biggest reef, about 30% of the corals died due to this bleaching event (Hughes et al., 2018). Recent estimates indicate that climate-related loss of reef ecosystem services will total around US $500 billion per year or more by 2100 (Gattuso et al., 2015; Hoegh-Guldberg et al., 2015; Heron et al., 2017).

In India, reefs are important mostly for fisheries and coastal protection and they hold strong potential for tourism. Loss of coral reefs due to climate change would have an adverse effect on reef fisheries and would directly affect the dependent fisher-folk. Reef fisheries in India are generally not reflected in the statistics of national fisheries though they are important as subsistence fishery for the local people (Wilkinson, 2004). Such fishery includes species like snappers, groupers, emperors, breams, barracuda, jacks, sprats, herrings and flying fish. There has been a definite and steady decline in marine fisheries in the Gulf of Mannar for the past few decades according to Venkatachalam (2004). Though no specific information on reef fisheries is available for the Gulf of Mannar (GoM), the annual catch of demersal fish, which includes reef fish, is about 45,000 metric tonnes per year (Wilkinson, 2004). Fishermen often complain that fishery resources have been depleted significantly along the coast of Gulf of Mannar.

In the Andaman and Nicobar Islands fishing is carried out mainly around the Andaman Islands, with less activities taking place around the Nicobar Islands. The main species targeted include sardines, anchovies, carangids, mackerel, mullets, perches, sharks and rays, catfish, pomfrets, silver bellies and catfish. In the Lakshadweep Islands, there is no organized commercial reef fishery for consumption or for ornamental purposes, but there is a thriving reef-fishery for subsistence (Wilkinson, 2004). No information is available on reef related fisheries in Gulf of Kachchh and along the west coast of India. Loss of reefs due to climate change would also affect tourism industry, especially in Andaman and Nicobar Islands, Lakshadweep Islands and on Malvan coast, Arabian Sea. Decline in coral cover damages low lying coral islands as they would not get enough supply of reef sand and would eventually submerge. Two coral islands in Gulf of Mannar have already submerged because of the loss of coral cover coupled with sea level rise (Raj et al., 2017).

3. Coral reefs of India

India has four major reef areas -Gulf of Mannar and Palk Bay, Gulf of Kachchh, Lakshadweep, and Andaman and Nicobar Islands. As per recent satellite data, the overall area cover of coral reefs in India is 3,062.97 sq km. This includes lagoons of 521.5 sq.km and coralline shelf of 157.6 sq.km (Bhatt et al., 2012). Fringing reefs are found in Gulf of Mannar and Palk Bay. Platform reefs are seen along Gulf of Kachchh while atoll reefs occur in the Lakshadweep archipelago. Fringing and barrier reefs are found in the Andaman and Nicobar Islands. Coral patches are seen along the west coast of India in Kerala, Karnataka, Goa and Maharashtra (Figure 1).

Figure 1: Map showing the coral reef areas in India

4. Impacts of climate change on Indian reefs

4.1 Gulf of Mannar and Palk Bay

It is reported that Gulf of Mannar has been affected by all three major bleaching events. During the first event in 1998, 89% of corals bleached with the rate of mortality being a huge 23% (Arthur, 2000). During 2002, the percentage of bleaching ranged between 50 and 60% in Palk Bay with maximum mortality of 4.5% (Kumaraguru et al., 2003). Edward et al. (2008) reported that there was annual coral bleaching event in Gulf of Mannar during summer of that year (April-June) when the temperature level varied between 31˚ C and 33.5˚ C. The percentage of bleaching was reported as 14.6, 15.6, 12.9 and 10.5 respectively for 2005, 2006, 2007 and 2008 in Gulf of Mannar. There was no significant mortality between 2005 and 2008 for the corals that recovered during June-July. However, mortality was significant among the bleached recruits that account to 80% during 2007 (Edward et al., 2008). Massive corals, in particular, *Porites* spp. were the first to bleach. The other corals that bleached during the period between 2005 and 2008 were *Acropora cytherea, A. formosa*, *A. intermedia, A. nobilis, Montipora foliosa*, *M. digitata* and *Pocillopora damicornis* (Edward et al., 2008).

In line with the second global bleaching event, an estimated 9.99% of coral colonies were found bleached in Gulf of Mannar (Edward et al., 2012). Mortality caused by this bleaching event was 9.65% as the live coral cover was reduced from 42.85 to 33.2%. The coral species that died due to coral bleaching include *Pocillopora damicornis*, *Acropora formosa*, *A. intermedia*, *A. nobilis*, *A. cytherea*, *Montipora foliosa, M. digitate, Favia* sp. and *Echinopora* sp. The bleaching-driven mortality in 2010 was attributed to a comparatively long exposure (April to July) to the elevated temperature levels (32.2 to 33.2˚ C) during 2010 (Edward et al., 2012). However, corals were able to recover from this mortality through new coral recruits and live coral cover improved to 38.86% during 2015.

During the third global coral bleaching event, corals in Gulf of Mannar were severely affected with massive mortality. The extent of bleaching was 23.92% during the period between March and June 2016, and the live coral cover was drastically reduced to 22.69% in 2016 from the 2015 level of 38.86%, with a mortality of 16.17% (Edward et al., 2018, Plates 1 & 2). Fast-growing coral forms, including the genera *Acropora*, *Montipora* and *Pocillopora* were the most affected, not only by bleaching but also by severe mortality. Boulders, including genera *Porites*, *Favia* and *Favites* were found to be resistant to bleaching (Edward et al., 2018). During the bleaching period, water temperature was between 31.2 and 32.6˚ C. Mandapam group of islands were the most affected by this bleaching event (mortality 22.17%) followed by Keelakarai (17.15%) and Tuticorin groups (9.19%) (Edward et al., 2018). Bleaching during 2016 started in the month of March, which is earlier than the annual summer bleaching, and it persisted until June 2016 (Edward et al., 2018). Fortunately, there was no significant bleaching during the summer of 2017 and there was no mortality. Fast growing corals of genera *Acropora*, *Montipora* and *Pocillopora* started to recover from the catastrophe and a slight increase (1.1%) of live coral cover was observed by October 2017. However, space competition between corals and with other organisms such as sponges, macroalgae and ascidians became a significant factor in the post-bleaching scenario of GoM.

Palk Bay has its corals predominantly at depths ranging between 0.5 to 5 m. The region is prone to elevated sea surface temperatures and annual bleaching events. During summer the temperature level ranges between 31 and 33˚ C. The percentage of coral bleaching ranged from 18.47 to 26.35% during 2007; in 2009, the range was between 16.74 and 23.15%; and in 2013, and it was between 6.28 and 9.78% in Palk Bay (Edward et al., 2015). Incidence of coral bleaching ranging from 25.8% to 41.3% was reported in Palk Bay during April and May 2010 (Ravindran et al., 2012).

4.2 Lakshadweep Islands

Significant coral bleaching between 80-90% was reported in 1998 in the Lakshadweep Islands with a mortality rate of 26%. Reefs in Kadmat and Agatti suffered a huge loss due to bleaching (Arthur, 2000). After the severe decline, corals in Lakshadweep started recovering and the pace of recovery varied significantly between atolls. A survey during 2002 by Arthur et al., (2005) showed that live coral cover was relatively low on most atolls, and thin algal turfs dominated the benthos. Where recovery was the most apparent, it was dominated by fast-growing and bleaching-resistant coral genera. The study showed that post-bleaching recovery was dominated by bleaching-resistant coral genera like *Porites* and *Favites*, and fast-growing taxa like *Acropora*, representing both remnant populations that survived bleaching as well as cohorts that were possibly recruited after 1998 (Arthur et al., 2005). Another follow-up study by Arthur et al., (2008) revealed that the benthic cover showed signs of recovery in most of the sampled locations from 2000 to 2007. Kavaratti West was an exception to this trend, where there was a slight decline in cover from the year 2003 (Arthur et al., 2008).

There was another widespread bleaching event in Lakshadweep Islands during the summer of 2010. A survey was conducted from November 2010 to April 2011 at 42 reef locations in 12 coral atolls by Arthur et al., (2012). The results showed that the western shallow reefs were affected significantly by bleaching with the highest coral mortality. Though the eastern reefs showed a similar trend, they suffered comparatively less declines in coral cover because of the inherently less coral cover. Lagoon sites had the highest live coral cover because of their acclimatisation to hotter temperatures. Atolls such as Agatti, Kadmat, Amini and Cheriyapani showed severe post-bleaching mortality and high overall declines in live coral, while reefs such as Kavaratti and Minicoy seemed to be resistant to the 2010 bleaching, with less damage (Arthur et al., 2012). A short-term survey conducted during May-June 2010 by Vinoth et al., (2012) at Agatti Island of Lakshadweep showed a mortality of 73% due to bleaching and exposure during low tides. There are reports on coral bleaching in Lakshadweep Islands during 2016, but there is no comprehensive information yet on this event and the consequent mortality. Arthur (2016) reported that 87% of corals were bleached in Kavaratti during 2016.

4.3 Andaman and Nicobar Islands

Significant bleaching was reported from some of the Andaman reefs during July 1998 by Ravindran et al., (1999). More than 90% of the massive corals and more than 75% of the branching corals were found bleached from three reef sites namely Ross Island, North Bay, and Marina Park (Ravindran et al., 1999). Pet-Soede et al., (2000) reported that up to 80% of corals in Andaman and Nicobar Islands were bleached during 1998.

A study by Krishnan et al., (2011) during 2010 in selected reef sites in the Andaman Islands showed that the percentage of bleaching was the highest at Havelock Island (69.49%), followed by South Button Island (67.28%), Nicolson Island (56.45%), Red Skin Island (43.39%), North Bay (41.65%) and Chidiyatapu (36.54%). The temperature level reached as high as 34° C during the summer of 2010. Branching corals were the worst affected, whereas the massive corals were found to be resistant to elevated temperature levels (Krishnan et al., 2011). The most affected were the branching acroporans that include *Acropora formosa, A.nobilis, A. robusta, A. breuggemann* and *A.grandis*. At South Button, 100% bleaching was observed among the acroporans (Krishnan et al., 2011).

Another study by Marimuthu et al., (2013) revealed that the intensity of bleaching was between 74 and 77% at south Andaman during the summer of 2010. The most affected coral species were *Acropora cerealis, A. humilis, Montipora* sp., *Favia pallida, Diploastrea* sp., *Goniopora* sp., *Fungia concinna, Gardineroseries* sp., *Porites* sp., *Favites abdita* and *Lobophyllia robusta*. Mondal et al., (2014) reported that the temperature range was 28 to 31.7° C between May and August 2010 at 55 selected sites in Andaman Islands. The intensity of coral bleaching was severe at Mayabunder with 90.43% while it was the lowest at 69.83% in Rani Jhansi Marine National Park. The level of temperature decreased by October 2010 when it ranged between 25 and 28˚ C, and the corals started to recover. The highest recovery was observed in Rutland Island with 85.1% and the lowest in Mayabunder with 77.4% (Mondal et al., 2014).

A survey conducted during March-April 2016, in the south Andaman Islands using the indigenously developed remote-operated vehicle found no trace of bleaching (Ramesh et al., 2017), though the water temperature was reported to range between 31 and 32° C. However, coral bleaching was reported in the same study after the survey period in some of the islands when temperatures increased to 33° C (Ramesh et al., 2017). The Coral Bleaching Alert System (CBAS) of Indian National Centre for Ocean Information Services (INCOIS) had warned (Alert Level-1) about coral bleaching at Andaman Islands through remote sensing analysis and it was confirmed by the field survey conducted on April 26, 2016 (Mohanty et al., 2017).

4.4 Gulf of Kachchh

Studies on the effect of climate change and coral bleaching in Gulf of Kachchh are few and sporadic. Arthur (1995) reported 1.2-1.4% of coral bleaching in Gulf of Kachchh during the summer months of that year. An average of 11% coral bleaching was reported in this region during the summer months of 1998 (Arthur, 2000).

Mass coral bleaching was reported in Narara and Poshitra of Gulf of Kachchh during the summer of 2010 (Joshi et al., 2014). The extent of coral bleaching ranged from 60 to 70% during May and June 2010 and the subsequent recovery was during October and November 2010. All the scleractinian corals observed during the survey suffered from moderate to severe bleaching. A total of 19 coral species belonging to 13 genera and 7 families were affected (Joshi et al., 2014). There was differential recovery pattern among the bleached corals. *Porites* colonies recovered partially during October 2010 and completely by November 2010. The monthly mean temperature of Gulf of Kachchh during May and June 2010 was 30° C and 32° C respectively and it was 28.4° C and 28.1° C respectively in October and November (Joshi et al., 2014).

4.5 West coast of India

Coral reefs in the west coast of India are yet to be explored and studies on the impacts of climate change are few and far between. Kalyan et al., (2015) surveyed the Malvan Marine Sanctuary, Maharashtra from October 2014 to January 2015 and reported a mean coral bleaching of 15%. Bleached corals included *Porites lichen*, *P. compressa, Favites melicerum, Turbinaria mesenterina, Pseudosiderastrea tayami, Cyphastrea serailia* and *Plesiastrea versipora*. Another detailed study by Raj et al., (2018) reported severe bleaching of 70.93% in the Malvan Marine Sanctuary during December 2015. This mass bleaching killed about 8.38% of corals and the bleached corals recovered by May 2016. Eleven coral genera which were affected by the bleaching were - *Pavona*, *Coscinaraea*, *Goniastrea*, *Favites*, *Favia*, *Cyphastrea*, *Leptastrea*, *Montastrea*, *Turbinaria*, *Goniopora* and *Porites*.The most affected genera were *Favia* (98.61%) and *Favites* (95.9%), and *Turbinaria* (17.34%).

5. Future of coral reefs in India

The projected stress exposure under different CO_2 emissions trajectories as used by the Intergovernmental Panel on Climate Change (IPCC) predicts a significant range of impacts in the years to come (Heron et al., 2017). According to the climate model projections of IPCC, 2014 the global surface temperature during the 21st century is likely to increase from 0.3 to 1.7° C for the lowest emissions scenario and from 2.6 to 4.8° C for the highest emission scenario (Zacharia et al., 2016). It has been estimated that the reef building corals may lose dominance between 2030






and 2040 in the Lakshadweep region and between 2050 and 2070 in other reef regions in India (Vivekanandan et al., 2009). Global sea surface temperature is expected to increase and Indian seas are no exceptions. Coral bleaching in the Indian reefs has occurred when the summer Surface Sea Temperature (SST) exceeded 31° C and persisted for more than 30 days (Vivekanandan et al., 2008). According to Vivekanandan et al., (2009), the annual average SST in Gulf of Kachchh increase from 27.0° C in 2000 to 30.5° C in 2099; and from 29.2° C to 32.2° C in the Lakshadweep Sea would result in coral bleaching becoming an annual event by the middle of the century and the number of catastrophic events increasing in all the reef regions in India (Vivekanandan et al., 2009).

Annual coral bleaching has already become a reality in Gulf of Mannar as witnessed in the summer months since 2005 (Edward et al., 2008). Apart from these annual bleaching events, catastrophic events that occurred in 2010 and 2016 killed a significant portion of corals in Gulf of Mannar (Edward et al., 2012; Edward et al., 2018). It is estimated that reef recovery after a catastrophic event would take a minimum of 10 years, and for a complete recovery about 50 years (Done et al., 2003). After the severe mortality in 2010, corals were able to recover and coral biomass increased significantly by 2015 in Gulf of Mannar but a second mass mortality during 2016 damaged the recovery process seriously (Edward et al., 2018). Likewise, in the other reef regions in India, the frequency and intensity of bleaching are likely to increase in the near future and the adaptation of corals to changing climate should be hoped for..

6. Non-climatic to Climatic threats (model from Gulf of Mannar)

In the Gulf of Mannar, during the past few decades, much attention was given to non-climatic human-induced threats. Strict implementation of rules by Tamil Nadu Forest Department coupled with awareness created among the coastal population by different governmental and non-governmental organisations and various other conservation initiatives have helped reduce human-induced impacts. Coral mining in particular has been completely stopped from 2005. Various destructive fishing methods practiced by fishermen such as blast fishing and poison fishing have also been discontinued. But climatic implications such as coral bleaching and sea level rise have now assumed serious proportions. Moreover, frequencies of bleaching and the consequent disease outbreaks and bio-invasion have increased in Gulf of Mannar. In the event of increased temperature anomalies and bleaching events the recovery of corals would be bleak in Gulf of Mannar. Figure 2 presents the decadal changes in the intensity of human-induced and natural threats in Gulf of Mannar. At present over 31% of the threat encountered by corals is due to bleaching and the subsequent mortality and diseases caused by climate change.

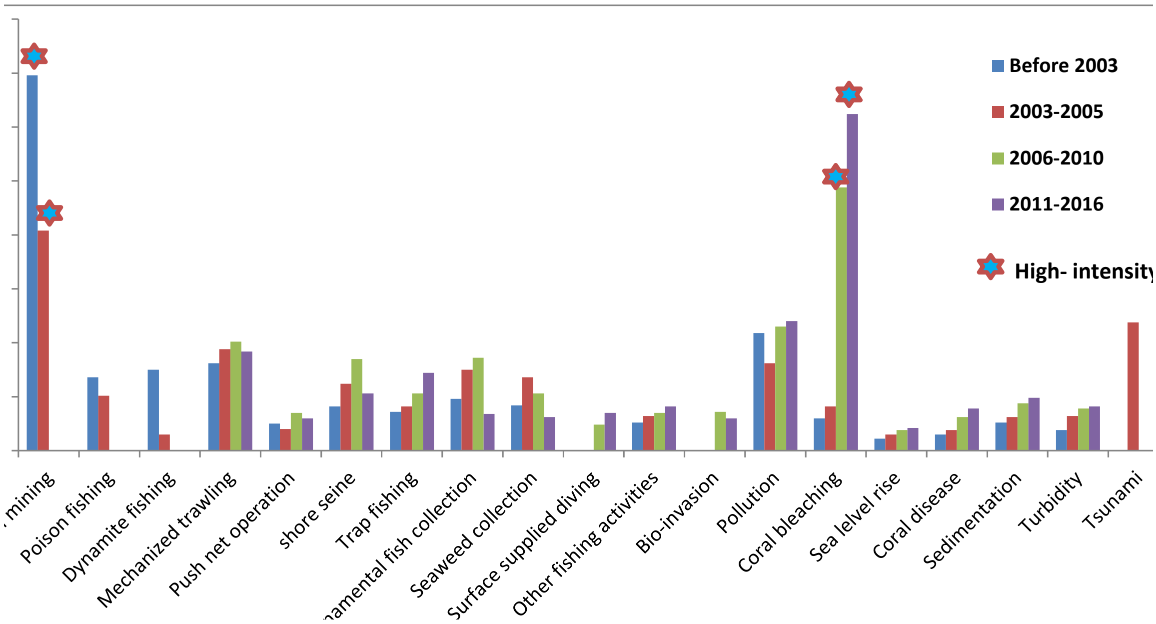

Figure 2: Decadal changes in threat scenario in Gulf of Mannar

Through a study under the auspices of NATCOM, funded by the Ministry of Environment, Forest and Climate Change, an ensemble of Coupled Model Inter-comparison Project phase 515 models was used to produce the downscaled (4-km resolution) projections (van Hooidonk, 2016) for Gulf of Mannar with emphasis on emissions pathway RCP8.5, which the present day emissions concentrations are currently tracking above. Annual severe bleaching (ASB) conditions refer to the start of a decade in which exceedance of 8 Degree Heating Weeks (DHWs) is projected for all 10 years. One DHW is equal to 1° C above the maximum monthly mean (bleaching threshold) for one week. 8 DHWs is higher than the mean optimum bleaching predictor of 6.1 DHWs for the globe; i.e. at 8 DHWs, it is doubtless that thermal stress will be sufficiently high for bleaching to occur. Results for ASB under RCP8.5 are summarized by island; projections based on RCP8.5 are compared to lower greenhouse gas emission scenario RCP4.5 and quantification of the effect of emissions reductions pledges made following COP21 on projected ASB timing (NATCOM Coral Project report, 2018).

The downscaled climate projections predicted that all islands across GoM can be expected to experience annual severe bleaching (ASB) under a ‘business as usual’ emissions scenario (RCP8.5) before 2070 and before 2060 they will experience bleaching twice per decade (Figure 3). However, the projections also highlighted high local-scale (10s km) spatial variability in the expected frequency of severe bleaching events in future across GoM (Figure 2). For a ‘business as usual’ emissions scenario (RCP8.5), there would be a clear east to west gradient in the onset of ASB; i.e. the reefs towards the eastern end of GoM (islands of Shingle, Krusadai, Pullivasal and Poomarichan) will experience ASB before 2045. Moving west, the onset of ASB generally gets delayed with the onset for Nallathanni Island pushed to 2061. Three islands towards the far eastern end (Koswari, Vilanguchalli, and Kariyachalli) are not expected to experience ASB until 2067. The patterns for severe bleaching twice per decade generally show the same east to west gradient (Figure 3). The reduced emissions scenario RCP4.5 (this approximates the pledges made following the 2015 Paris Climate Change Conference), has clear ameliorating effects, and it means that the majority of islands will not experience ASB (not even severe bleaching twice per decade) between now and 2070. Exceptions to this are the four islands towards the far eastern end of GoM, but they are still predicted to experience ASB before 2089 and severe bleaching twice per decade before 2070 under RCP4.5 (Figure 3).

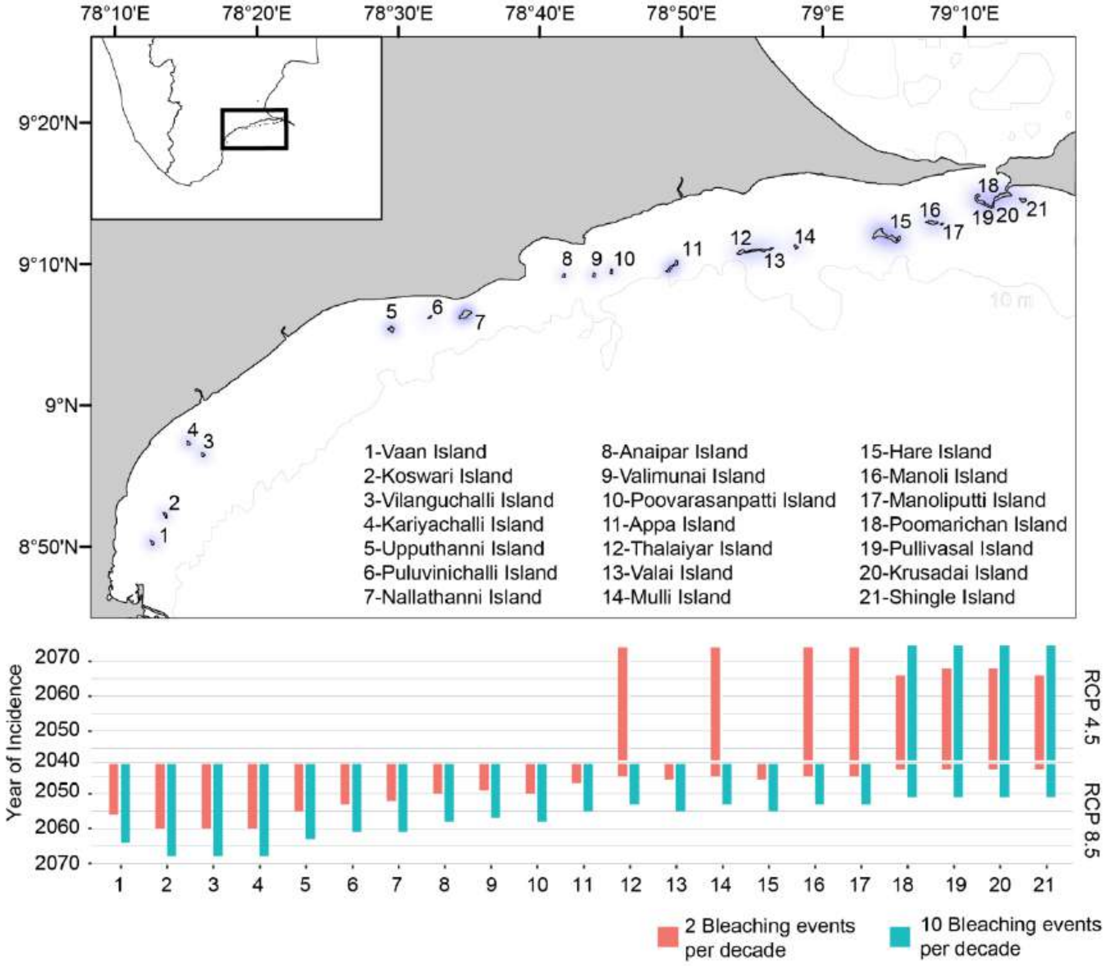

Figure 3: Statistically downscaled projections of the timing of the onset of severe bleaching every 5 years (red bar) and annual severe bleaching (blue bar) conditions across the Gulf of Mannar (GoM) under RCP8.5 ('business as usual') and a reduced emission scenario RCP4.5.

Note the high local-scale (10s km) variation seen in the projections across the GoM, with a clear gradient in the timing of onset from east to west.

Conclusion

Climate change is global in nature and international initiatives are being taken to reduce its effects. However, local and regional actions too are needed to reduce the impact of climate change on coral reefs. It is understood that there is a huge lacuna in our knowledge of climate change impacts. In India, except for Gulf of Mannar and Lakshadweep Islands regular and continuous data are not available for the other reef regions. Hence, the first step would be to monitor all reef areas regularly and continuously. The existing warning system that warns of bleaching can be strengthened and made readily available to all reef researchers and managers. Steps can be taken to reduce stress to the bleached corals by checking fishing and tourism activities. Degraded reef areas should be restored with resilient and resistant native coral species to assist the recovery process. More bleaching events and more mass mortalities are highly likely in the near future. Hence, it is imperative to harmonise and coordinate the efforts to protect the coral reefs of India and consequently to the protection of the livelihoods of poor dependent people.

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Plate 1: Bleached corals in Gulf of Mannar during 3rd Global Bleaching Event

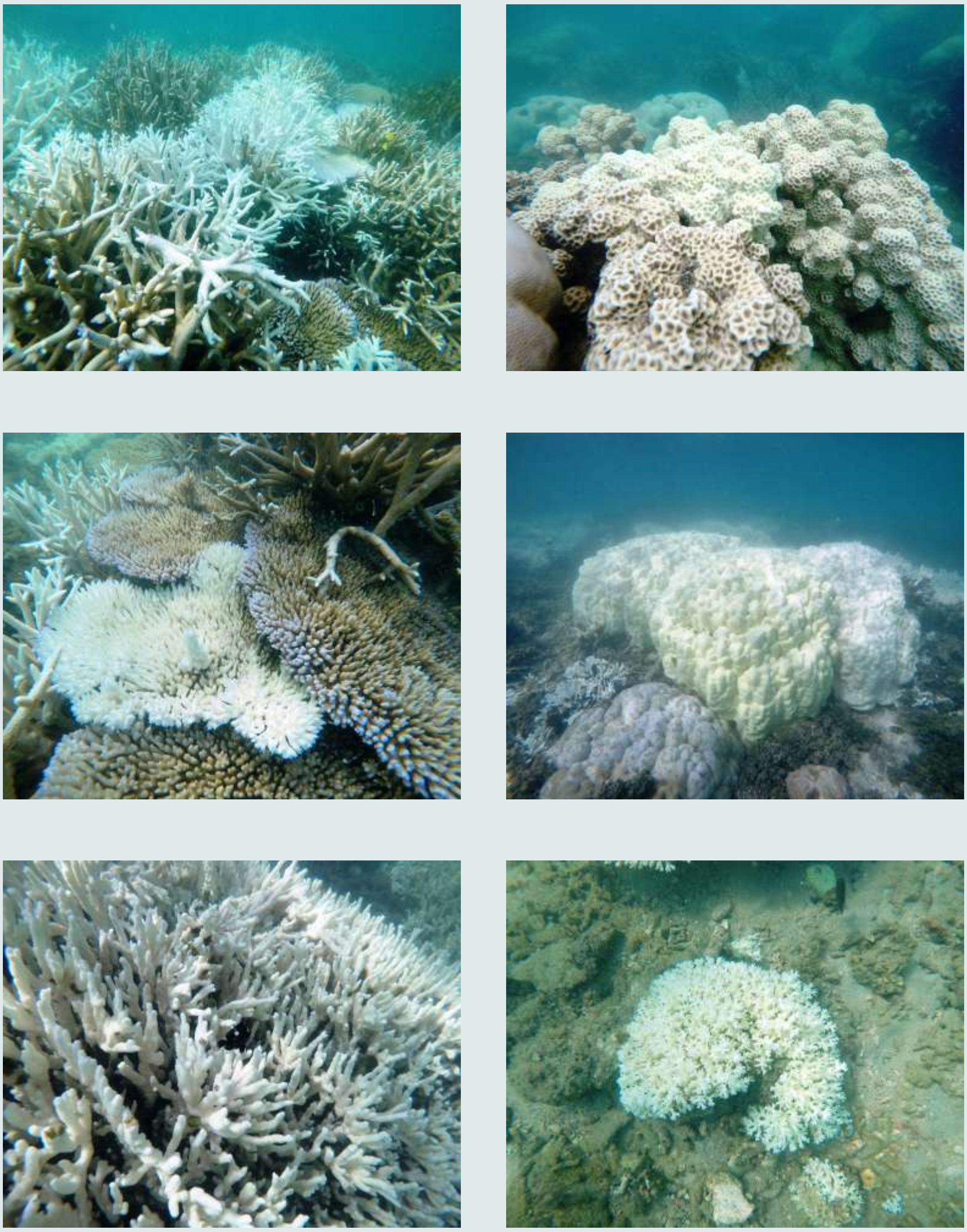
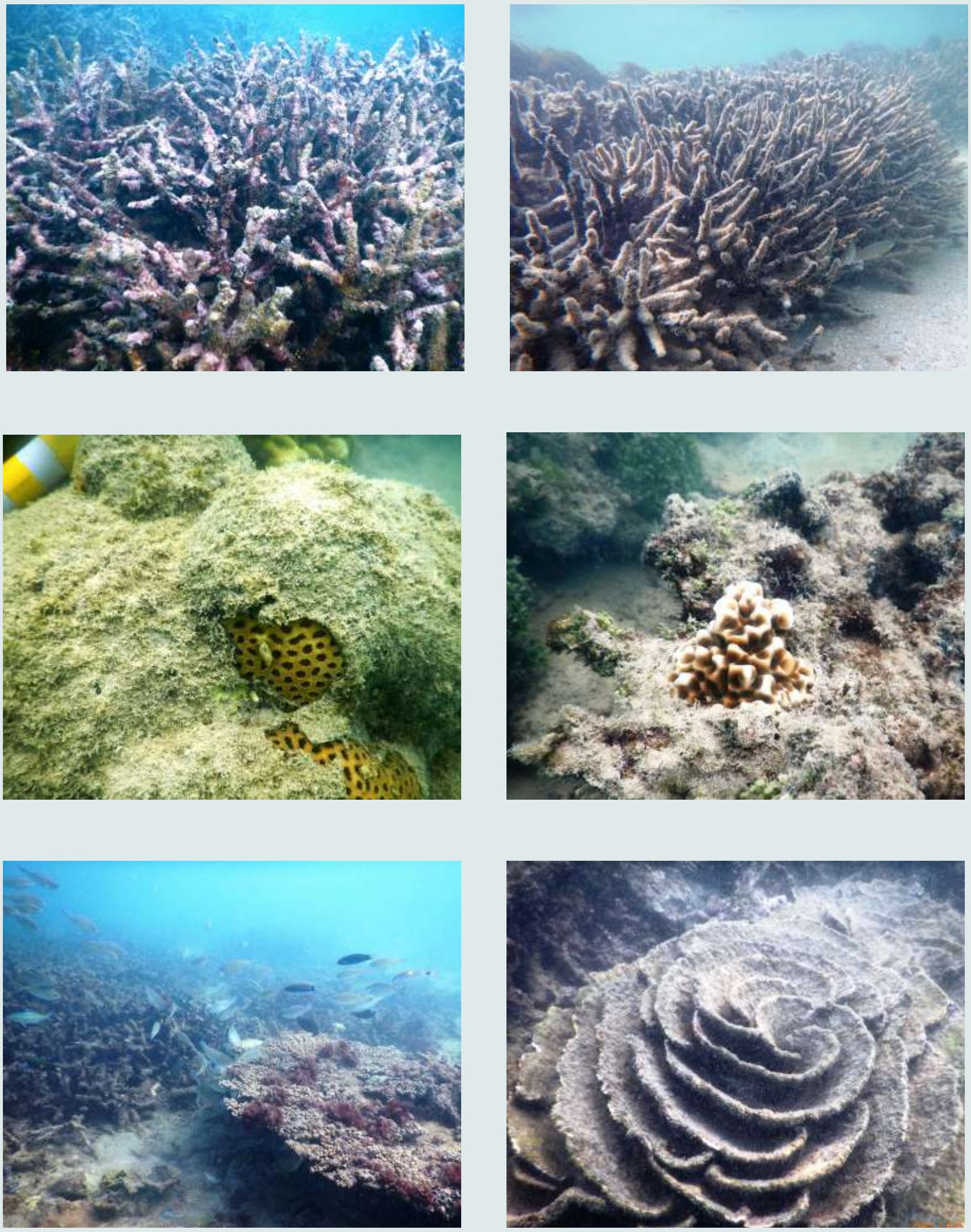
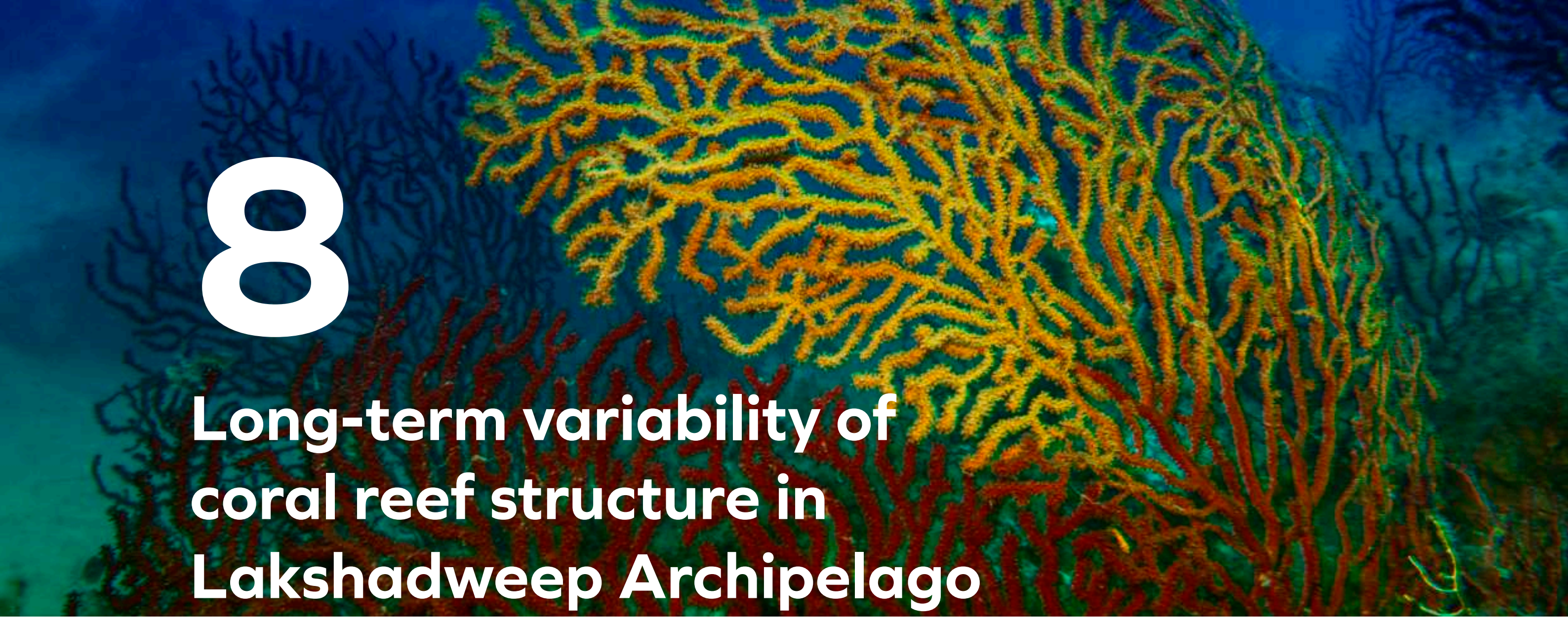


Plate 2: Post bleaching coral mortality in Gulf of Mannar during 3rd Global Bleaching Event





8

Long-term variability of coral reef structure in Lakshadweep Archipelago

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ABSTRACT

The status of community structure and coral health, crucial aspects for developing baseline information on coral reefs were not documented till the mass bleaching event of 1998 from Lakshadweep Islands, India. In an attempt to create accurate baseline information on reef structures through intensive long-term monitoring, data from these reefs were compiled for the last 17 years. The reefs of the Lakshadweep Islands experienced multiple bleaching-related mortalities since the El Nino of 1998 and in 2010, around 65% of the shallow reefs bleached as observed through continuous monitoring of the reef resilience. The year 2016 was declared as an El Nino year with the global sea surface temperatures higher than average. This study documented the status of coral reefs in 12 atolls from 2005 to 2017, highlighting the generic composition and percentage occurrence of different coral species and benthic substrate types. This baseline information will be of much importance to assess the effect of natural and anthropogenic alterations in the coral reef ecosystem of these atolls and its resilience pattern from a long-term perspective.

1. Introduction

Coral reefs, highly restricted in their distribution in tropical and subtropical seas, are the only ecosystem that is strongly defined by geological component (Kleypas et al., 2001). Darwin postulated that the subsidence of volcanic island can result in the evolution of fringing reefs to barrier reefs and atolls (Maragos et al., 1996). Reefs are recognized as complex ecosystems having both biological and geological features. The growth potential of reefs and carbonate platforms depends largely upon the growth of the frame-building organism (Dullo, 2005). The reef is built from coral species but not all corals produce reef (Barnes and Hughes, 1999; Veron, 2000). Scleractinian hermatypic corals with symbiotic zooxanthellae build the reef (Barnes and Hughes, 1999). Coral growth depends on various exotic and endogenic factors prevailing in the region (Buddemmeier and Kinzie, 1976).

The vastness of coral reef ecosystems may be seen in their numerous ecological, aesthetic, economic and cultural functions. Atoll and barrier reef islanders recognize that healthy reefs are essential to support, create, and repair coral islands upon which they live. Coral reefs protect coasts from shoreline erosion, and serve as a living pantry for the subsistence harvest and consumption of many reef organisms and benefiting millions of people around the world (Mongbay, 2011). The cycle of reef accretion and erosion maintains beaches and provides habitat for sea grasses and mangroves. Coral reefs are important recreational resources for most of the world's people having the privilege of living near them (Crosby et al., 1995; Crosby and Maragos, 1995). South Asia, Pacific, Australia, Indian Ocean, Atlantic and the Middle East are the major coral reef regions of the world (Figure 1). The major coral reefs in South Asia occur in the Andaman and Nicobar Islands, Chagos, Maldives and Lakshadweep.

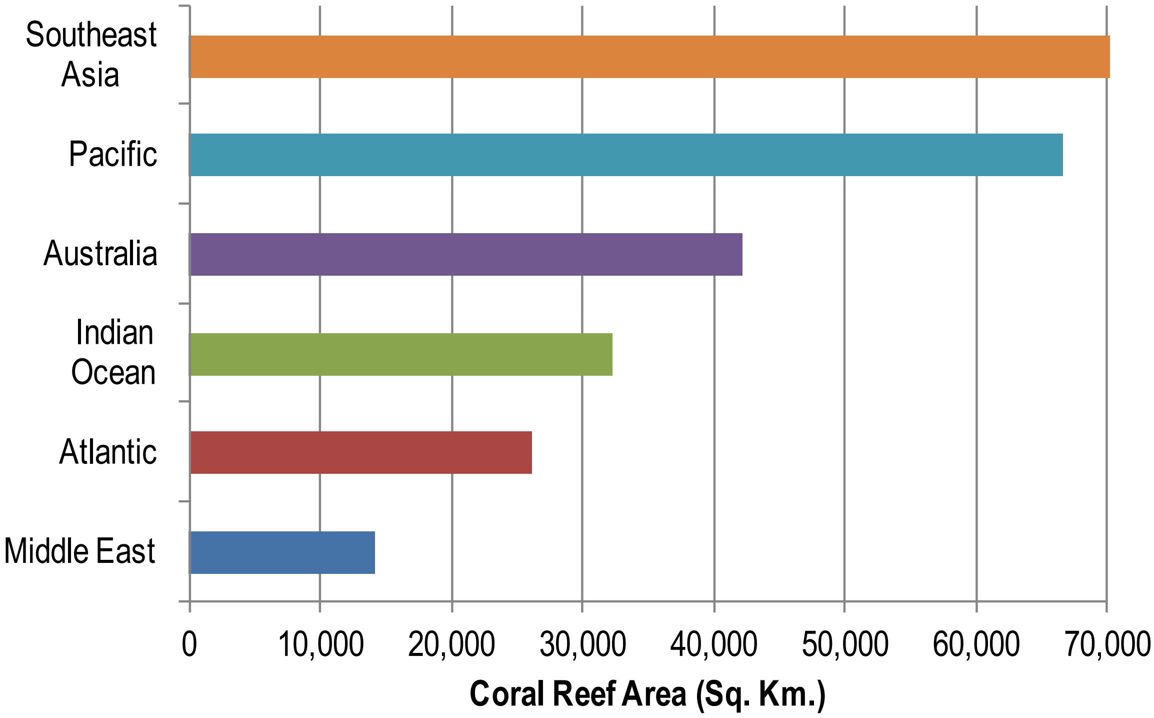

Figure 1: Area of Coral reefs (Sq. Km.) for each coral reef region of the world.
(Source: IMaS/USF, IRD, NASA, UNEP-WCMC, World Fish Centre, WRI 2011)

The reefs of the Indian Ocean consist of atolls, fringing reefs, barrier reefs, patch reefs, elevated banks and submerged banks (Sacratees and Karthigarani, 2008). Coral reefs in India occur principally in the Lakshadweep, Andaman and Nicobar Islands, Gulf of Kachchh, Gulf of Mannar and Palk Bay. The Gulf of Mannar and Palk Bay islands are a series of uninhabited islands with shallow fringing reef. The reef fauna is closely allied to Sri Lankan coral reefs (Arthur, 2000). Corals are also mined illegally in many areas (Pillai, 1986; Arthur et al., 2005). Anthropogenic pressure on this reef, high density of trawlers and boats ply in these waters and high nutrient influxes are the major threats to these reefs systems. Corals, Shells, algae, and echinoderms are extensively collected from the reefs (Arthur, 2000). The major oceanic reefs in India are found in the Lakshadweep islands and the Andaman and Nicobar Islands. Atoll formation of coral reefs occurs only in the Lakshadweep islands. The reefs enclose the islands in extensive lagoons and protect them from storm damage and other ravages of the sea. Coral diversity is high in Lakshadweep and the islands share much of their fauna with the reefs of the Maldives, with some faunal affinity to the reefs of mainland India (Sheppard, 1987). The other minor coastal reefs are in the Gulf of Kachchh, Central West Coast and Vishakapatnam (Rajasuriya et al., 2004). The reefs at Kachchh are fringing reef formations, found primarily in the intertidal region of Kachchh (Arthur, 2000); Coral survives in shallow tidal pools within the vast intertidal flats that characterize this coastline. Several polluting industries fringe the coastline and development continues unabated, sometimes directly affecting reef areas, as in the case of oil refineries building their receiving pipelines through the reef (Arthur, 2000). The reef flat areas of India have been estimated, the extent in Gujarat coast is 148.4 sq.km, of Tamil Nadu coast is 94.3 sq.km, of Lakshadweep is 140.1 sq.km and the Andaman and Nicobar Islands is 813.2 sq.km reef flat (Baldev, 1994).

Lakshadweep is an archipelago in the Arabian Sea in the west coast of India (Figure 2). The islands of the Lakshadweep group are irregularly scattered in the Arabian Sea between 8° and 12°30'N latitude and 71° to74°E longitude (Wagle and Pravin, 1999). Lakshadweep Archipelago consists of 15 atolls. These atolls consist of 10 inhabited islands, 17 uninhabited islands and 3 submerged reefs with a total lagoon area of 4200 km^2. The Lakshadweep group of atolls lies on the prominent North-South Lakshadweep ridge and the alignment appears to be a continuation of the Aravalli strike of Rajasthan. Based on this, many geologists have speculated that the islands are a buried continuation of the Aravalli mountain chain and that the Deccan Traps have been faulted down in the sea along the west coast of India. A great thickness of traps and associated sediments occur to the west, based on a seismic study (Ermenko and Datta, 1968). It was postulated that 1.5 km to 2 km thick volcanic rocks lie below the sea floor on the Lakshadweep ridge. Initial reports of deep sea drilling project indicate the possible connection with western and through this to the eastern shelf of India. Other evidence indicated that the ridge was faulted down in the Lower Eocene when the Lakshadweep Sea was formed and the ridge was separated from peninsular India (Francis and Shor, 1966). The Lakshadweep ridge runs for a distance of 2000 km from Lakshadweep Islands at 14°N latitude to Chagos Islands at 6°N latitude. The ridge rises from the deep sea from a depth of 2000-2700 m in Lakshadweep Sea. The eastern flank of the ridge appears to be steeper than the western one.

Figure 2: Map of Lakshadweep showing various Islands
(Source: Maps of the world)

The atolls show various stages of development of the islands. The reefs at Cheriyapanni, Perumalpar, Bangaram and Suheli represent the earliest stage while Kalpeni, Kavaratti, Agatti and Kadmat are in an intermediate stage and Chetlat and Kiltan are in an advanced or mature stage of development. Lagoons of Kiltan and Chetlat islands are growing at a very fast rate; lagoons are likely to be filled up with sediments in a decade or so, while Andrott Island is one of the matured island formations in this archipelago (Wagle and Pravin, 1999). A typical Lakshadweep island has a north-south orientation and a shallow lagoon on the west with an average depth of 6 m that is connected to the open sea through entrance channels. The sea around Lakshadweep and reef lagoons are of great ecological significance as they influence the fauna and flora associated with the coral reef and the high sea resource to great extent. The water has been found to be highly productive at primary and secondary levels. It is explained that tropical coral reefs, the benthic and symbiotic plants are the key participants in production (Lewis, 1977; Colinvaux, 1986).

The status of community structure and coral health, the important aspects for developing the baseline information on the coral reefs, were not documented till the mass bleaching event of 1998 from Lakshadweep Islands. The attempt to create accurate baseline information on reef structures through intensive long-term monitoring and long-term data from these reefs were compiled over a period of 17 years. The reefs of Lakshadweep islands experienced multiple bleaching-related mortalities since the El Nino of 1998. In 2010, around 65% of the shallow reefs bleached and we continuously monitored the reef resilience and subsequent events in 12 islands of Lakshadweep (Table 1). The status of the coral reefs in 12 atolls of this archipelago highlighting the generic composition and percentage occurrence of different coral species and benthic substrate types has been documented. This baseline information will be of much importance to assess the effect of the natural and anthropogenic alterations in the coral reef ecosystem of these atolls and its resilience pattern from a long-term perspective.

Table 1: Details of islands and lagoon area of Lakshadweep selected for the study

Name of the Island	Latitude	Longitude	Lagoon area	No. of transects used
Agatti	10° 51.347′N	72° 10.530′E	17.5 km^2	25
Amini	11° 07.359′N	72° 43.151′E	1.5 km^2	17
Andrott	10° 48.953′N	73° 40.305′E	0	6
Bitra	11° 35.000′N	72° 10.031′E	45.6 km^2	29
Bangaram	10° 56.932′N	72° 17.384′E	46.2 km^2	28
Chetlat	11° 41.651′N	72° 42.401′E	1.6 km^2	21
Kavaratti	10° 34.057′N	72° 38.353′E	4.9 km^2	25
Kiltan	11° 29.012′N	73° 00.039′E	1.7 km^2	22
Kadmat	11° 13.296′N	72° 45.888′E	37.5 km^2	27
Kalpeni	10° 05.513′N	73° 37.849′E	25.6 km^2	27
Suheli	10° 04.453′N	72° 16.552′E	78.6 km^2	38
Minicoy	08° 17.963′N	73° 02.179′E	30.6 km^2	27

A preliminary attempt was made to assess the status of the coral reefs of 12 atolls of Lakshadweep Archipelago. Benthic substrate composition, quantitative description of the percentage cover of the coral species and relative abundance and proportional distribution of corals in these atolls were documented.

Most serious threat to Lakshadweep coral reef happened in 1998 with the massive bleaching of corals that laid bare several reefs stretches, more than 80% of the coral cover was adversely affected (Srivastava and Koya, 1998; Arthur 2000; Vivekanandan et al., 2008). This estimation of bleaching is based on a study in two selected island after the bleaching events took place (Arthur, 2000).

The status of coral health and trends of the coral reef of islands were not known before the mass bleaching event of 1998 as reported by Srivastava and Koya (1998), Arthur (2000) and Ravindran et al. (2001). After the 1998 bleaching event, there was a stress on the live coral cover during 2002 and 2003, manifested by the slower resilience of corals in these atolls (Idreesbabu and Sureshkumar, 2016). The maximum temperature recorded during 2016 was 31.29°C. However, the western shallow reef especially the reef flat depth ranging from 6 to 10 m showed high impacts of bleaching with maximum coral mortality and decline in live coral cover during 2015-2016 bleach event. Besides natural threats, anthropogenic activities due to the changing demographic pattern and lifestyle, coupled with resource harvest from reefs at more than sustenance levels, have brought various degrees of stress to the reef. Sewage, dredging and coral mining are other major anthropogenic threats to these atolls.

2. Field survey techniques and data analysis

Data on the benthic community were collected using line intercept transects (LIT) at water depths from 1 m to 21 m to obtain the reef profile and coral percentage cover (Loya, 1972; English et al., 1994). Transects were laid horizontally along the substratum and data collected along each transect. The projected length of each substrate category or coral species beneath the 20 m line was recorded to the nearest centimetre. Among the substrate category, live corals were identified up to genus/species level and the position of every change in substrate type was recorded as suggested by Global Coral Reef Monitoring Network (GCRMN) manual (Hill and Wilkinson, 2004). Underwater photography and video documentation were also conducted to refine the quality of the data collected manually by further observation and discussion. A total of 296 LIT of 20 m long transects line were laid parallel to the reefs of the selected atolls. All the LIT were laid at randomly selected locations covering lagoon, inner reef slope and outer reef slope which were marked using permanent submerged markers and GPS locations during April to December 2005. The number of transect for each island was decided based on the area of the atolls and the lagoon area (Table1).

All these transect were monitored on yearly basis during August to April for continuous recording of data; however additional surveys were conducted soon after the bleaching from 2010 onwards. Percentage cover of coral was observed from different atolls with the help of snorkelling and SCUBA diving to collect the information on the broader geographic variation of coral species distributed in different geomorphologic zones. Genus and species level data on the corals were collected using the Indo Pacific Coral Finder robust underwater plastic book (Kelley, 2009). Data on the interval of occurrence of coral species and other mixed benthic substratum were recorded on a PVC slate. From the base data, the quantitative description on the percentage cover of the coral species and benthic substrate composition status were worked out. Photographic and video documentation was also carried out to find the different types of anthropogenic and other natural threats to the corals. Reference data on the live coral cover during 2001-2004 were collected from Lakshadweep Coral Reef Monitoring Network (Sayed Ismail and Idreesbabu, 2011).

The length of each substrate type directly underneath the tape measure of each line intercept transect (LIT) was averaged over the replicates separately for the lagoon and outer reef slope of each atoll. Calculation of the percentage of benthic substrate composition type was based on the contribution of each substratum to the total length of the projection. Mean percentage occurrence of coral species in the different sites was estimated directly from their densities in transects. The average percentage covers estimated were compared between islands to determine variation in the benthic substratum. Microsoft Excel for Windows was used for tabulation and descriptive statistical analysis. Primer 6 software (Clarke and Warwick, 2001) was used for diversity analysis. Bray-Curtis similarity method was used to evaluate the distance or similarities between the coral reef area of different atolls and similarities in the mixed picture of the benthic status and percentage of coral species coverage in different reefs of the studied atolls. Non-metric multidimensional scaling was also adapted to configure the points in Euclidean space between the coral reef area based on the mixed picture of the benthic status and percentage of coral species coverage in different reefs of various atolls (Clarke and Warwick, 2001). Temperature data collected based on the real-time data buoys and under water Hobo data loggers deployed in and around Lakshadweep Sea by the Department of Science & Technology in association with NCSCM, SAC and NIOT.

3. The mixed picture of the benthic status of the Lakshadweep reefs

The plot with the help of reference data from 2001 to 2004 showed that we could realize a mixed picture of the benthic status of the Lakshadweep reefs, after the 1998 bleaching event, there was a stress on the live coral cover during 2002 and 2003 manifested by slower growth in these atolls (Figure 3). This rapid loss of coral structure could have major flow-on consequences for a host of ecological processes dependent on the complexity of the reef framework. Recovery of the live coral cover was observed from 2005 onwards and reached 35.25% by March 2010. Algal turf was found to be the dominant benthic component in the reefs of Lakshadweep atolls subsequent to the bleaching event, which reached 32% of the total area in 2010 (Figure 3). Significant variability was observed in the cover of turf algae between the atolls. A sharp decline in the percentage of live coral cover was observed after the last week of March 2010 bleaching event due to the SST variability in Lakshadweep Sea (Figure 4) in all the 12 atolls of Lakshadweep archipelago. The benthic status of the reef, before the 2010 bleaching event, showed that live coral cover was above 35% which indicates a good health status of the reef of this archipelago (Figures 5 and 6).

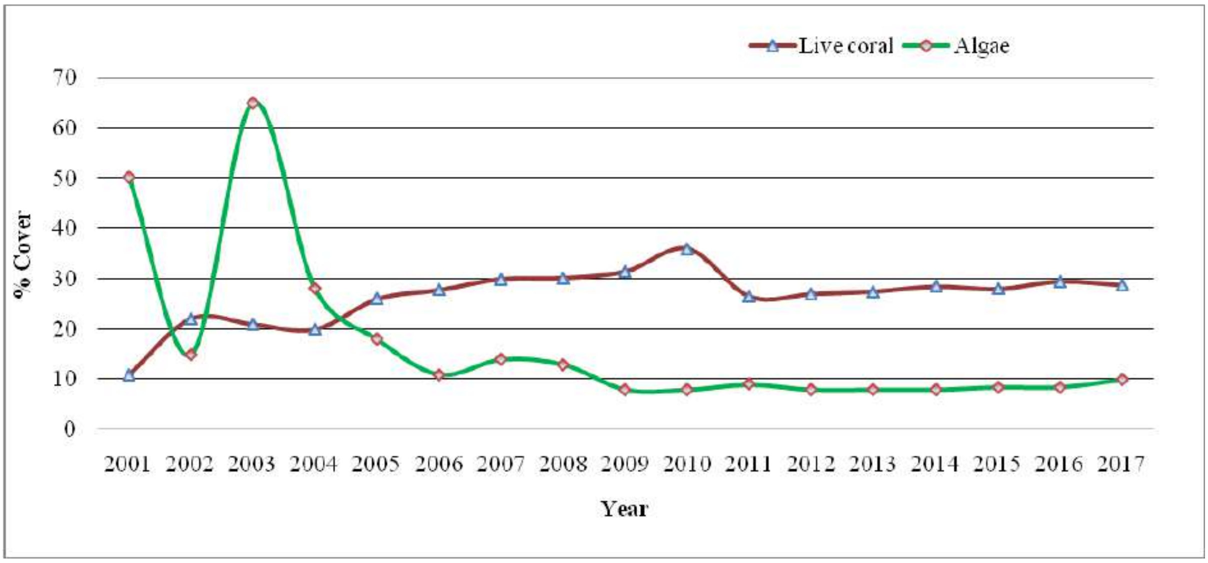

Figure 3: Mean percentage cover of live coral and algal turf during 2001-2017

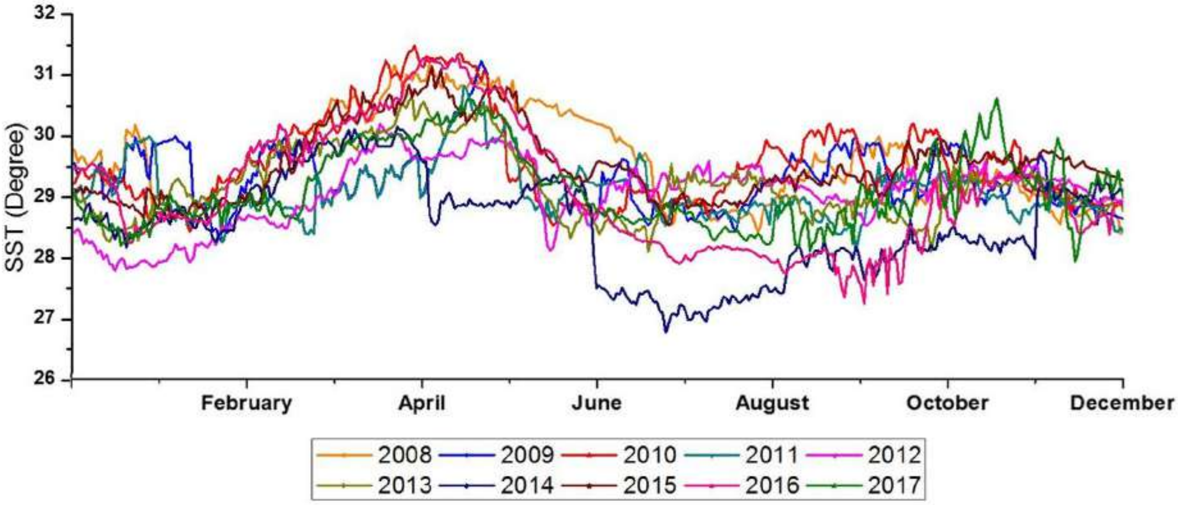

Figure 4: Sea Surface Temperature (SST) variability in Laksksshadweep Sea

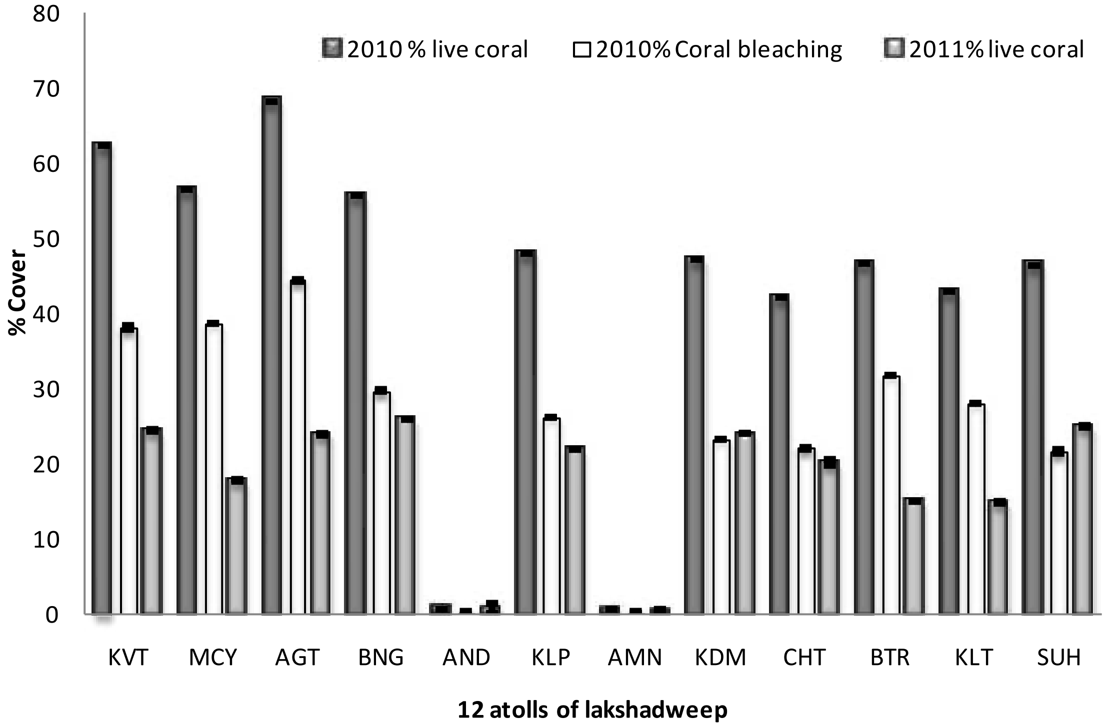

Figure 5: Percentage cover of live corals in various lagoons of Lakshadweep archipelago during 2010-2011
KVT-Kavaratti, MCY- Minicoy, AGT-Agatti, BNG-Bangaram, AND- Andrott, KLP-Kalpeni, AMN-Amini, KDM- Kadmat, CHT-Chetlat, BTR-Bitra, KLT-Kiltan and SUH-Suhel

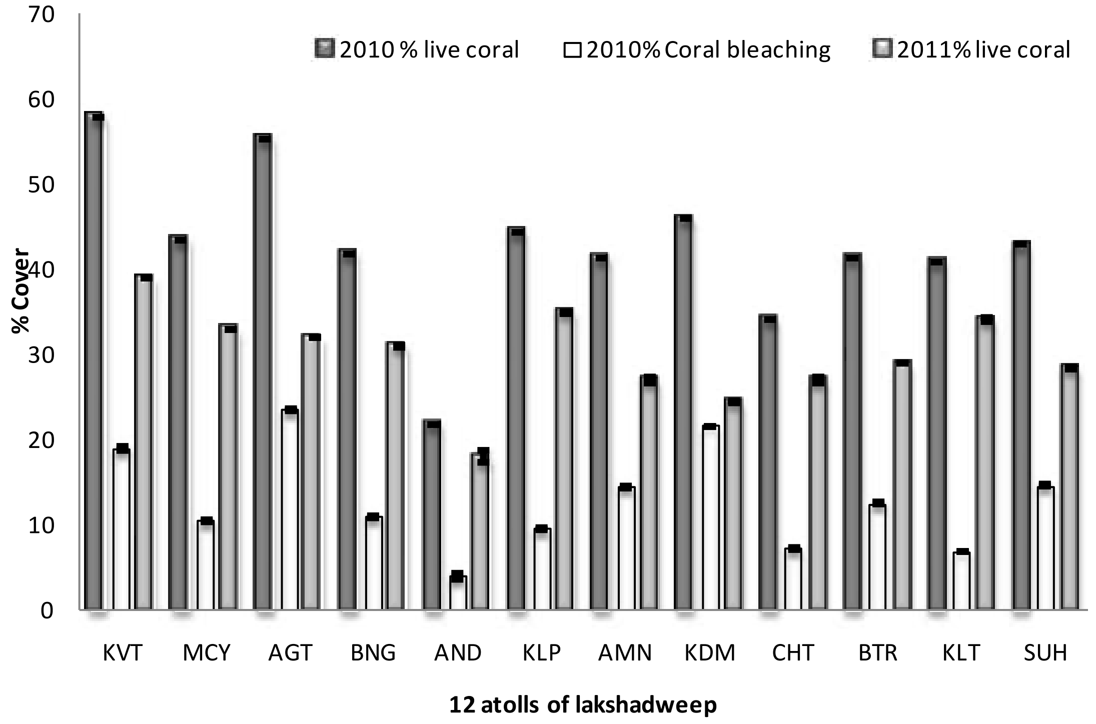

Figure 6: Percentage cover of live corals in the outer reef slope of various islands of Lakshadweep archipelago during 2010-2011
KVT-Kavaratti, MCY- Minicoy, AGT-Agatti, BNG-Bangaram, AND- Andrott, KLP-Kalpeni, AMN-Amini, KDM- Kadmat, CHT-Chetlat, BTR-Bitra, KLT-Kiltan and SUH-Suheli






In early 2015, the National Oceanic and Atmospheric Administration (NOAA) officially declared it to be an El Nino year, predicting that global sea surface temperatures might be higher than normal, the continued monitoring and recording of the Lakshadweep coral reef SST during 2010 to 2016 confirm that the average SST during these years was 29.14°C this probably resulted in adaptation of corals in shallow areas of these lagoons to the hotter temperature which showed moderate bleaching of live corals in intermediate lagoon and inner slope of lagoon area during 2015-2016 El Nino effect. The maximum temperature recorded during April 2016 was 31.29°C. However, the western shallow reef especially the reef fladepth ranging from 6 to 10 m showed high impacts of bleaching with maximum coral mortality and decline in live coral cover during 2015-2016 bleach events (Figure 3).

4. Benthic cover

Live coral cover varied considerably in reef across the atolls of Lakshadweep and clear difference in benthic composition was apparent between the lagoon and outer reef slope and also between east and west reef of the atolls. Lagoons in the Lakshadweep archipelago with a depth range of 1m to 6m had comparatively higher live coral cover. Table 2 details the benthic status worked out for the twelve atolls. Western shallow reefs showed the highest impacts of bleaching, with the highest coral mortality and decline in live coral cover. Western deep reef sites, largely dominated by massive, bleaching resistant coral species, showed relatively low bleaching impacts. Eastern reefs too illustrate a similar trend, but owing to naturally low pre-bleaching coral cover, showed fewer declines in the coral cover than western reef sites. Lagoon sites had the highest live coral cover, owing, most probably, to the adaptation to hotter temperatures in shallow environments. Composition and percentage occurrence of different coral genus/species in different atolls showed significant variations. Percentage cover of live coral species in the reefs of Agatti, Bangaram, Kavaratti, Suheli and Bitra islands showed 83% similarity among them. Kalpeni and Minicoy (85%) and Chetlat and Kiltan (92%) showed greater similarity in their percentage of the live coral cover, while Kadmat and Amini showed only 63.5% similarity. Andrott Island showed only 40% similarity with all other atolls based on percentage cover of live coral species in the reef (Figure 7).

The most common genera projected in the line intercept transect include Acropora, Pocillopora, Porites, Platygyra, Favites, Favia, Hyndnopora and Pavona. Echinopora, Goniopora, Stylophora and Montipora established weak geographic trends in the composition of coral species across the atolls (Table 3). Similarly, atolls of Kavaratti, Kalpeni, Kadamat, Bangaram and Minicoy formed a group, while, Agatti, Amini, Bitra, Chetlat, Kiltan and Suheli atolls form another group and Andrott is very distinct in the case of benthic substrate composition (Figure 8).

Table 2: Percentage mixed picture of the benthic status of reef of Lakshadweep Island 2011

Atolls	Live Coral	Dead Coral	Rubbles	Rock	Sand	Algae	Others
Agatti	42.80± 0.06	38.50± 0.09	1.00± 0.11	2.00± 0.11	5.50± 0.21	9.00± 0.04	2.00± 0.63
Amini	30.50± 0.26	38.00± 0.06	7.00± 0.91	2.00± 0.26	9.50± 0.28	8.50± 0.09	5.00± 0.63
Andrott	11.50± 0.66	31.00± 0.19	6.50± 0.91	1.50± 0.61	8.00± 0.19	34.50± 0.06	7.00± 0.33
Bangaram	31.00± 0.06	32.00± 0.09	11.00± 0.11	9.00± 0.21	7.00± 0.16	3.00± 0.23	6.50± 0.63
Bitra	30.10± 0.06	38.50± 0.09	6.00± 0.11	3.00± 0.21	5.50± 0.16	9.00± 0.06	8.00± 0.73
Chetlat	25.00± 0.32	41.80± 0.21	3.50± 0.61	5.60± 0.91	5.50± 0.36	12.00± 0.16	6.00± 0.63
Kadmat	34.80± 0.06	35.00± 0.09	10.00± 0.11	4.80± 0.21	3.50± 0.16	5.60± 0.16	6.30± 0.35
Kalpeni	35.00± 0.08	29.00± 0.09	5.60± 0.13	20.00± 0.21	2.40±0.16	5.00±0.16	3.00± 0.63
Kavaratti	39.00± 0.06	40.00± 0.09	4.00± 0.21	8.00± 0.21	3.50±0.16	3.00±0.26	2.50± 0.63
Kiltan	29.03± 0.16	38.00± 0.19	8.00± 0.21	2.00± 0.23	6.00±0.17	13.00±0.04	4.00± 0.61
Minicoy	33.00± 0.06	34.50± 0.09	6.50± 0.11	3.00± 0.21	5.00±0.16	3.50±0.26	4.00± 0.73
Suheli	30.07± 0.06	45.00± 0.09	1.50± 0.11	2.50± 0.21	5.50±0.16	7.30±0.06	8.00± 0.61

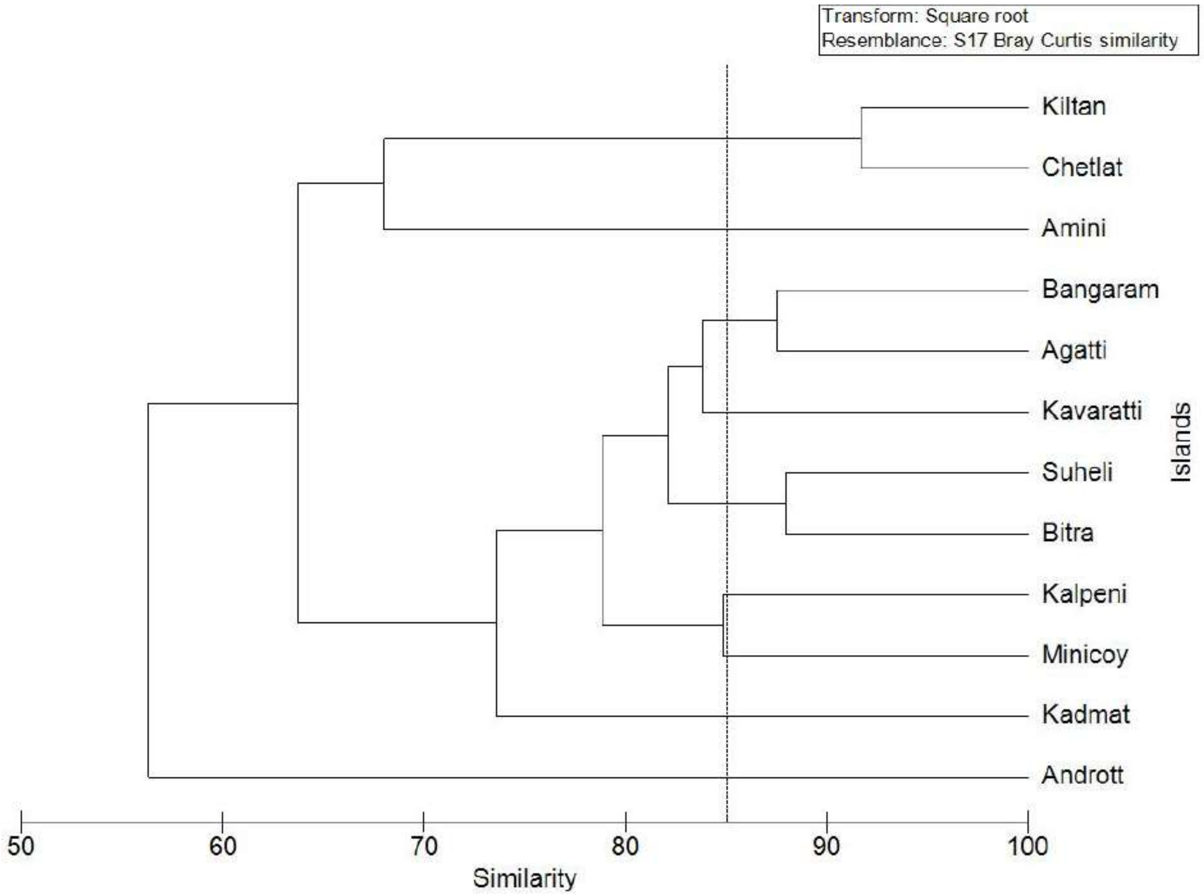

Figure 7: Clustering of the reefs of Lakshadweep based on the percentage cover of live coral cover

Table 3: Generic composition of live coral cover in various islands of Lakshadweep

	KVT	MCY	AGT	BNG	AND	KLP	AMN	KDM	CHT	BTR	KLT	SUH
Acropora formosa	1.8	0.8	2.4	3.4	0	0	0.25	0	0	2.4	2.02	0.9
Acropora hyacinthus	2.8	0.3	5	0.4	0.4	0.3	0	4.02	0.2	0.8	0.2	0.6
Acropora humilis	1.08	2.2	2.8	0.17	0.1	2.2	0	3.3	0.12	0.12	0	0.12
Acropora digitifera	2.4	2.5	3.08	2	0	0.4	0	3.3	0.13	0.6	0	0.6
Pocillopora damicornis	5	1.02	7	1.03	0.7	0.6	0.1	0.3	0.3	1.6	0.3	1.6
Porites solida	8.6	8.9	6.8	3.1	2.3	9.6	6.2	8.5	6.3	9.2	6.3	10.02
Porites lutia	5.2	3.8	3.2	2.01	1.4	3.8	2.05	6.6	3.2	5.3	3.2	7.3
Porites sp.	3.04	4.02	4	4	4.3	3.01	1.4	1.2	0.2	3.5	0.7	3.5
Platygyra sp.	1.3	0.5	1.3	1.3	0.02	0.5	0.5	4.2	0.4	1.04	0.4	3.2
Favites sp.	0.8	0.3	1	1	0.3	0.3	0.2	3	0.6	3.2	0.6	0.08
Favia sp.	0.6	0.4	0.6	0.6	0.02	0.3	0.1	1	0.3	3.1	0.3	0.6
Hyndnopora sp.	0.2	0.8	2.1	2.1	0	0.8	0	0	1.2	0.32	1.2	0.32
Pavona sp.	3.6	0.19	1.1	1.1	0	2.8	0	2	0	2.2	0	0.8
Echinopora sp.	3.1	0.08	4	4	0.2	3.8	4	3	0.38	4.8	0.38	2.5
Goniopora sp.	2.2	1.63	0.8	0.8	0.7	1.63	0.2	1.3	0.3	1.03	0.3	1.03
Stylophora sp.	1.3	1.43	2.5	2.5	0.1	4	0.3	0.7	4.2	3.6	4.2	3.6
Montipora sp.	0.9	1.6	1.8	1.8	0.8	2.1	3	1.3	9.8	2.3	9.8	2.3
soft corals	2	0.6	4	3.01	0	0.6	0	0	0.13	2.01	0.13	3.29

KVT-Kavaratti, MCY- Minicoy, AGT-Agatti, BNG-Bangaram, AND- Andrott, KLP-Kalpeni, AMN-Amini,
KDM- Kadmat, CHT-Chetlat, BTR-Bitra, KLT-Kiltan and SUH-Suheli

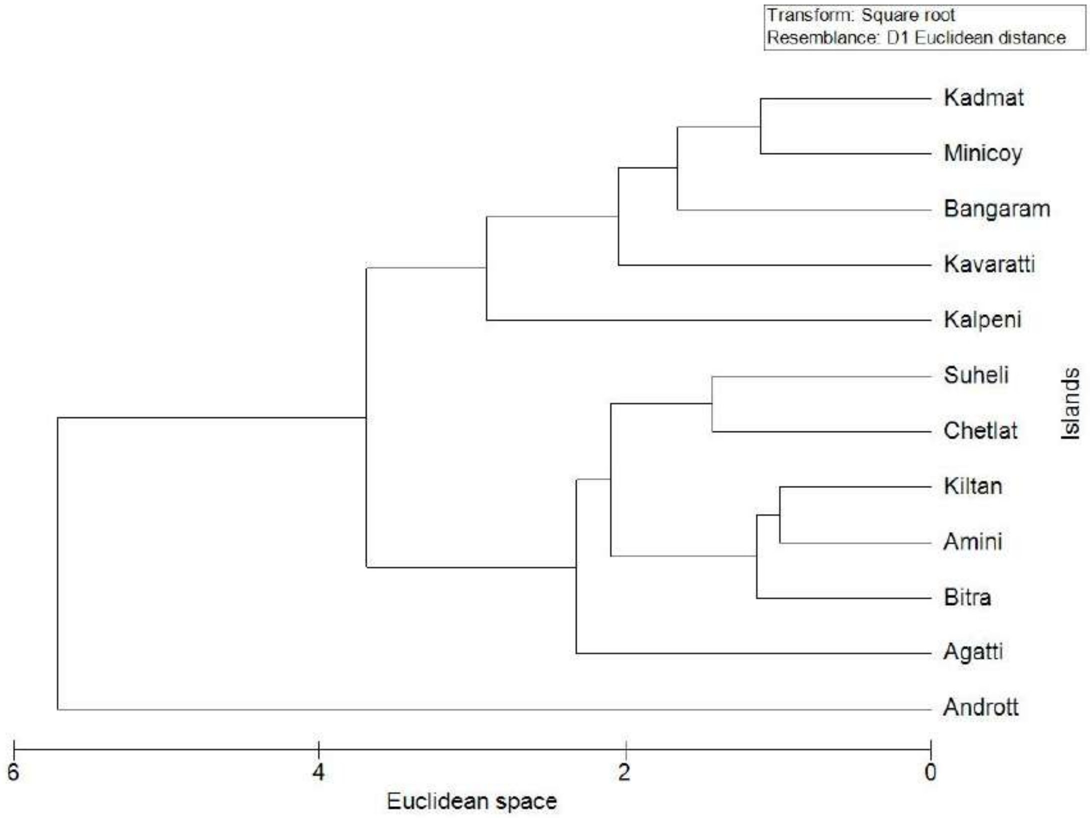

Figure 8: Clustering of the reefs of Lakshadweep based on the status of benthic substrate

5. Structural complexity through biological and physical factors

Reduction in live coral cover could bring in a major shift in the benthic status with the luxurious growth of macroalgae in elevated temperature using dead coral as substratum. On an average, 36% of the total benthic substratum was occupied by algal turf in the reefs of Lakshadweep atolls after the 2002 bleaching event (Figure 3). The loss of live coral benefitted opportunistic species like fleshy macroalgae, which often rapidly dominate benthic substrate, drastically shifting functional position, and potentially hinder the re-colonisation of corals in these areas (Bellwood et al., 2004, Arthur et al., 2006). Present findings point towards the structural changes in the benthic status of coral reef ecosystem with the loss of live coral cover. Reduction in live coral cover eventually leads to a change in ecosystem structure, which indicates their significance in maintaining functional element in the coral reef ecosystem.

Andrott Island showed a significantly different benthic mixture substrate composition compared to other atolls of the archipelago (Figure 8). During field observation, the sighting frequencies of the shoal of herbivore fishes in Andrott reef were comparatively low, in contrast to the other reefs of the archipelago. Fishes of families of Acanthuridae and Scaridae play important role in controlling algal biomass on Lakshadweep Island (Cernohorsky et al., 2015). This may be the reason for the low percentage cover of live coral in Andrott Island among the atoll chain. Result also indicated that live coral percentage covers were 11.50% which was considerably low, as algal coverage dominated and restricted the projection of live coral. Loss of live hard coral either by anthropogenic or natural causes and the consequent shifts in the structure of coral communities will almost universally have impacted on fish communities (Wilson et al., 2006; Coker et al., 2012). The dominance of algal turf in benthic substratum may be due to the low sighting frequency of shoal of herbivorous fishes when compared to the other reefs of the atolls. Herbivorous fishes potentially provide opportunities for corals to recover between the disturbance events (Cote and Darling, 2010; Gilmour et al., 2013).

During the beginning of the bleaching event there was a decrease in sighting frequency of butterflyfishes and other corallivorous fishes, however sighting frequency of *Acanthaster planci* was relatively high, generally in all the atolls of the archipelago. Furthermore, zooxanthellae symbiotic organisms such as giant clams, sea anemones and zoanthids were found to be affected by the increase in SST (Plate 1). A change was observed in reef-associated fishes and other reef-associated organisms in Agatti during the 2010 bleaching event. Besides the effect of SST on coral reef, other natural threats that directly or indirectly stress the island coral reef are predation of corals by starfish *Acanthaster planci*, coral diseases and other anthropogenic activities.

6. Climate Change and Lakshadweep coral reef

The status of coral health and trends of the coral reef of Lakshadweep Islands were not known before the mass bleaching event of 1998. Moreover, the status of the coral reef is restricted to qualitative descriptions. A quantitative description on the percentage cover and abundance of the coral species and the benthic substrate composition status of the Lakshadweep reefs are essential for the assessments of reef health and inevitable to create accurate baselines for long-term monitoring (Idrees Babu, 2014). The Lakshadweep atoll reef is high diversity coral formations that appear to be particularly vulnerable to changes in sea surface temperatures. The pan-tropical 1998 El Niño resulted in a coral mass mortality of between 80-90% in most surveyed reefs (Arthur 2000), and our work over the last decade in this island group has focused on tracking the further decline and recovery of these systems from that event (Arthur, 2005; Arthur 2008; Arthur et al., 2006; Arthur et al., 2005, Idrees Babu, 2014; Idrees Babu and Suresh Kumar, 2016).

Long-term data on coral reef ecosystem provide good opportunity to examine and explain the temporal variation in the impact of various stressors on the coral reef health and trends (Sutthacheep et al., 2013). The last 15 years have witnessed a mixed reef recovery in Lakshadweep, including some surprisingly rapid rates of coral recolonisation and growth at some locations, and very shallow recovery at others (Arthur, 2000; Arthur, 2005; Arthur 2008; Arthur et al., 2006; Idrees Babu 2014; Idrees Babu and Suresh Kumar, 2016). The graph, plotted with data from 2001 to 2016, provided a long time trend in status and impact of the corals and its structural changes in the Lakshadweep atolls (Figure 3). The result of the finding showed that after the 1998 bleaching event, there was a stress on the live coral cover during 2002 and 2003 manifested by slower growth in these atolls. This stress was due to increased sea surface temperature (SST) which follow-on bleaching of coral in these atolls during 2002. Annual mean SST trend showed that the reef areas of Lakshadweep have warmed from 28.50°C in 1985 to 28.92°C in 2005, at a rate of 0.21°C per decade (Vivekanandan et al., 2008). Such temperature rises affect the Indian coral reefs, which have experienced widespread bleaching events in 1989, 1998 and 2002 (Arthur, 2000; Rajasuriya, 2002; Rajasuriya et al., 2004). Arthur (2000) and Arthur et al. (2005) found that the effects of El Niño corresponded to the mass mortality of coral in the Arabian Sea. Coral bleaching follows anomalously high seawater temperatures, usually interacting with high levels of irradiation (Hoegh-Guldberg, 1999). The finding shows that atolls of Lakshadweep coral reef experienced coral bleaching after 1998 El Niño, in 2002 and 2010. The results of this study also indicate that the 2010 coral bleaching phenomenon was more severe than the 2002 bleaching event. The impact of earlier experience on coral bleaching susceptibility may become increasingly significant in shaping coral responses to temperature and solar radiation stresses in the future (Brown et al., 2002). Observations also showed that the reduction in live coral cover resulted in major changes in the benthic status, which will lead to the growth of macroalgae by using dead coral as the substratum to grow. Algal turf was found to be the dominant benthic component subsequent to the 2002 and 2010 bleaching event. On an average 36% of the total benthic substratum was occupied by algal turf in the reefs of Lakshadweep atolls (Figure 3). Considerable variability was observed in the cover of turf algae among the atolls. Similar observation was also made consequent to the 2010 and 2016 bleaching event. Loss of live coral benefitted opportunistic species like fleshy macroalgae, which often rapidly dominate benthic substrate, drastically shifting functional position, and potentially hinder the re-colonisation of corals in these areas (Bellwood et al., 2004, Arthur et al., 2006). The findings point towards the structural changes in the benthic status of coral reef ecosystem with the loss of live coral cover. Reduction in live coral cover will eventually lead to a change in ecosystem structure and maintenance of the functional element in the coral reef ecosystem (Plate 1).

Plate 1: Effect of bleaching on different zooxanthelle symbiotic organisms in Agatti and Kavaratti Atolls

A. Coral before bleaching, January 2010
B. Coral after bleaching (Outer reef slope Kavaratti, April 2010
C. Anemone, before bleaching, February 2010
D. Lagoon of Kavaratti after bleaching, April 2010
E. *Tridacna maxima* (Giant clam) before bleaching, January 2010
F. Inner reef of Agatti after bleaching

7. Anthropogenic Intervention

Beside natural threats, anthropogenic activities have also increased stress of the coral reef. The people of Lakshadweep Islands have traditionally been dependent on fishing for livelihood and socioeconomic benefits. Coral reefs, which are economically important resources to most tropical countries, are declared as the critically endangered ecosystems on the globe (Sutthacheep et al., 2013). Unmanaged harvesting of coral-associated fishes as live bait for tuna pole and line fishing and unsustainable harvesting of herbivorous fishes like surgeonfishes and parrotfishes also cause destruction of habitat and cause stress to the coral reef system. Approximately 75% of the world's coral reefs are categorized as threatened and combined with the local stresses and thermal due to rising seawater temperature will lead to widespread weakening and mortality of corals (Burke et al., 2011).

Changing demographic pattern and lifestyle, coupled with resource harvest from the reefs at more than sustenance levels, have brought various degrees of stress to the reef. Sewage, dredging, sedimentation and coral mining are the other major anthropogenic threats to these atolls (Plate 2).

The people do not maintain any record of the quantity of live bait used in a particular tuna fishing season, but they talk about the decline in live bait fishes. There is a high decline of live bait population in lagoons like Agatti and Kavaratti. Species like *Spratelloides delicatulus* and *S. japonicus* are preferred live bait for pole and line fishery. Due to the decline in the population of these two species, fishermen now target other easily available fishes like Chromis sp. (Family Pomacentridae), which are closely associated with Acropora corals, invariably increasing the negative pressure on the corals. Fish assemblages display a negative relationship to the two stressors, climate impacts and fishing, independently resulting in a different combination of species (McClanahan et al., 2014). The ability of coral reef ecosystems to exist in balanced harmony with other naturally occurring competing/limiting physicochemical and biological agents has been severely challenged in the last several decades by the dramatically increased negative and synergistic impacts from poorly managed anthropogenic activities (Crosby and Reese, 1996). Some other relevant anthropogenic pressure on the coral reef of Lakshadweep was documented also during the study.

8. Management measures

Systematic monitoring of the reef is one of the prime necessities to frame conservation and management strategies. Preliminary inventorisation of biodiversity was initiated with the collaboration of the Department of Science and Technology, UT of Lakshadweep with other National Institutes and Universities. Coral monitoring Programme initiated a decade back is continuing which forms the database for assessment of coral damages and coral health on a long time perspective. Variability in physicochemical parameters of many of the reefs has been monitored in a systematic manner. Improvements in the educational status and awareness of the islanders and higher involvement of NGOs towards conservation has supported in their participation for data acquisition and implementation of conservation programmes. It is important to have the participation of all stakeholders for the conservation of coral reefs.

Plate 2: Natural and anthropogenic threat to the reefs of Lakshadweep

A. Coral bleached inside the lagoon of Kavaratti during 2010 bleaching event
B. Algae dominated coral subsequent to the bleaching event at Kavaratti inner reef
C. Pink band coral diseases observed during the study at Agatti reef
D. Predation of corals by Acanthaster planci in Kavaratti reef
E. Unsustainable harvest of Acanthurus triostegus (Convict Surgeonfish a predominant herbivore fish) leading to stress of corals
F. Distraction of habitat and impart stress, increase negative pressure on the corals. Octopus-fishing at Kavaratti reef

Recommendations

Some of the immediate measures that is necessary for conservation of the biodiversity of the island are -

- Strengthening of coral reef monitoring with inclusion of more species in the programme to provide baseline information on biodiversity changes and environmental transformation
- Emphasising continuous monitoring of the oceanographic parameters of Lakshadweep Sea at local points pertaining to islands
- Increasing awareness programs for creating knowledge on management and conservation among the public
- Declaring some of the uninhabited islands as Marine Protected Areas (MPA)/ non-fishing area/ restricted area for in situ conservation of the biodiversity
- Regulating through community-based approach to develop local stakeholders
- Carrying out impact assessment in all islands specifically on discharge of domestic sewage and tourism
- Formulating conservation measures with the collaboration of National Institutes and Universities and mobilising necessary funds for the implementation

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9

Mass coral bleaching responses from Indian coral reef regions

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ABSTRACT

Frequent coral bleaching events occurring over larger geographical scales or Mass Coral Bleaching (MCB) is a relatively new phenomenon. Application of satellite- derived SST data and data products are used to understand coral bleaching phenomena over Indian reefs. This chapter discusses historical MCB responses from the Indian coral reef regions in light of two major bleaching indices based on sixty-seven years' historical SST reconstructed from HadISST1 data. The five Indian coral reef regions show distinct regional sensitivities towards bleaching thresholds, anomalous Sea Surface Temperature (SST) and MCB responses. HadISST1 data proves its potential towards a long-term SST reconstruction and hindcast past MCB events for Indian reef regions. MCB forecasts can be significantly improved if regional sensitivities are embedded in the forecast models. Long- term coral bleaching forewarning programmes need to be supported with *in situ* bleached cover monitoring for better feedbacks and improvisation of the forewarning capabilities.

1. Introduction: Coral Bleaching and Bleaching Indices

Coral bleaching events are considered as 'biological signal'(s) or consequences of global warming (Hughes, 2000). Bleaching is a cellular response to environmental stresses (Lesser, 2004) wherein marine invertebrates are forced to expel their endosymbiont, unicellular microalgae or zooxanthellae from their host tissues. These unicellular algae are called zooxanthellae due to their yellow-brown colour and are classified as dinoflagellates belonging to the genus *Symbiodinium* sp. (Stambler, 2011). The loss of zooxanthellae and reduction in their photosynthetic pigment concentration per cell leads to the visible paling or whitening of the host organism as the yellow-brown pigment of the endosymbiont is lost. Reef-scale bleaching events not only affect the principal reef-builders or the corals but also involve numerous other reef-invertebrates like sea anemones, snails, clams, sponges and even some single-celled ciliates (Ray Chaudhury, 2013). Hence, coral reef bleaching is considered to be a better descriptor of these reef-scale events rather than the restrictive term `coral bleaching' (Baker et al., 2008). Coral bleaching at local scales (10 – 1000 sq. m) has been recorded for almost a century ever since Yonge and Nichols reported a mass bleaching event from the Great Barrier Reef of Australia in 1931 (Hoegh-Guldberg et al., 2009). Frequent coral bleaching events occurring over larger geographical scales or more precisely Mass Coral Bleaching (MCB) is rather a relatively new phenomenon. Worldwide MCB events have been routinely documented since the 1980s with very few records prior to 1980 (Glynn 1993; Hoegh-Guldberg et al., 2009; Brown and Cossins, 2011).

Thermal stress is identified as the principal cause of coral bleaching (Lesser, 2011). However, other environmental factors can either cause bleaching independently or act synergistically by effectively lowering the threshold temperature for coral bleaching (Lesser, 2004). The other abiotic factors include low-temperature thermal stress, exposure to supra-optimal irradiances of visible radiation, exposure to ultra-violet radiation, salinity changes, sedimentation (Brown 1997; Lesser 2011), extreme low-tidal exposures and sudden fall in the sea-level (Glynn, 1993) while the common biotic factors include bacterial and microbial infections (Brown, 1997; Hoegh-Guldberg et al., 2009). The principal abiotic factor that has a significant influence on the severity of thermally induced coral bleaching is solar radiation, both its visible (Photosynthetically Active Radiation or PAR: 400- 700 nm, Sridhar et al., 2012) and ultra-violet (UVB: 290-320 nm and UVA: 320-400 nm, Lesser, 2011) components. Ultra-violet radiation is known to have a detrimental effect on photosynthesis and growth in zooxanthellae as it damages the critical proteins. Localised coral bleaching may occur due to any of the stresses while MCB events are correlated with excursions of seawater temperature above the local summer maxima (Hoegh-Guldberg et al., 2009).

Corals live within 1° to 2° C of their upper thermal threshold, beyond which bleaching occurs (Lough, 2011). Currently the maximum Sea Surface Temperatures (SSTs) on global coral reefs averages 29.5° C and ranges between 28.2° and 34.4° C (Kleypas et al., 1999). There is no absolute temperature at which corals bleach; rather the threshold varies with ambient SSTs and species-specific acclimatisation and adaptation over long- term (Lough, 2011). The occurrence and severity of coral bleaching events varies significantly in space and time. The extent of bleaching event and subsequent mortality are related to the magnitude of temperature rise and duration of the exposure (Lesser, 2011).

Design of a suitable metric combining temperature, light and other meteorological variables which can predict bleaching and can be universally applied has proved to be a rather challenging task. In theory, a bleaching threshold for a particular coral species at a particular location is a function of absolute temperature, light and exposure time (Berkelmans, 2009). Ideally, it should also incorporate additional stress factors like salinity, water quality or mitigating factors like water movement. However, construction and application of such a multi-parameter model to predict bleaching events have proven extremely difficult due to insufficient species-specific real-time data and simulations related problems. Literature indicates that bleaching thresholds and predictors are generally derived empirically using correlations between bleaching events and environmental factors. The empirical relations so far developed globally, considers multi-species coral assemblages, use a single parameter and simple metrics of readily available data and are either location-specific or 'best-fit' approximations applied over large spatial scales i.e. from tens to thousands of kilometres (Berkelmans, 2009). Accordingly, bleaching thresholds and predictors appear in different forms of indices. These indices neither remain universally applicable nor can be compared over different locations. Examples of bleaching indices include satellite-derived SST based metrics like monthly means, anomalies above monthly means (e.g. 'HotSpots' and 'ReefTemp'), Degree-Heating Weeks (DHWs), Degree Heating Days (DHDs or DDs), etc. (Baker et al., 2008; Berkelmans, 2009). Indices derived from *in situ* data on the other hand include maximum daily SST, monthly means, weekly means and anomalies, degree-days, coefficient of variation of SST and time-temperature curves (Berkelmans, 2009). Each of these indices has merit of its own applications to specific research questions, the spatial and temporal scales of interest, the best possible data available and location specific conditions and responses.

2. Application of satellite-derived SST for understanding bleaching in Indian coral reef regions

Indian coral reefs represent a subset of an oceanographic ecotone which epitomizes the biogeographical transition in the Indian Ocean observed across its east-west boundaries (Spalding et al., 2001). The Indian coastal zone is endowed with spatially limited but strategically located coral reef habitats. These coral reefs form an integral part of the coastal and island ecosystems of the country. The continental coastline of India has rather limited coral reef development as compared to other tropical, maritime nations of Indian Ocean due to the natural adverse conditions of high turbidity, fluctuating salinity and high wave energy (Ajai et al., 2012). Indian coral reefs occur in two major gulf locations on the mainland coast (Gulf of Kachchh in the Arabian Sea and Gulf of Mannar in Bay of Bengal) and two major Island groups (Lakshadweep in Arabian Sea and Andaman and Nicobar in Bay of Bengal). In addition coral reefs are also found at Malvan in Maharashtra coast and at the Palk Bay in Tamil Nadu coast of mainland India. Indian coral reefs provide habitat for myriad marine biodiversity combined with unique regional characteristics.

In the last decade, application of satellite derived SST data and data products became increasingly popular in understanding coral bleaching phenomena observed over Indian reefs. Bi-weekly NOAA SST maps were used to determine the regime of anomalous temperatures in three Indian reef regions for 1998 coral bleaching event (Arthur, 2000). The study revealed an exposure of 78 days for Lakshadweep and 99 days for Gulf of Mannar to anomalous SSTs rising 3°C above the seasonal averages (Arthur, 2000). The effect of thermal stress on corals and other benthic components were correlated with *in situ* observations. The study observed that two months of anomalous SSTs led to bleaching and then successive large-scale mortality in Lakshadweep and Gulf of Mannar. Monthly SST data (9 km resolution) for 1985-2005 period from NOAA/NESDIS were used to determine the thermal threshold for coral bleaching for Indian reefs (Vivekanandan et al., 2008). The warming estimated during 1985 to 2005 was correlated with a Multivariate ENSO Index (MEI) as part of this study. Both the studies confirmed that warming was more pronounced between 7° to 12° N latitudes and the intensity reduced towards the northern latitudes (i.e. 23.5° N or in Gulf of Kachchh). This study worked out different indices on thermal thresholds including Degree Heating Month (DHM) and observed excursion of summer SST maxima above 31°C and a duration of 30 days as lethal combination for mass coral bleaching (Vivekanandan et al., 2008). NOAA NASA Oceans Pathfinder monthly SST series for the period 1985-2005 was used as a historical series to project the vulnerability of Indian corals to the warming seas in the twenty-first century (Vivekanandan et al., 2009).

MCB of Andaman in 2010 was correlated with elevated SSTs (above 31°C) based on MODIS Global SST (level 3) observations from Aqua and Terra sensors (Krishnan et al.,2011). These SST products are available as eight-day composites at 4.63 km spatial resolution and are based on thermal IR daytime SST data. The SST observations indicated development of relatively warm water masses near and around Andaman Islands during the last three weeks of the month of April almost every year (Krishnan et al., 2011). NOAA NESDIS SST products showed 1° to 2° C rise of SST both in case of Andaman bleaching event of 2010 (Marimuthu et al., 2013) and in case of Pirotan Island in summer 2014 (Adhavan et al., 2014). Both the studies opined that delay in the onset of southwest monsoon in respective cases led to the rise of SST above normal summer maxima (Marimuthu et al., 2013; Adhavan et al., 2014).

An integrated study pointed out Photosynthetically Active Radiation or PAR as a critical parameter for coral bleaching in northern Indian Ocean based on two study sites: Gulf of Mannar and Kadmat Island of Lakshadweep (Sridhar et al., 2012). This study utilized Tropical Rainfall Monitoring Mission Microwave Imager (TMI) SST time series (December 1997 to December 2002) on 2° x 2° grid and NOAA AVHRR for site-specific comparison of SST for the same period. PAR was obtained from SeaWiFS and Sea Surface Height Anomaly (SSHA) was taken from existing altimeter observations. The study concluded that a high PAR with minimum SST of 30°C is critical for mass coral bleaching as exemplified during 1998 and 2002 (Sridhar et al., 2012).

This chapter discusses historic MCB responses from the Indian coral reef regions in light of two major bleaching indices based on sixty-seven years' historical SST reconstructed from HadISST1 data at 1 degree x 1 degree spatial resolution.

3. Long-Term SST Data

Historical global SST data (HadISST1) for sixty-three years' period (1950-2012) were obtained from http://badc.nerc.ac.uk/browse/badc/ukmo-hadisst/data/sst website. Hadley Centre sea ice and sea surface temperature dataset version 1 (HadISST1) has been developed at the UK Met Office Hadley Centre for Climate Prediction and Research and comes as an improvement upon the previous global sea ice and SST datasets (GISST version 1, 2 and 3; Rayner et al., 2003). HadISST1 is a 1° latitude-longitude resolution, monthly data set which integrates globally complete historical SST and sea ice analyses, available since 1871 (Rayner et al., 2003). HadISST1 dataset based its SST analysis on gridded, quality-controlled *in situ* SST observations for the period 1871 to 1981 and incorporates bias-adjusted blend of satellite-derived (NOAA AVHRR) and *in situ* SSTs available from 1982. Thus, HadISST1 dataset provides a spatially complete, monthly SST analysis from 1871 to date, preserving real climate signals on global, ocean-basin and sub-regional scales while minimizing random errors, sampling noise and systematic biases (Rayner et al., 2003).

The ASCII data stores the SST values in °C x 100 while 100% sea-ice covered grid-cells are flagged as -1000 and the land grids are set to -32768. The raw data is first read as 1° x 1° gridded data for generating monthly images. The five major coral reef regions of India (Lakshadweep, Andaman, Nicobar, Gulf of Mannar and Gulf of Kachchh) were extracted as spatial subsets for each month of the year for sixty-three years' period. Minimum, maximum and mean SST values were computed for each of these spatial subsets. The spatial mean of monthly SSTs computed for each of the region for sixty-three years' period have been used to reconstruct the regional SST climatologies.

4. Bleaching Indices for Indian reef regions

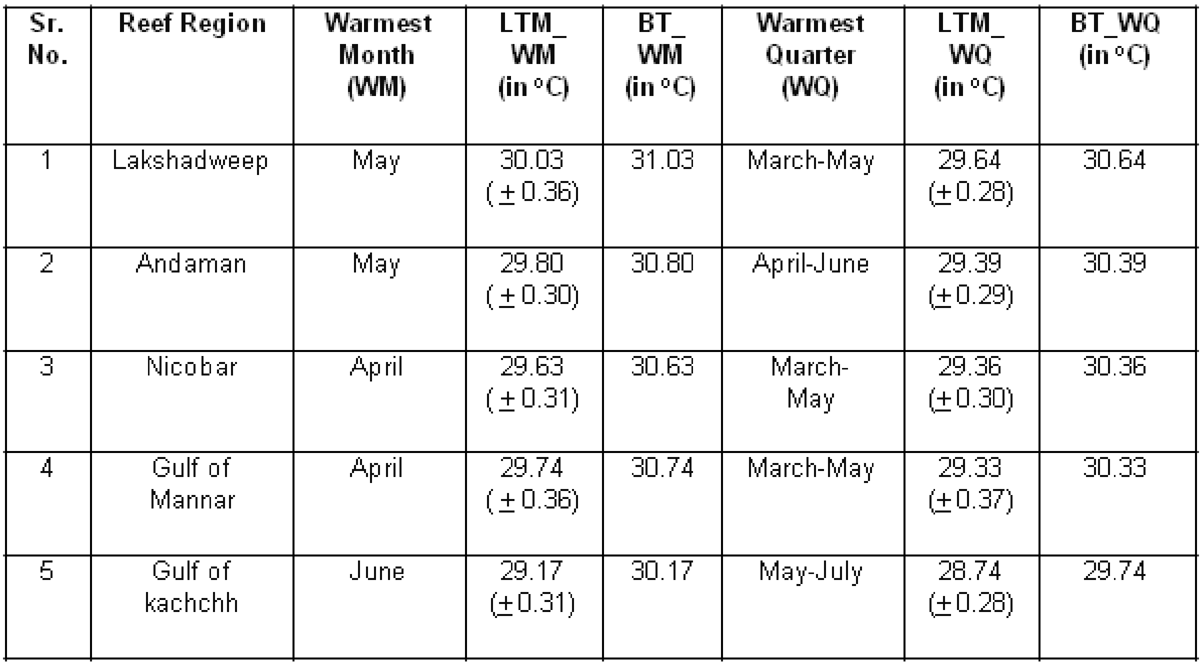
4.1 Bleaching Thresholds (BT)

Both BTs and SST anomalies have been computed on the basis of climatologically Warmest Month (WM) and Warmest Quarter (WQ) analyses. Based on the maximum frequency of the summer month recording the maximum monthly mean temperature in the year, the climatologically WMs were identified for each of the five reef regions. Once the climatologically WMs were identified, climatologically WQs were identified comparing SST values averaged over three summer months' period from a combination of the Warmest Month and 2 adjacent months (i.e. the pre and post month) or both the months either before or after the WM. Long Term Mean (LTM) for 63 years' was computed for both WM and WQ. Bleaching Threshold is defined as the SST condition exceeding the climatological mean temperature of the climatologically hottest or Warmest Month (popularly referred to as Maximum Monthly Mean or MMM climatology). BTs corresponding to LTM of WM and WQ were calculated as: LTM + 1° C following NOAA's Coral Reef Watch (CRW) program. Table 1 summarizes the BTs calculated for Indian reef regions.

4.2 SST Anomalies

SST anomalies for the climatologically WMs and WQs for the Indian reef regions were calculated as the absolute difference between the monthly SST and the LTM. The WM anomalies were plotted for 63 years for all the reef regions and the absolute range of positive anomalies were classified into equal interval classes as: Very High, High, Moderate, Low and Very Low. The years corresponding to Very High, High and Moderate Anomalies recorded for the reef regions were then compared with the past global and/or regional coral bleaching records.

Table 1: Bleaching Thresholds for Indian Coral Reef Regions
(Figures in the parenthesis indicate errors equivalent to ± 1 Std. Dev.)



Sr. No.	Reef Region	Warmest Month (WM)	LTM_ WM (in °C)	BT_ WM (in °C)	Warmest Quarter (WQ)	LTM_ WQ (in °C)	BT_WQ (in °C)
1	Lakshadweep	May	30.03 (±0.36)	31.03	March-May	29.64 (±0.28)	30.64
2	Andaman	May	29.80 (±0.30)	30.80	April-June	29.39 (±0.29)	30.39
3	Nicobar	April	29.63 (±0.31)	30.63	March-May	29.36 (±0.30)	30.36
4	Gulf of Mannar	April	29.74 (±0.36)	30.74	March-May	29.33 (±0.37)	30.33
5	Gulf of kachchh	June	29.17 (±0.31)	30.17	May-July	28.74 (±0.28)	29.74

4.3 HADISST1 Case Studies for Lakshadweep and Gulf of Kachchh

4.3.1 Lakshadweep

In case of Lakshadweep region, the WM was May while the WQ was between March to May during 1950-2012 periods. The LTM SST for 63 years for WM and WQ were 30.03°C and 29.64°C respectively (Table 1). Accordingly, the corresponding BT values computed for Lakshadweep are 31.03°C and 30.64 °C respectively (Table 1; Figure 1). The linear trend fitted to the WM SST and WQ SST reveals that there is an average warming of the summer SST at 0.08°C/decade. There has been a stark rise in the number of years recording the Positive SST Anomaly (or PA) in the last three decades. Twenty-one out of the past thirty three years i.e., during 1980 to 2012 have recorded PA, while seven years recorded PA during 1950 to 1979. The absolute range of PA for Lakshadweep region varies between 0.01°C to 1.09°C. The year 1998 records Very High PA while 2010 records a High PA. The years 1969, 1980, 1987, 1991 and 2003 recorded Moderate PA values. Out of all these years, 1998 and 2010 are well-known MCB years with MCB events reported from number of countries across the globe (Baker et al., 2008). MCB events have been reported from Lakshadweep region for 1998 (Arthur, 2000) and also during 2010 (Vinoth et al., 2012). The years 1980 and 1987 are known to be MCB years from the Great Barrier Reef (GBR) Australia while 1991 recorded a Regional Coral Bleaching (RCB) from Moorea and Andaman Sea (Baker et al., 2008). For all these MCB years, the PA values for Lakshadweep region are greater than 0.50 °C.

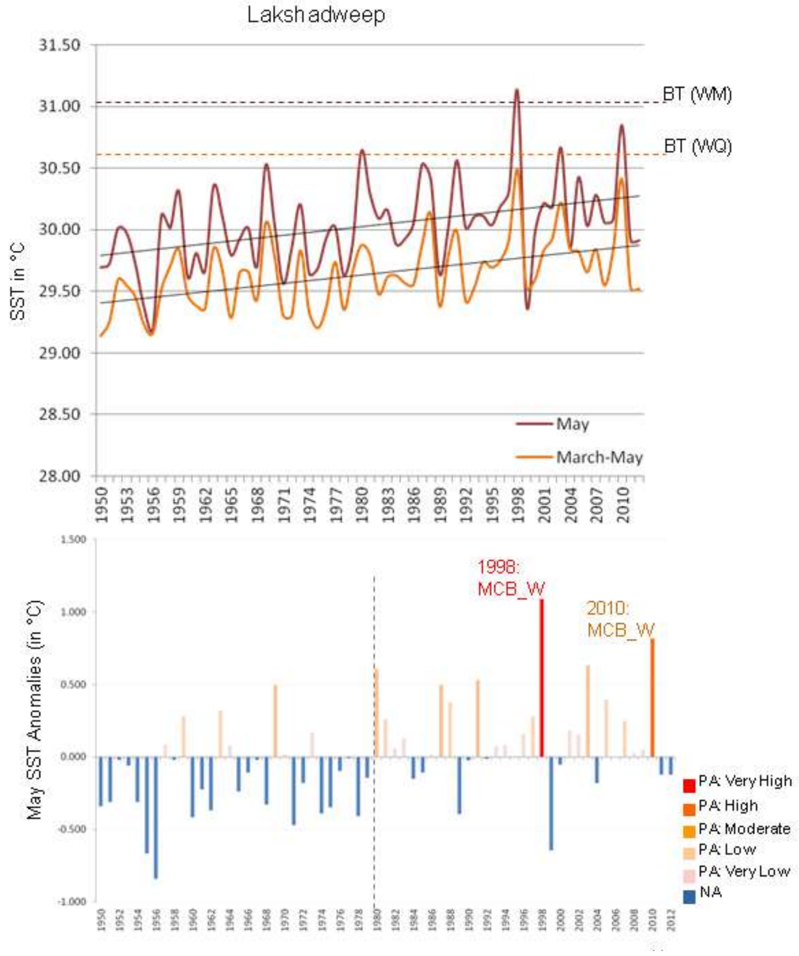


Figure 1: WM and WQ SST Trends for Lakshadweep.
The lower panel shows WM SST Anomalies observed during 1950-2012.
(PA = Positive Anomaly; NA = Negative Anomaly)

4.3.2 Gulf of Kachchh

Climatologically WM for Gulf of Kachchh is June while the WQ is May to July. The LTM for the WM and WQ are 29.17° C and 28.74° C respectively (Table 1). The corresponding BT values based on WM and WQ are 30.17° C and 29.74° C (Table 1; Figure 2). The linear trend fitted to the WM SST and WQ SST reveals that there is an average warming of the summer SST at 0.03°C/decade. Gulf of Kachchh records 18 PA events for WM SST after 1980 while there are 13 PA events during 1950 to 1979. The absolute range of PA for Gulf of Kachchh varies from 0.02°C to 0.65°C. The years 1988 and 2010 record Very High PA for Gulf of Kachchh region along with 1958 and 1959 in the past. Surprisingly, the PA for 1998 for Gulf of Kachchh falls below the specified ranges of Very High to Moderate categories. The year 1987 records a High PA while 1961, 1979, 1980 and 2003 record Moderate PA values. The PA values for Gulf of Kachchh during the global MCB year of 2010 and MCB-GBR event of 1987-88, are higher than 0.60°C.

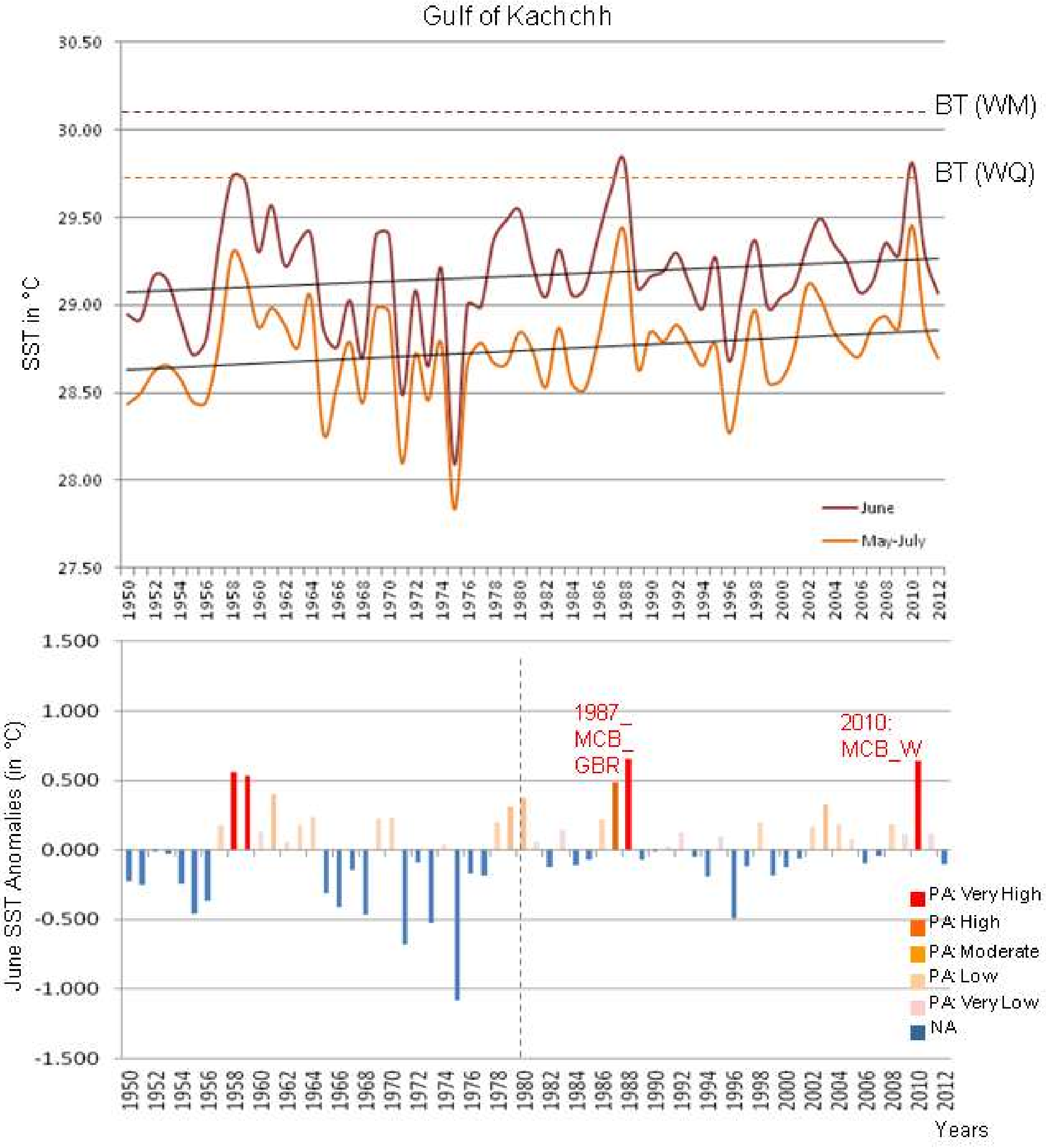


Figure 2: WM and WQ SST Trends for Gulf of Kachchh.
The lower panel shows WM SST Anomalies observed during 1950-2012.
(PA = Positive Anomaly; NA = Negative Anomaly)

Warmest Month (WM) SST anomalies computed from HADISST1 data for each of the Indian coral reef regions (Table 2) conformed well with the MCB event of 2016 with Nicobar region recording the highest magnitude and Andaman recording the least SST Anomaly. However, WM PA values for 2016 were the highest among the PA values observed for the last four years from this SST data series. Krishnan *et al.* (2018) have confirmed an average of 55% of bleached coral cover in Gulf of Mannar during April-May 2016. A ground-validation of daily SST anomaly monitoring over Gulf of Kachchh region in 2016 confirmed 3.9% bleached coral cover (at colony scale) for 13 species of zooxanthellate corals and a sea-anemone in July, 2016 (Arora et al,. 2019; in press).

Table 2: WM SST Anomalies for Indian coral reef regions for 2013 to 2016 based on HADISST1 data

Coral Reef Regions	2013	2014	2015	2016
Lakshadweep	- 0.10	0.68	0.34	0.94
Andaman	0.09	0.47	0.52	0.82
Nicobar	0.44	0.53	0.18	1.60
Gulf of Mannar	0.25	0.28	0.10	1.31
Gulf of Kachchh	-0.13	0.67	0.30	1.03

n summary, it can be commented that the Indian coral reef regions follow the latitudinal gradient of annual heating pattern observed in Indian Ocean. Nicobar and Gulf of Mannar regions record their WMs in April while Andaman and Lakshadweep's WM is May and Gulf of Kachchh heats up the last in June. Based on the WM and WQ SST data for the sixty-three year's period, it is observed that all the regions are warming, with Nicobar recording the highest warming rate of 0.09°C/decade and Gulf of Kachchh recording the minimum warming rate 0.03°C/decade. Thus, the average rate of warming for Indian coral reef regions is 0.07°C/decade during 1950-2012. Vivekanandan et al., (2008) has reported that Lakshadweep region is warming fastest at the rate of 0.21 °C/decade while Gulf of Kachchh is warming at the slowest rate of 0.12°C/decade based on NOAA SST data for a twenty years' period from 1985 to 2005. The higher warming rate for Indian reef regions as reported by Vivekanandan et al. can be a function of the smaller time-window considered in the study. The thermal thresholds for coral bleaching as estimated by Vivekanandan et al. for Indian reef regions stand at 31.4 °C for Lakshadweep, Andaman and Gulf of Mannar while 31.0 °C for Nicobar and 30.0°C for Gulf of Kachchh based on 1998 event data. Numbers of years recording Positive SST Anomalies for the respective WM for the five coral reef regions are evidently more during 1980 to 2012 period as compared to previous thirty years spanning from 1950 to 1979. In this case, reef regions with oceanic settings show higher increase in the frequency of PA years after 1980 with event frequency rising thrice in Lakshadweep and nearly twice for Nicobar and Andaman. The PAs as observed for all the five regions show association with historic global MCB years of 1998 (other than Gulf of Kachchh) and 2010 (other than Gulf of Mannar). The other major MCB event observed from the data corresponds to the 1987-88 MCB of the Great Barrier Reef, Australia. However, Lakshadweep region does not conform to this trend very prominently as in this year Lakshadweep recorded a Moderate PA. The PA values associated with global MCB events for Indian reef regions range from 0.50°C to 1.12°C.

Conclusions

The five Indian coral reef regions indeed show distinct regional sensitivities towards bleaching thresholds, anomalous SSTs and MCB responses. HadISST1 data proves its potential towards a long-term SST reconstruction and hindcast past MCB events for Indian reef regions. The association of historic global MCB events with PAs equivalent to 0.50°C or greater as observed over Indian coral reef regions indicates that conventional definition of BT as the local or regional LTM+1°C need more rigorous time series analysis of SST anomalies and its correlation with historical regional bleaching events. For this, residence period of the SST anomaly in each of these regions during MCB events needs to be studied as the next step. MCB forecasts can be significantly improved if regional sensitivities are embedded in the forecast models.
Long term coral bleaching forewarning programmes needs to be supported with *in situ* bleached cover monitoring for better feedbacks and improvisation of the forewarning capabilities.

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Geographical expansion of oil sardine fishery along the Indian coast

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ABSTRACT

Change in geographical distribution is one of the confirmed consequences of climate change on marine species globally. Along the Indian coast, the commercially important oil sardine *Sardinella longiceps* has extended its northern and eastern boundaries of distribution, resulting in expanded fishery all along the coast within the last three decades. While initial publications have identified warming of seawater as the potential cause, a few later publications have indirectly pointed to the possibility of natural processes and fishery-related factors as causes for expansion of the fishery. In this paper, four hypotheses – that oil sardines were always abundant along the entire coast but were not target species before the 1980s; that though the centre of distribution remains the southwest coast, the species may move due to unfavourable conditions in its home range; that removal of larger predators causes an increase of smaller planktivorous pelagic fishes and finally that the warming sea surface temperature is conducive to extend its distributional boundaries. On analysis it appears, seawater warming may be the prime cause for increased abundance and expanded fishery for oil sardine along the Indian coast. However, given the complexity of marine ecosystems, several other environmental factors need to be modelled to arrive at firm conclusions. More research is needed to increase our understanding of the process and magnitude of the impact of climate change on fisheries, not only to confirm the response of fish and fisheries but also to develop adaptation plans.

1. Introduction

Multiple factors such as environmental conditions, climate and fishing determine the distribution and abundance of fish species. Changes in these factors influence a species to shift or expand or shrink the area it occupies. Until now, changes in geographical distribution and phenology are the confirmed consequences of climate change on marine species globally. Of a global dataset of 651 published marine species' responses to climate change, Brown et al. (2016) found that 485 measurements were on changes in geographical distribution. Among marine fish species too, a large body of evidence has demonstrated that climate change influences their geographical distribution and abundance (for example, Perry et al., 2005; Cheung et al., 2010; IPCC, 2014). Of 21 fish species studied in the north Atlantic, environmental changes and fishing had joint influence, but mainly changes in temperature influenced the distribution of 16 species while intensity of fishing was the strong driver for change in distribution and abundance of 10 species (ICES, 2016). Along the Indian coast, Vivekanandan et al. (2009), for the first time, reported that the oil sardine *Sardinella longiceps* gradually extended its northern and eastern boundaries of distribution resulting in geographically expanded fishery all along the coast in the last three decades. Considering catch as surrogate of abundance, they concluded that, with warming of sea surface, the oil sardine is able to find temperature to its preference, thereby extending its distributional boundaries and establishing fisheries in larger coastal areas.

Later publications indicated a few more probable causes such as fishing down the marine food web (Vivekanandan and Krishnakumar, 2010), introduction of efficient fishing gear, namely ring seine (Abdussamad et al., 2015; Jadhav et al., 2017) and increasing market demand (Ponnusamy et al., 2012) as probable causes for the expansion of oil sardine fishery in India. While these publications did not discuss about seawater warming as a cause, they point to the fishery-dependent factors as plausible causes for expansion of oil sardine fishery. This raises question on the cause(s) for expansion of the oil sardine fishery: Is it (i) a natural process, or (ii) climate change-related, or (iii) fishery-related?

Indeed, the geographical expansion of oil sardine fishery has generated benefits in the form of food security, livelihoods and profitable economics to individuals and communities. On the other hand, there are concerns on the sustainability of fishery as it is now subjected to immense fishing pressure. For successful fisheries management, it is necessary to move beyond the symptoms of the fishery and take into account the drivers of the fishery that influence changes. The paper aims to analyse the available information and find out the plausible causes for the geographical expansion of the oil sardine fishery along the Indian coast in the last three decades. This causal factor analysis will be useful to take management decisions for the fishery.

2. Geographical expansion of oil sardine fishery along the Indian coasts

The oil sardine *S. longiceps* (Figure 1), in terms of volume of catches, is the single largest fishery along the Indian coast. This clupeid is a coastal, pelagic, schooling fish, reaching a maximum of 24 cm total length. It feeds mainly on phytoplankton, zooplankton and small crustaceans. It is a fast- growing fish with protracted spawning period and longevity of about 2.5 years. Besides being a favoured, nutritionally rich and affordable table fish occurring abundantly almost throughout the year, it also serves as a source of valuable by-products like sardine oil and fish-meal for aquaculture feed production. The fishery supports several ancillary industries such as boat building, fish processing, marketing and fish meal plants and is of immense economic, social and cultural importance.

Figure 1. Indian oil sardine Sardinella longiceps

The landings of oil sardine reflect its abundance (Longhurst and Wooster, 1990), and hence, the landings are often taken as surrogate of abundance (see 'Suggestions for future research' in this paper). In the last three decades, oil sardine landings have increased along the Indian coast (Figure 2), by 3.4 times during 2012-2016 compared to 1985-89 (Table 1). The remarkable feature of the fishery is that it has expanded into new coastal areas. From 1923 to mid-1980s, the fishery for oil sardine was prevailing only along the southwest coast (SW; consisting of maritime states of Kerala, Karnataka and Goa; Figure 3), which contributed > 95% to the oil sardine landings in the country (Pillai et al., 2003). The fishery started expanding to the northwest coast (NW; consisting of Maharashtra and Gujarat) by the year 2000, southeast coast (SE; consisting of Tamil Nadu, Puducherry and Andhra Pradesh) by late 1980s and northeast coast (NE; consisting of Odisha and West Bengal) by late 1990s (Figure 4). The landings increased from 1,840 t in 1985 to the peak of 36,930 t in 2014 along the NW coast, from 4533 t in 1985 to 1,92,607 t in 2013 along the SE coast, and from 230 t in 1996 to 2,703 t in 2012 along the NE coast. Among the four regions, the major change was along the SE coast. Interestingly, the landings along the SW coast, the 'home' of oil sardine also increased from 1, 14,105 t in 1985 to a peak of 5, 61,378 t in 2012. While the SW coast remained as the major contributor (albeit with annual fluctuations), oil sardine emerged as a major fishery along the SE coast and as a minor fishery along the NE and NW coasts within a period of 20 to 30 years. Thus, fishery has expanded from southern latitudes, i.e., from the 'home' region of 8°N-15°N to 24°N along the west coast; and from 8°N to 22°N along the east coast (Table 1). Thus, oil sardine fishery has experienced geographical *expansion* and not a *shift*. Further to the emergence of minor fishery along the NE coast of India, the species has been recently reported for the first time in the contiguous coastal region of Bangladesh (Shamsunnahar et al., 2017), with the possibility of developing into a fishery in future.

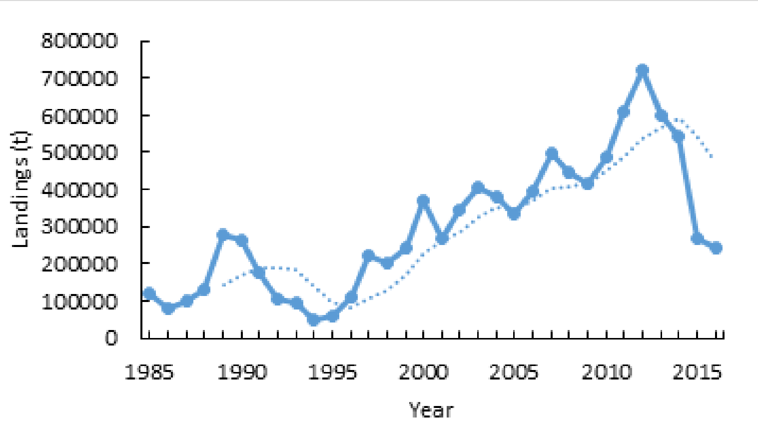

Figure 2. Oil sardine landings along the Indian coast; the dotted line represents 5-year average (Data source: CMFRI, 2006; Annual reports of CMFR))

Table 1. Comparison of oil sardine landings during 1985-1989 and 2012-2016

Region	Maritime State/Union Territory	Lat/Long position	Annual average oil sardine landings (t)			Annual average All fish landings (t)		
			1985-1989	2012-2016	Increase	1985-1989	2012-2016	Increase
Northwest coast	Gujarat, Maharashtra	15°N-24°N; 68°N-74°N	5590	24415	4.4 times	5,85,866	1074791	1.8 times
Southwest coast	Goa, Karnataka, Kerala	8°N - 15°N; 74°E-78°E	127998	324706	2.5 times	6,99,958	1116914	1.6 times
Southeast coast	Tamil Nadu, Puducherry, Andhra Pradesh	8°N-18.5°N; 78°E-84.5°E	8069	124650	15.4 times	4,09,858	929333	2.3 times
Northeast coast	Odisha, West Bengal	18.5°N-22°N; 84.5°E-90°E	72	1137	15.8 times	73,357	519922	7.1 times
All India			141729	474908	3.4 times	17,69,039	3640960	2.1 times

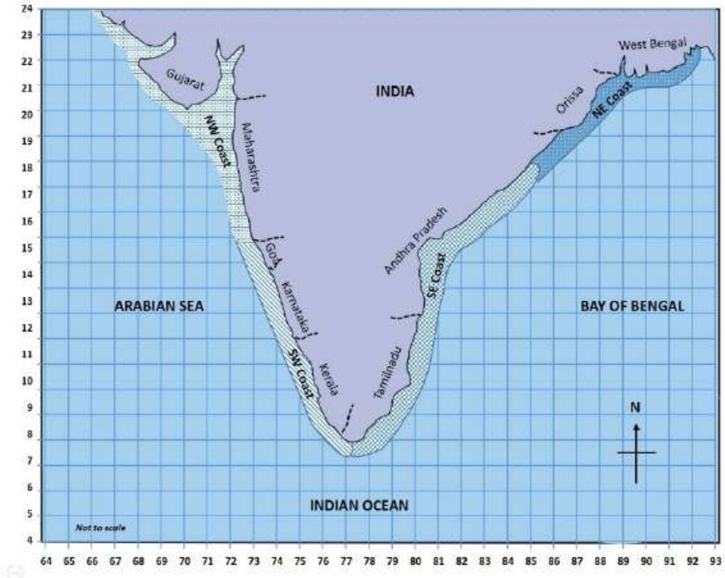

Figure 3. Map showing four coastal regions of India

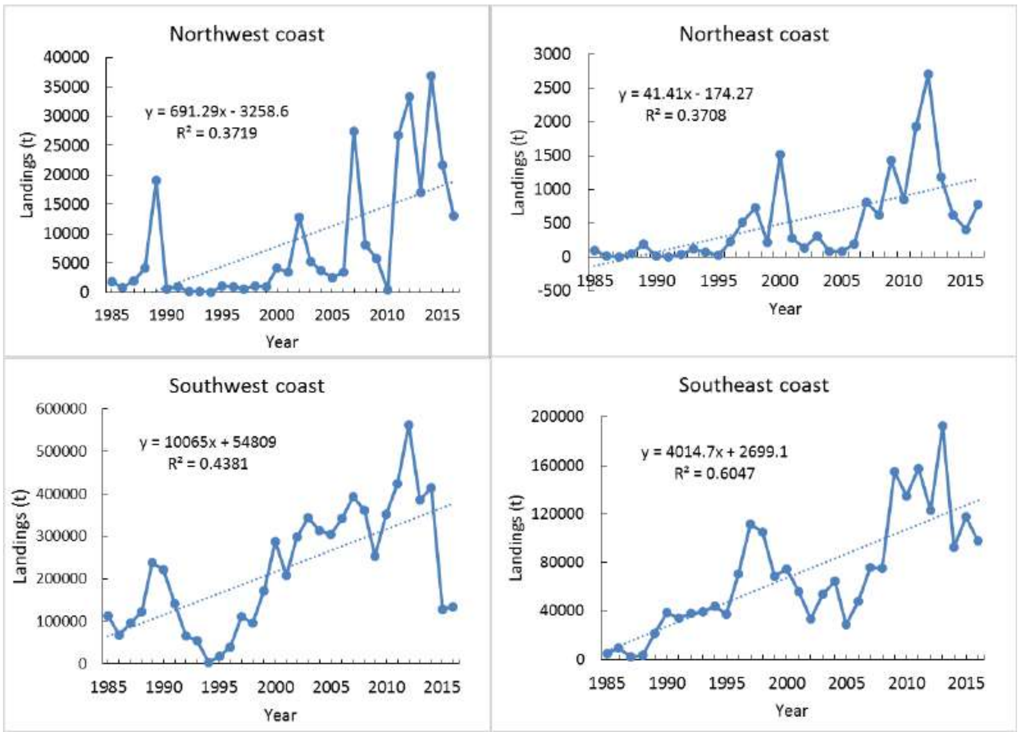

Figure 4. Oil sardine landings along four regions of the Indian coast; the dotted lines represent 5-year moving average (Data source: CMFRI, 2006; Annual Reports of CMFRI)

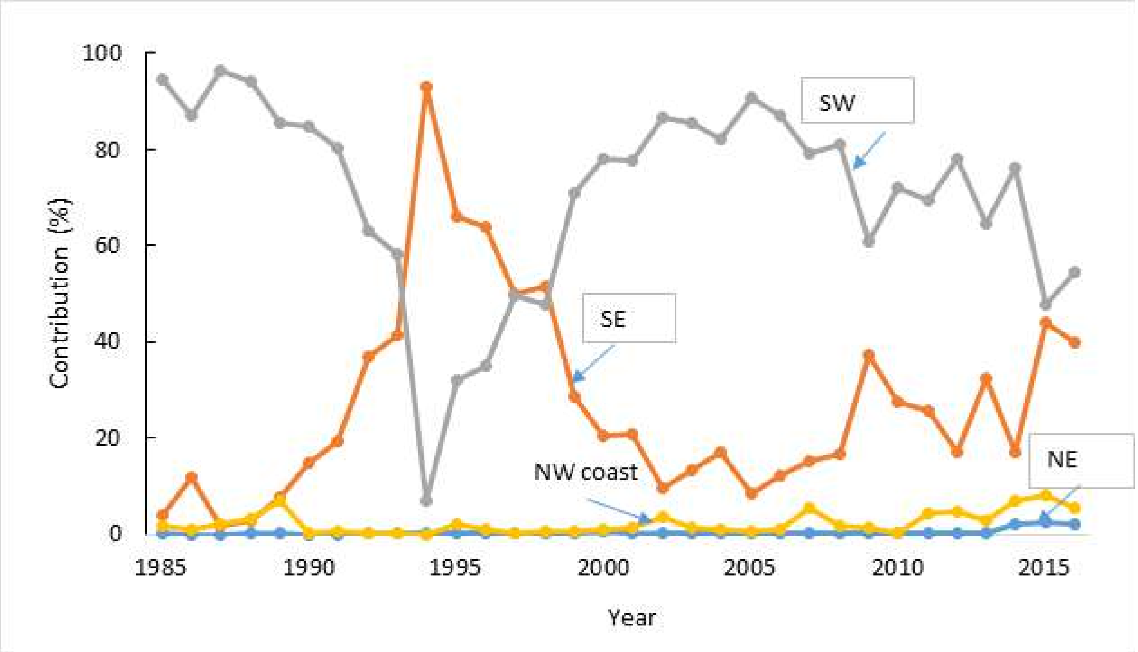

Figure 5. Contribution (%) of four coastal regions to all India oil sardine landings; NW = northwest coast; SW = southwest coast; SE = southeast coast; NE = northeast coast

During the last 30 years, the efficiency of commercial fishing operations has substantially improved along the entire Indian coast, reflecting two-time increase in total marine fish landings, i.e., from annual average of 1.77 million tonnes during 1985-1989 to 3.64 m t during 2013-2016. In comparison, increase in oil sardine landings was higher (3.4 times) than the combined landings of all fishes. The increase in oil sardine landings was the highest along the SE coast, by an order 15.4 times (Table 1). This has been reflected in the contribution of the SE coast to the all India oil sardine landings from a mere 3.8% in 1985 to a peak of 93.0% in 1994, which declined to 40.0% in 2016 (Fig. 5).

Being a small pelagic fish with fast turnover of generations, the fishery is characterised by large-scale fluctuations on annual and decadal scales mainly due to intra and inter-annual environmental variabilities. The characteristic fluctuation in annual oil sardine fishery is evident in the four coastal regions (Figure 4). For example, the landings along SW coast decreased from 2, 38,250 t in 1989 to a mere 3,187 t in 1994, but peaked to 5, 61,378 t in 2012. Another characteristic of the fishery is that trend and years of 'highs' and 'lows' in landings almost synchronised between regions, which is evident from the peak landings during 2012-2013, and sharp decreases thereafter in all regions. In spite of these fluctuations, the 5-year moving average shows an increasing trend in the landings in the four regions in the last 30 years (Figure 4).

2.1 Plausible causes for geographical expansion of the fishery

Geographical expansion of a fishery indicates the increase in abundance and availability of fish in new areas. In the case of oil sardine, the plausible causes for increase in abundance could be due to natural process or fishery-related or climate change-related. In the following paragraphs, available information on probable causes for the extended area of oil sardine abundance have been analysed under four hypotheses.

Hypothesis 1. (Fishery-related):
Oil sardine is widely distributed. It was always abundant along the entire Indian coast, but the fishery did not target the species before mid-1980s except in the southwest coast as there was no commercial value for the species.

i. Oil sardine is distributed in the northern and western parts of tropical Indian Ocean, in the Gulf of Aden, Gulf of Oman, eastward along the western coast of India in the Arabian Sea and along the southern east coast to up to part of Andhra Pradesh (www.fao.org-Fish Species Fact Sheets; www.fishbase.org; Figure 6). The distribution map does not show occurrence of oil sardine in northern parts of Andhra Pradesh and northeast coast of India. However, emergence of a minor fishery along the northeast coast and a major fishery along the southeast coast indicates increased abundance of the species within the last 20 to 30 years.

ii. The oil sardine never formed a fishery along the SE coast prior to mid-1980s. Gnanamuttu and Thangaraj Subramanian (1989) reported on the emerging fishery for oil sardine using bagnet and boat seine off Chennai in May 1987. They stated that juveniles and adults in different stages of gonadal development including spent recovering stage were observed for the first time in November 1987. They further commented that it is interesting to note that the oil sardine spawns along the Chennai coast.

iii. In the last 20 years, ring seine has emerged as the specialised gear to catch oil sardine along the Indian coast. However, in the last 50 to 60 years, before the advent of ring seine, small pelagic fishes like lesser sardines and anchovies were caught traditionally by a variety of gears like boat seines, gillnets and trawls along the Indian coast (Pillai and Rohit, 2003; Pillai et al., 2003). Along the SE coast, small meshed gillnets were used to catch the small pelagics for more than 60 years and are still continue to be used. The oil sardine, which co-occurs with other small pelagics, was absent in gillnet catches before mid-1980s. This shows the absence of the fish in adequate quantities to form a fishery along the east coast before mid-1980s.

iv. Considering (i), (ii) and (iii) above, the hypothesis that the oil sardine was always abundant along the entire Indian coast is rejected.

v. Oil sardine was a preferred food for a very long time along the SW coast. Moreover, about 700 small units extracted 12,500 t of sardine oil in 1922 (Kini, 1968). The trade continued and 2073 t of oil was extracted in 1967 (Madhavan et al., 1974). Fish transport from Tamil Nadu (SE coast) to Kerala (SW coast) existed even during 1960s, and had the oil sardine landed along the Tamil Nadu coast during that period, it would have been transported to Kerala markets.

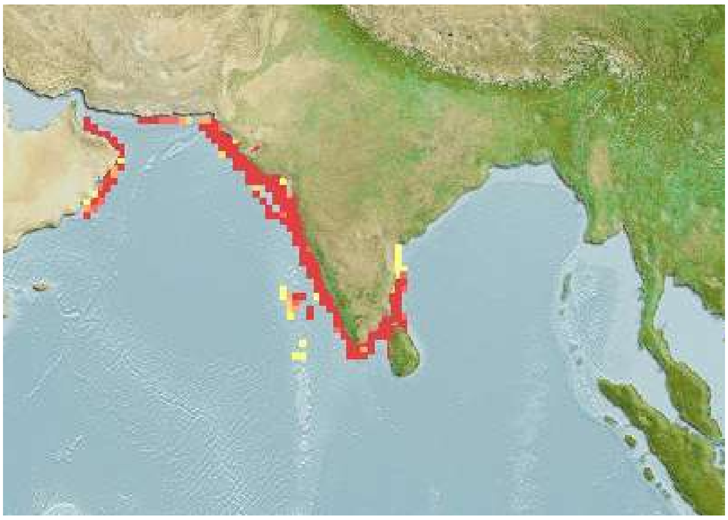

Figure 6. Distribution map of oil sardine S. longiceps; source: www.fishbase.org; see also www.fao.org - Fish Species Fact Sheets

Thus the hypothesis that there was no commercial value for oil sardine and because of that the fishermen were not interested in catching oil sardine before mid-1980s is also rejected.

Hypothesis 2. (Natural process): *Oil sardine is a migratory fish. The centre of its distribution remains as southwest coast, and the fish moves out to other geographical areas whenever the environmental and biological conditions are not suitable in its 'home' range.*

The oil sardine is known to migrate between nearshore and relatively offshore waters for spawning and feeding, respectively (Nair, 1959). There is no evidence to demonstrate that the fish undertakes long distance latitudinal migrations along the Indian coast. However, a striking inverse relationship on the contribution (percentage) of SW and SE coasts to the all India oil sardine landings (Figure 5) indicates the possibility that the fish may migrate between the two coasts and form high volume fishery in the region of increased abundance. While this appears to be a possibility, it needs to be proved by tagging studies. For accepting or rejecting this hypothesis, the following aspects need to be considered:

i. Though the percentage contribution of SW and SE coasts showed an inverse relationship, the volume of landings did not show the inverse relationship and there was synchrony between the regions. For example, the landings were at the peak simultaneously along both the coasts during 2012-2013 (and along the NW and NE coasts as well) and reduced simultaneously in subsequent years (Figure 4). It appears that favourable environmental conditions that prevailed along the entire Indian coast would have increased the primary and secondary productivity and thereby the biomass of oil sardine during 2012-2013. When the conditions were not favourable in the later years (2014-2016), the biomass of oil sardine as well as the volume of landings declined. Hence, the theory that the fish migrates away from the SW coast and forms fishery along the SE coast does not seem to be correct.

ii. Stock structure analysis of oil sardine sampled from SW and SE coasts using truss network analysis (Remya et al., 2015) and DNA barcoding (Sukumar et al., 2016) reported minor morphological differences between the two coasts, but concluded that the two morphotypes belonged to the same stock. Sukumar et al. (2016) inferred that the two variants are mostly confined within the respective coasts.

iii. The life traits of the species are strongly attached to the respective geographical regions of its distribution. Intense reproductive activity was reported along the NW, SW and SE coasts, reflected by occurrence of fishes in different stages of maturity, indicating gonadal development and spawning. Consolidating the information from several publications, Vivekanandan et al. (2010) reported that the oil sardine has prolonged spawning period along east and west coasts. Along the east coast, the spawning activity is at its peak during the northeast monsoon (October-December) and extends up to March. On the other hand, the peak spawning along the west coast is during southwest monsoon (May-July) and extends up to September. The spawning is followed by larval development and recruitment into the fishery every year in the respective regions (Rohit et al., 2018). This shows that the fish completes its life cycle in the respective regions and does not migrate for spawning.

The fish is also able to find food of its preference in the respective regions. A number studies confirm that the fish primarily feeds on phytoplankton, particularly on a wide choice of diatoms. The capacity to switch over to the available species of diatoms is evident from many studies. For example, the dominant food item of oil sardine varies between different locations, probably based on the dominant diatoms that occur in the location (Table 2). This indicates the capacity of the fish to adapt to the geographical area of its occurrence. The examples mentioned on two life trait characteristics, namely, reproduction and feeding provide evidence that the oil sardine is completing its full life cycle and has established population by intrinsically attaching itself to the geographical location where it is distributed.

Table 2. Top five food items of oil sardine in three geographical locations

NW coast **(Rohit et al., 2018)**	**SW coast** **(Remya et al., 2013)**	**SE coast** **(Gomathy, 2013)**
Coscinodiscus	*Pleurosigma*	*Thalassiosira*
Copepods	*Biddulphia*	*Coscinodiscus*
Skeletonema	*Thalassiosira*	*Bacillaria*
Ceratium	*Nitzschia*	*Navicula*
Pleurosigma	Copepods	Tintinnids

Considering the occurrence of two morphotypes, establishment of populations in the respective geographical area of occurrence and absence of evidence on migration between SW and SE coasts, it is unlikely that the fish moves in and out of its 'home' range.

Hypothesis 3. Fishing Down Marine Food Web (Fishery-related):
Removal of large predators by fishing causes proliferation of smaller fishes and there is a gradual transition in abundance and fishery toward planktivorous pelagic fish like the oil sardine.

Long-term analysis of global marine fish landings data has shown that there is gradual transition in landings from long-lived, high trophic level, piscivorous bottom fish toward short-lived, low trophic level invertebrates and planktivorous pelagic fish, a process called 'fishing down marine food web (FDFW)' (Pauly et al., 1998). FDFW causes depletion of large predatory fish on top of the food web by fishing, and turn to increasingly smaller species on the bottom of the food web. FDFW is indicated by reduction in mean trophic level of fish landings over long time periods. Along the SE coast of India, the mean trophic level in fish landings decreased by 0.04 per decade during 1950-2002 (Vivekanandan et al., 2005). For the same time period, Bhathal and Pauly (2008) reported faster decrease of trophic level, at rates averaging 0.06 trophic level per decade along the entire Indian coast. These publications underline the view that proliferation of oil sardine is due to removal of relatively higher proportion of large predators like sharks, tunas, barracudas, ribbonfishes, etc., which feed upon small pelagics like the sardines, thereby releasing the predatory pressure on small pelagics.

In this context, it is worth re-visiting the following statement by Vivekanandan et al. (2005), who first detected occurrence of FDFW along the SE coast: '*It is interesting to note that the landings of top predators, viz., lizardfishes, rock cods, horse mackerel, seer fishes, and barracudas keep increasing along with fishes in lower trophic levels in the 1990s and 2000s; the landings of other predators such as sharks, ribbonfishes, tunas, and Indian halibut did not increase, but did not decrease either… One of the major changes in the fisheries along SE coast is the incursion of oil sardine with low trophic level. The oil sardine, which did not contribute to the fishery during 1950–1988, suddenly emerged as a major fishery in 1989, and since then, continued to increase in the landings. It is the emergence of oil sardine fishery that has reduced the mean trophic level of the landings rather than decline in the abundance of large predatory fishes along the SE coast*'.

Thus, along the SE coast, which has experienced the most conspicuous FDFW as well as the largest increase in oil sardine catches, the cause for FDFW is the increase in oil sardine abundance; and it is not that the cause for oil sardine abundance is FDFW. Hence, the hypothesis that removal of large predators has caused proliferation of small pelagics, does not hold good in the case of oil sardine.

Hypothesis 4. Seawater warming (Climate change-related):
Warming of sea surface has enabled the oil sardine to find temperature to its preference, thereby extending the distributional boundaries and establishing fisheries in larger coastal areas.

Analysing the dataset on sea surface temperature (SST) obtained from International Comprehensive Ocean – Atmosphere Data Set (ICOADS) (*www.cdc.noaa.gov*) and 9-km resolution monthly SST obtained from Advanced Very High Resolution Radiometers (AVHRR) satellite data (provided by the NOAA/NASA at http:/podaac.jpl.- nasa.gov/), it was reported that the sea surface temperature increased in the Indian seas, by 0.2°C along the NW, SW and NE coasts, and by 0.3°C along the SE coast during 1961 - 2005 (Vivekanandan et al., 2009). It is suggested that the oil sardine, being a tropical fish, has found warming of sea surface advantageous and has expanded to larger geographical areas (Vivekanandan, 2011).

As the SE coast has experienced higher increase in SST among the four regions, and is also the major beneficiary of expanded oil sardine fishery, the relationship between SST and oil sardine landings along the SE coast was analysed for the period 1985-2016. The SST data was sourced from the ICOADS for three locations along the southeast coast, namely, off Tuticorin, Chennai and Visakhapatnam and averaged to arrive at annual SST for the SE coast. The SST, thus estimated, increased from 28.19°C in 1985 to 28.55°C in 2016 (Figure 7). In spite of inter-annual variabilities, a positive linear relationship was obtained between the SST and landings, but the landings deviated from the linear trend at higher temperatures (Figure 8). Earlier publications on relationship between changes in SST and fish abundance show diverse results. While climate change has been reported to impact fishes negatively in many geographical areas (for example, in the Arabian Gulf; Wabnitz et al., 2018), there are also reports on positive relationships. For example, a strong relationship was observed between SST and abundance of sardines in the Mediterranean Sea, with a positive correlation for a range of 18.5 to 22°C and negative correlation for lower temperatures (Abdellaoui et al., 2017). Seasonal analysis of oil sardine catches along Tamil Nadu coast also showed a positive relationship with SST particularly during summer months (Shoba et al., 2014). Obviously, there is an optimum temperature window that determines the catches depending upon spawning success, larval development and abundance (Pankhurst and Munday, 2011). It appears that, with warming of the Indian seas, the oil sardine is finding the optimum SST window in the coastal regions of India.

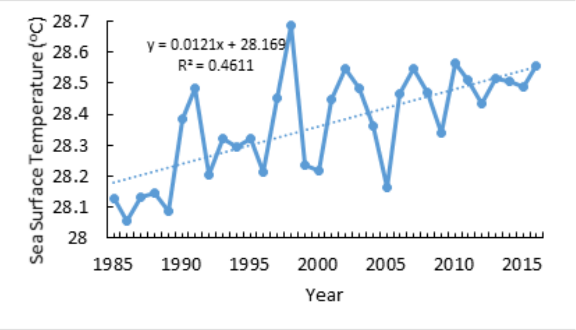

Figure 7. Annual average Sea Surface Temperature along the southeast coast of India; the dotted line is a trend line (Data source: International Comprehensive Ocean-Atmosphere Data Set (ICOADS)

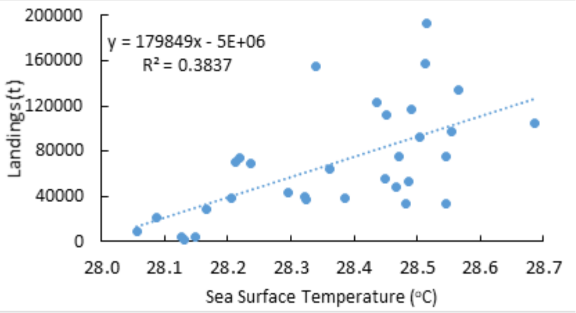

Figure 8. Relationship between Sea Surface Temperature and oil sardine landings along the southeast coast during 1985-2016

The SST anomaly, calculated from smoothed 3-year moving average, ranged between -0.2°C and 0.2°C along the SE coast (Fig. 9). This anomaly is a combination of effects due to climate change as well as inter-annual variabilities in events like El Niño–Southern Oscillation (ENSO). To understand the effect of the anomaly on the variations in landings, Normalised Catch Deviation (NCD) of oil sardine was calculated considering the deviation of actual landings from predicted landings (calculated from linear trend of the landings). For easy understanding, the negative signs in SST anomaly and NCD values were ignored and the relationship between SST anomaly and NCD was plotted (Figure 10). The plot showed that with increasing SST anomaly, the catch deviation also increased, indicating uncertainty in catches.

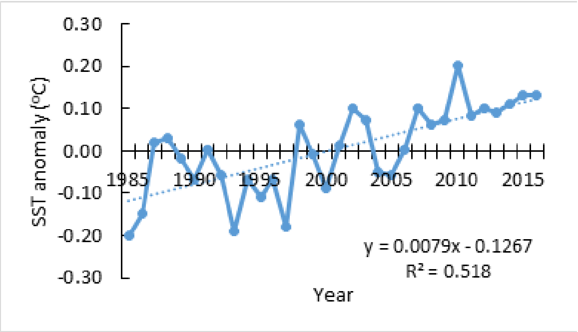

Figure 9. Sea Surface Temperature (SST) anomaly along the southeast coast; the values are smoothed with 3-year moving average; the dotted line is a linearised trend line

The positive trend in the oil sardine landings with SST; and the large deviations in the landings whenever the SST anomalies are high, shows the response of oil sardine to long term changes and annual variabilities in SST. The ability of fishes to adapt to rising water temperatures will depend on their capacity to shift to more favourable environments, and acclimatise to new environments (Perry et al., 2005). Like the vast majority of marine fish species, the oil sardine is ectothermic and temperature directly determines its vital physiological processes including reproduction and survival. Mobile species are able to adjust their ranges over time even for a difference of 1°C (Perry et al., 2005). A number of publications have documented shift in distribution of fish species to cooler latitudes (for example, Barange and Perry, 2009). In the case of Indian oil sardine, the fish has adapted to higher temperatures not by shifting its distribution, but by expanding its geographical distribution to warmer waters. The major areas of distribution of oil sardine are within the SST window of 25-30°C with an average of 28°C (Chidambaram, 1950; Sekharan, 1962; Kripa et al., 2015).

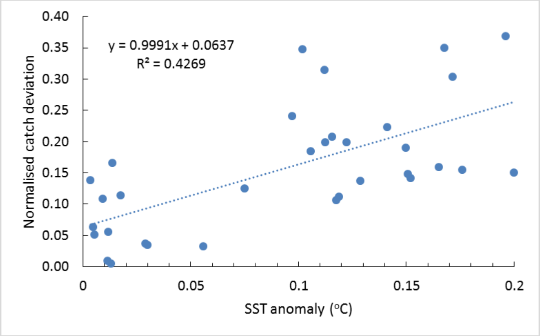

Figure 10. Relationship between annual Sea Surface Temperature anomaly and Normalised Annual Oil Sardine Catch Deviation along the southeast coast during 1985-2016; the dotted line is a linearised trend line

The oil sardine is known by r-type life strategy (high-speed multiplication populations), characterised by high fecundity and fractional spawning (spawning batch) over a long duration. A change of even 0.1°C influences fish during spawning, and at the development and survival of the eggs and larvae, as well as influencing distribution (Laevastu and Hayes, 1981). Long-term changes and annual fluctuations in catches are a consequence of spawning and recruitment variabilities, particularly difficult to prove for species with a short life cycle. Unfortunately, reliable information on the impact of SST on spawning, larval development and recruitment of oil sardine is not available in the Indian seas.

The present analysis has used simple relationships between annual variabilities and increasing SST on the oil sardine fishery. Relationships between SST and landings need not be totally linear as interaction between environment and biology is complex due to the non-linear population dynamics response. The present analysis did not consider the impact that ocean warming may have on primary productivity of oceans and, consequently, on the abundance of planktonic organisms and prey availability. Moreover, ocean warming is predicted to occur simultaneously with other environmental stresses, such as ocean acidification and expansion of hypoxic zones. Given the great complexity of marine ecosystems, these factors should be considered for arriving at firm conclusions on the impact of climate change. These phenomena can be better modelled using non-linear model such as generalized additive models (GAMs).

With these caveats, considering the evidence available until now, the geographical expansion of the oil sardine fishery along the Indian coast can be attributed to the gradual, but consistent warming of sea surface temperature.

The preceding arguments on different hypotheses have been consolidated and presented in Table 3.

Table 3. Geographical expansion of oil sardine (OS) fishery along the Indian coast: Testing the hypotheses

Hypothesis	Component	Comment	Remarks on hypothesis
H1. Fishery-related	(i) OS was distributed along the entire Indian coast.	Distribution maps of FAO & Fish Base do not show distribution along major part of east coast. First report of (minor) fishery along Tamil Nadu coast was only in 1987.	H1 rejected
	(ii) Fishery did not target OS prior to 1985.	OS was caught by gillnet in SE coast along with co-occurring species before and after mid-1980s; but as OS was not available along the SE coast before mid-1980s, it did not occur in gillnet catches.	
	(iii) No commercial value for OS before mid 1980s.	Good demand existed for OS as seafood and for fish oil.	
H2. Natural process	(i) Centre of distribution of OS is SW coast. The fish moves in and out to other contiguous areas.	Two morphotypes of OS belonging single stock exist along SW and SE coasts, but confined to respective coasts. The life traits of OS are strongly attached to respective regions indicating establishment of separate populations within each region after mid-1980s.	H2 rejected
	(ii) Percent share of SW and SE coasts shows inverse relationship, indicating movement between the two coasts.	The volume of landings did not show inverse relationship. The trend in volume of landings is uniform along both the coasts.	

Table 3(Continued). Geographical expansion of oil sardine (OS) fishery along the Indian coast: Testing the hypotheses

Hypothesis	Component	Comment	Remarks on hypothesis
H3. Fishery-related	(i) Removal of large predators has facilitated proliferation of OS, leading to Fishing Down Marine Food Web (FDFW).	The volume of landings of large predators also has continuously increased for the last 25 years, showing their abundance. Proliferation of oil sardine has caused FDFW along SE coast, rather the decline in abundance of large pelagics.	H3 Rejected
H4. Climate change-related	(i) Warming of sea surface has enabled the oil sardine to find temperature to its preference, thereby extending the distributional boundaries and establishing fisheries in larger coastal areas.	Positive linear relationship between SST and OS landings along SE coast; and large deviations in the landings whenever SST anomalies are high, indicate the response of OS to long term changes and annual variabilities in SST.	H4 Accepted for now, but more evidences on the response of the fish to combination other environmental factors are needed.

Suggestions for future research

With the possibility of climate change intensifying in the future, expansion of oil sardine fishery may continue only until threshold temperature for performing biological cycle of the fish is reached. The fishery may show reverse trend beyond a critical point. Considering the importance of oil sardine, it is necessary to identify and fill the existing knowledge gaps before a reversing trend starts taking place:

(i) The biggest knowledge gap is non-availability of estimates on fish abundance and biomass. All the prevailing analysis and interpretations are based on data on commercial landings, and not on abundance estimates. While data on landings is considered as a proxy to abundance, the biased nature of commercial fishing concentrating in areas and seasons of fish abundance will often lead to overestimates on stock biomass. In addition, data from commercial fisheries lack important details such as location of fishing grounds. Hence, it is necessary to complement commercial fisheries data with fishery-independent data by undertaking scientific surveys at sea. If coverage in space and time is good, survey data are considered to be of higher quality for abundance estimates because sampling and collection are scientifically designed and standardised. In addition, accurate biological information on target species can be collected from surveys-at-sea.

(ii) The relationships between environmental factors and stock biomass, spawning stock biomass and recruitment variability of oil sardine need to be established.

(iii) Early life stages (prior to recruitment into fishery) are critical phase in the life cycle of fish which determine the abundance. For oil sardine (like many other fish species), information on the effects of environmental factors on survival and distribution of fish eggs and larvae are lacking. By combining sea survey and biophysical models, spatially and temporally resolved long-term environmental connectivity on survival and dispersal of early life phases need to be simulated.

Clearly, more research is needed to increase our understanding on the process and magnitude of impact of climate change on marine fisheries along the Indian coast, not only to confirm plausible causes of expansion of oil sardine fishery, but also to develop adaptation plans.

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11

Impacts of climate change on the fishing and coastal communities

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ABSTRACT

Climate change has a profound impact on aquatic ecosystems affecting the distribution and productivity of fisheries. Coastal communities dependent on fishery resources for their livelihood are most vulnerable to such changes. This study undertaken in the coastal districts of Karnataka, India documents the effect of climate change on the environment, fishery, social, economic and development drivers. Vulnerability indices were constructed to identify the districts which would be most affected by climate change. The study revealed that the coastal district of Udupi was the most affected with the highest vulnerability index of 0.46. Among the various drivers, development ranked foremost among the fishers perception of climate change.

1. Introduction

Climate Change is rapidly impacting aquatic ecosystems including marine, fresh and brackish water. Climate change plays a major role in influencing fish distribution, fish migration and also in deciding the fish productivity in various countries of the world. It will have a profound impact on humans and ecosystems during the coming decades through variations in global average temperature and rainfall. It is predicted to bring about diverse impacts with extreme weather conditions across regions like intense rainfall and flood risks while on the other side there would be extreme droughts besides higher tides, intense storms, warmer oceans and erosion along coastlines as an outcome of sea level rise. Climate change can affect lives, livelihoods and production systems posing high risk to people living in rural areas, particularly the poor. This is seen as a challenge and threat specifically to India's growing economy. Fish spawning is especially sensitive to temperature, and several species of marine fish are known to spawn only at a particular water temperature. Climatic changes are already affecting the availability, behaviour and distribution of some commercial fish. It has been observed that there is a positive relationship between the sea surface temperature and spawning activity of threadfin breams. The fish are shifting their reproductive activities to a period where the temperature is closer to their optimum. The changes in reproduction patterns will play an important role in the availability of these fish and the livelihoods and incomes of fisher folk. One of the popular food fishes with which changes in behaviour were noticed due to climate change is the Oil Sardine, a coastal, schooling fish with a high reproductive rate (Badjeck et al., 2010). Its distribution is restricted to the Malabar region along the southwest coast; however, it plays a crucial ecological role in the ecosystem both as a plankton feeder and as food for large predators. It has economic importance in that the annual average production is 3.37 lakh tonnes which comprises 8.8 % of India's total catch. (CMFRI, 2018) It is also important in terms of food and nutritional security as it is a good source of protein, serving as a staple food for millions of coastal people. Due to the current warming of the Indian Ocean, the oil sardine has already spread to the northern and eastern boundaries of its original distribution in the Indian Ocean. Vulnerability has become the key concept of climate change. Vulnerability is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change including climate variability and extremes (IPCC, 2001). Climate related vulnerability assessments are based on the characteristics of the vulnerable system spanning over physical, economic and social factors (Gillman et al., 2008). The impacts of climate change can be addressed through adaptation and mitigation. The costs and benefits of adaptation are essentially local or national, while the costs of mitigation are essentially national whereas the benefits are global. Several international agencies, including the World Bank and the Food and Agriculture Organization (FAO, 2007) have programs to help countries and communities adapt to global warming, for example by developing policies to improve the resilience (Allison et al., 2007) of natural resources, through assessments of risk and vulnerability, by increasing awareness (Dulvy and Allison, 2009) of climate change impacts and strengthening key institutions, such as for weather forecasting and early warning systems (Gillman et al., 2008). The World Development Report 2010, shows that reducing overcapacity in fishing fleets and rebuilding fish stocks can both improve resilience to climate change and increase economic returns from marine capture fisheries by US$50 billion per year, while also reducing GHG emissions by fishing fleets. Consequently removal of subsidies on fuel for fishing can have a double benefit by reducing emissions and overfishing. Investment in sustainable aquaculture can buffer water use in agriculture while producing food and diversifying economic activities.

Throughout the world, fisher folk are poorly informed of climate change and its consequences that would impact the livelihood of fishers. Fishers at first instance are not aware of the terminology of climate change, but when it is explained to them by a change agent /extension worker at the field level that climate change is a significant and lasting change in the distribution of weather patterns over periods ranging from decades to millions of years, they are able to relate to various weather phenomena in which they have observed a change/departure from the normal course of events over the last few decades.

In projected climate change scenarios, the main threats to coastal populations and ecosystems are sea-level rise, the intensification of extreme weather events and ecosystem changes. (Nicholls et al., 1999). Other expected impacts are a rise of up to 3 °C on sea surface temperature, changes in precipitation and fresh water input, salt water intrusion into soils and coastal aquifers, and ocean acidification. (Wu and Siewert, 2008) These climate alterations will have varied effects on coastal ecosystems and human populations, with a likely increase on flooding and loss of wetlands as observed by Nicholls, 2004. Flooding of populated areas and infrastructure, results in severe economic impacts and changes in the availability of natural resources, with consequences for the livelihoods of those who rely directly on them for survival, such as traditional or neo-traditional coastal populations, including fisher folk (Badjeck et al., 2010).

Fishing communities have a major role to play in the process of adaptation and mitigation of climate change effects. Fisher folk should shoulder the responsibility that they are not only mere harvesters of fish, but they are also the guardians of these scarce resources and should be at the forefront of initiatives that support and maintain sustainable activities and facilitate coastal resource conservation and management. They should be involved in the restoration of natural barriers such as mangroves, coral reefs and sea grasses. Restoration of coastal habitats will in the long run increase fish productivity and aquatic biodiversity of any given area. Fisher folk can also engage in rebuilding depleted fish stocks by strictly observing government fishing regulations which include limited entry, seasonal and area closure, mesh size limits, appropriate fishing methods, among others. They should also participate in crafting innovative gear modifications to mitigate the problems. Increasing social participation of fisher folk in local organisations and co-operatives, can promote integrated coastal resource management. Their inherent capacities and local knowledge can be used to modify and improve conventional practices supporting community adaptations to extreme conditions. In addition, they should be willing to learn to raise their awareness and help them understand how climate change will impact their daily life, livelihood productivity and well-being. By actively participating, they can access information and influence decision-making especially with respect to development activities that may threaten their lives and resources. Collective action is also a good strategy for deterring illegal activities. Along with these are affordable communication technology/tools such as mobile phones, radios, etc. that can be used to receive up-to-date weather forecasts and storm warnings.

Against this back ground, it was proposed to take up a study with the following objectives:

1. To assess the vulnerability of coastal districts of Karnataka by construction of vulnerability indices.
2. To study the climate change effects with respect to environmental impact, fishery impact, social impact, and economic impact and development drivers' impact as was perceived by the fisher folk.

3. Methodology

An overview of coastal Karnataka
The study was carried out in coastal Karnataka. Karnataka's coastline stretches for 320 kilometres and consists of the three coastal districts namely, Uttara Kannada, Udupi and Dakshina Kannada. Of these, Uttara Kannada has 160 kilometre long coastline, Udupi district has 98 kilometres coastline and the rest 62 kilometre length of coastline falls in Dakshina Kannada district (Figure 1). The distinct agro-climatic zones range from coastal flatlands in the west with undulating hills and valleys in the middle and high hill ranges in the east that separates it from the peninsula. There is a narrow strip of coastal plains with varying width between the mountain and the Arabian Sea. 14 rivers drain in to the shore waters of Karnataka. Sand bars have developed in most of the estuaries. There are 90 beaches with increasing scope for beach tourism.

The coastal zone of Karnataka hosts better developed geographical areas of the State with high degree of economic development and high density of population. There are a total of 144 marine fishing villages with 86 fishing villages in Uttara Kannada, 41 in Udupi and 17 in Dakshina Kannada district. The occupational pressure of the region can be attributed to agricultural activities, aquaculture, fish landing and processing, port maintenance, mining for lime shells, bauxite and silica sand, cashew processing industries, rice mills and coconut oil extraction mills.

3.1 Coastal erosion

Coastal Karnataka is subject to three types of erosion, occurring along the open beaches, mouths of rivers/estuaries and the tidal reach of rivers causing considerable loss of land, vegetation and revenue. About 30 percent of the area under coastal zone is subjected to moderate soil erosion and 16 percent of the area to severe soil erosion. The annual rates of soil erosion vary from 5-15t/ha to 15-40 t/ha in moderate to severe soil erosion areas. This problem is severe in Dakshina Kannada and Udupi coasts.

3.2 Selection of the coastal district:

Among the three coastal districts of Karnataka, Udupi district was selected for the study based on secondary data such as historical data on extreme weather events, sea erosions, loss in fishing days. 46 km of the total 95 km stretch of Udupi's coastline is under critical coastal erosion (Dwarkish et al., 2009). Besides, his studies have revealed that 59 per cent of the 95 km of shoreline of Udupi district is at a very high risk due to future Sea Level Rise (SLR).
In addition, secondary data collection, Participatory Rural Appraisal methods (PRA) and Rapid Rural Appraisal (RRA) methods were used for the selection of the district.

3.3 Selection of coastal villages:

Six villages of Udupi district were selected based on historical data for factors such as shoreline change, agricultural lands, wetlands, salt pans, beaches, population density, literacy rates, occupation, infrastructure and craft and gears in the fishery. The six villages selected for the study were Thenkayermal, Mattu, Kadekar, Udyavara, Paduthonse, and Maravanthe (Figure 2)

Data was collected using well-structured interview schedules using village survey schedules for individual villages and household schedules for individual households. Data was collected from 125 households per village thus totalling to 750 households which formed the total sample for the study. Besides data collection using structured schedules, focus group discussions, freewheeling interviews and PRAs and RRAs techniques were used in the study villages in order to get greater access to the fisher communities.

The vulnerability index for each coastal district was worked out by adopting the method developed by Patnaik and Narayanan, 2005.






VI=Vulnerability index

$$VI = \left[\sum_{i-1}^{n} (AI_i)^{\alpha} \right]^{1/\alpha} \Big/ n$$

Where VI=Vulnerability index

(AI) is the average index for each source of vulnerability, n is the number of source of vulnerability and **α** = n.
Accordingly for the present study, five parameters of vulnerability namely demography, occupation, infrastructure, climate components and fishery components and their respective sub indicators were used for the study. They were a) Demography- number of fishing villages, number of fishermen households, total fisher folk population, literacy; b) Occupation-Full time fishermen, part-time and occasional, c) Infrastructure- kutcha houses, educational institutions, number of hospitals/ dispensaries, number of banks, number of fishermen co-operative societies, number of community centres; d) climate components- temperature, rainfall and wind velocity e) Fishery components- mechanised, motorised, non-motorized, and number of active fishermen. Since all the five parameters were in different units and scales, the methodology used in UNDP's Human Development Index (HDI) (UNDP, 2006) was used to normalise them using their functional relationship with vulnerability. When variables such as rainfall had an increasing functional relationship with vulnerability, the normalisation was done using the formula:

$$x_{ij} = \frac{X_{ij} - \underset{i}{Min}\ \{X_{ij}\}}{\underset{i}{Max}\ \{X_{ij}\} - \underset{i}{Min}\ \{X_{ij}\}}$$

When variables such as literacy had a decreasing functional relationship with vulnerability the normalisation was done using the formula:

$$y_{ij} = \frac{Max\ \{X_{ij}\} - \underset{i}{X_{ij}}}{\underset{i}{Max}\{X_{ij}\} - \underset{i}{Min}\ \{X_{ij}\}}$$

The perceptions of the fisher folk towards climate change effects with respect to Environmental impacts, fishery impact, social impact, economic impact and development drivers impact were studied by administering a psychometric scale (***Likerts summated rating technique, 1932***) on a 1-5 continuum.

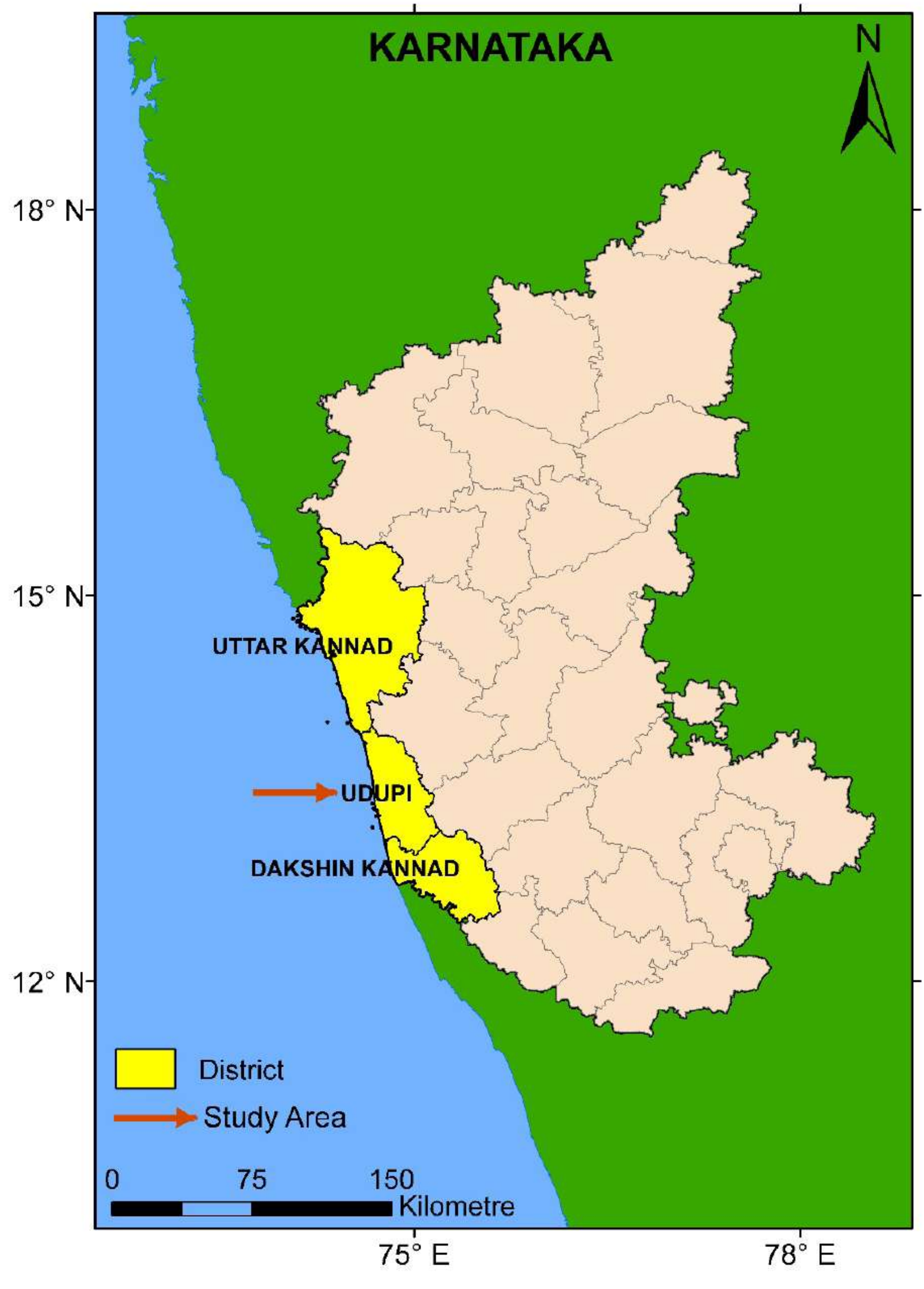

Figure 1: Map showing the coastal districts of Karnataka

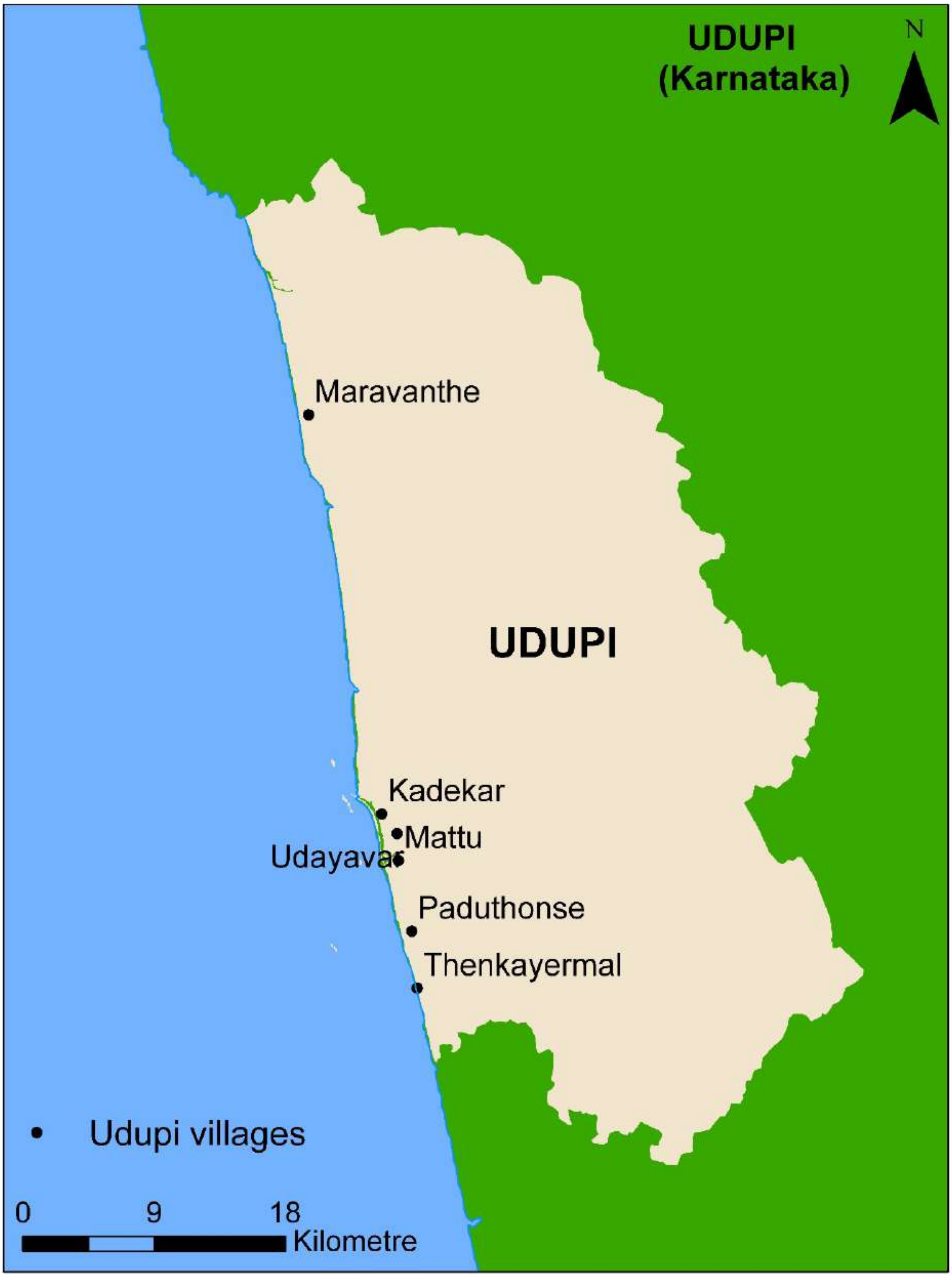

Figure 2: Map of the study area showing the sample villages

4. Findings and discussion

The five most important climate parameters such as Demography, Infrastructure, Occupation, Climate and Fishery were used for the construction of the vulnerability index.

Table 1: Vulnerability assessment of coastal districts of Karnataka

District	Demography	Infrastructure	Occupation	Climate	Fishery	Vulnerability Index (V.I)
Uttara Kannada	0.30	0.78	0.13	0.32	0.28	**0.362**
Udupi	0.30	0.84	0.56	0.35	0.25	**0.460**
Dakshina Kannada	0.32	0.69	0.22	0.29	0.57	**0.418**

The vulnerability index of the three coastal districts of Karnataka are shown in Table 1. It could be observed that, Udupi district has the highest vulnerability index of 0.460, followed by Dakshina Kannada with an index of 0.418 and Uttara Kannada with the lowest index of 0.362. Udupi district consists of 41 fishing villages. Udupi district is vulnerable to accelerated sea level rise (SLR) due to its low topography and due to its high ecological and touristic value (Dwarakish et al., 2009). Of the 41 fishing villages of Udupi district, six fishing villages namely Thenkayermal, Mattu, Kadekar, Udyavara, Paduthonse, and Maravanthe were selected for the study based on social, economic and geographical parameters. The vulnerability indices were worked out for the selected fishing villages (Figure 4). It can be inferred that the fishing village of Maravanthe had the highest V.I of 62.05 closely followed by Thenkayermal with V.I of 61.58 and Udyavara with V.I of 61.55. However, it could be observed that all the six fishing villages were more or less uniformly impacted by climate change parameters. Paduthonse had the lowest V.I of 58.89.

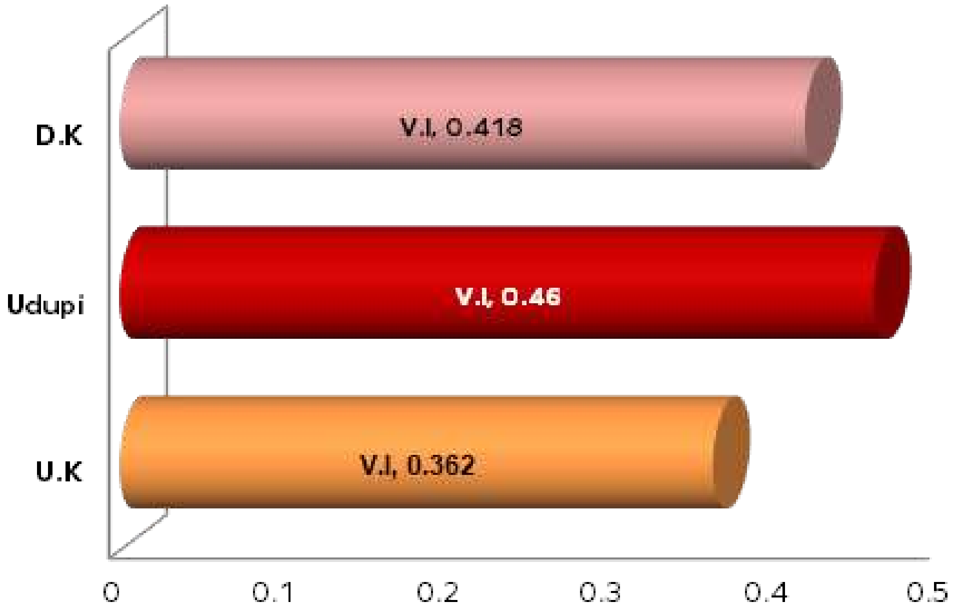

Figure 3: Vulnerability indices of coastal districts of Karnataka

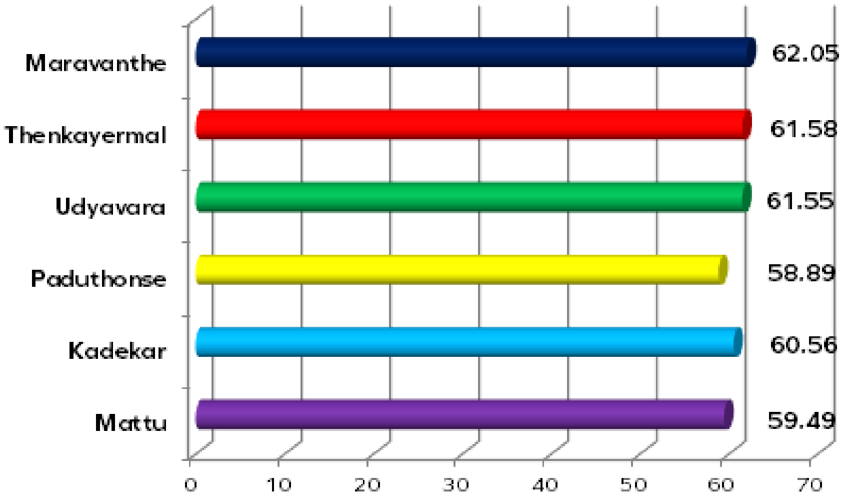

Figure 4: Vulnerability indices for fishing villages in Udupi district

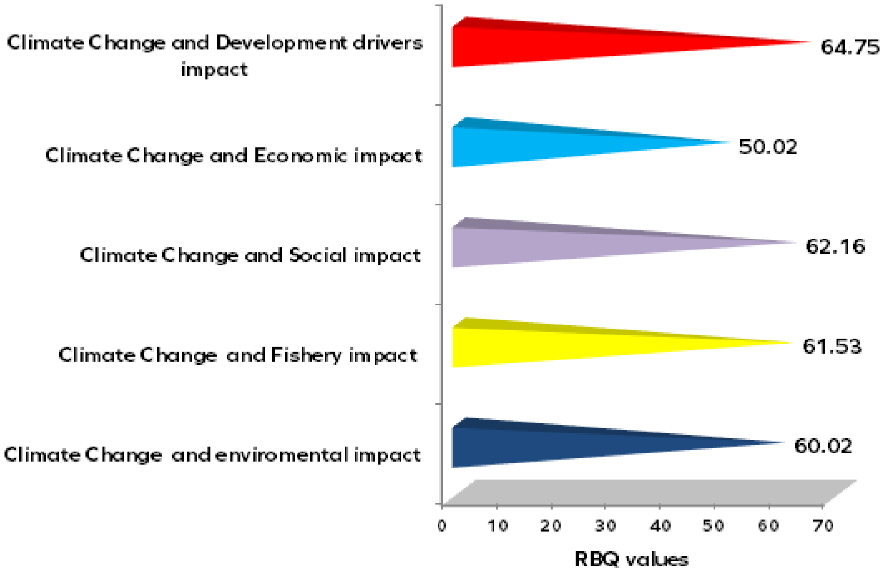

Figure 5: Climate parameter assessment of the composite villages

The climate parameter assessment of the composite villages is depicted in Figure 5. It could be observed that the parameter namely climate change and development driver ranked first (RBQ of 64.75) among fisher folk followed by climate change and social impact (RBQ of 62.16), followed by climate change and fishery impact (RBQ of 61.53). An attribute analysis for the development drivers (Figure 6) indicated that among the development drivers such as infrastructure drivers, productivity enhancement drivers, anthropogenic drivers, ICT enabled drivers and policy support drivers, anthropogenic drivers had impacted the fisher folk most with an RBQ value of 60.68. (Rank 1). The sample of six fishing villages undertaken for the study namely Thenkayermal, Mattu, Kadekar, Udyavara, Paduthonse, and Maravanthe had witnessed an increased influx of tourists over the years. This had led to an increase in developmental activities and impacts such as beach tourism, increased deposition of litter, plastics; and the respondents are of the perception that in the process of development, sustainability issues have been overlooked, and there has been spurt in the anthropogenic activities over the years.

The parameter namely climate change and social impact ranked second with respect to fisher folk perception on climate change parameters (Figure 7). Among the social impacts the fisher folk perceived infrastructure sensitivity as having the highest attribute. Among the resilience indicators to this attribute it was observed that the households in the study area were highly prone to disasters and sea water inundation and coastal erosion was high in these villages.

Climate change and fishery impact ranked third in order with a RBQ of 61.53 (Figure 8). It could be inferred from the attribute analysis that the fishery was impacted mostly by catch. The analysis on the resilience indicator to this attribute indicated that fish catch has decreased drastically over the years and effort has increased fairly and targeted groups of fishes have changed significantly.

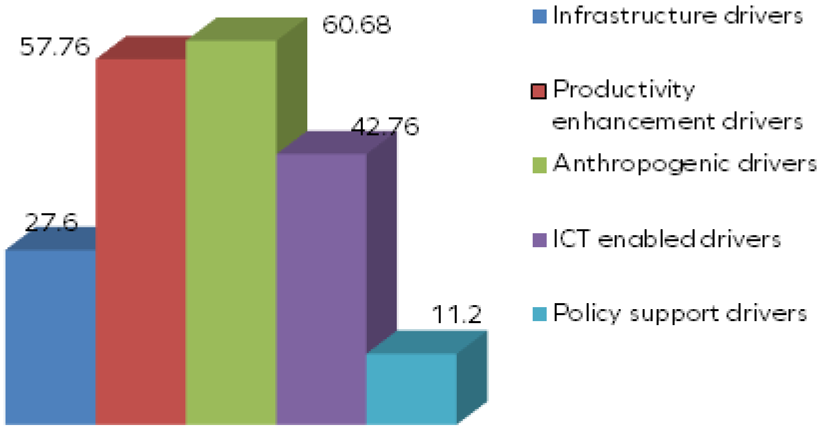

Figure 6: Attribute analysis for Climate Change and Development drivers impact

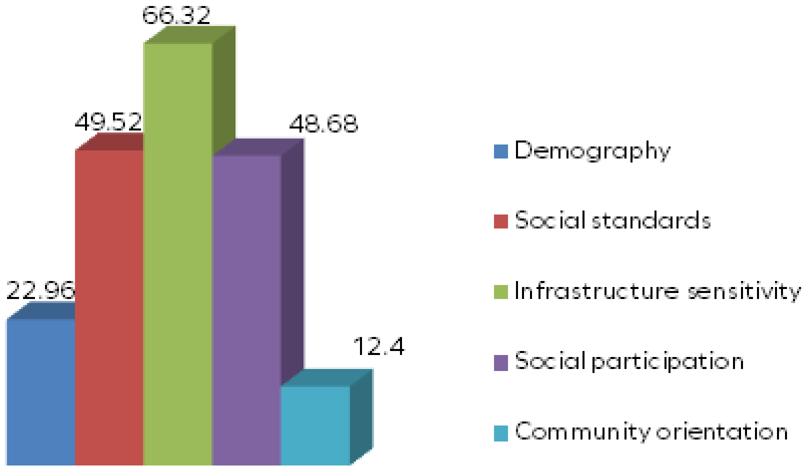

Figure 7: Attribute analysis for Climate Change and Social impact

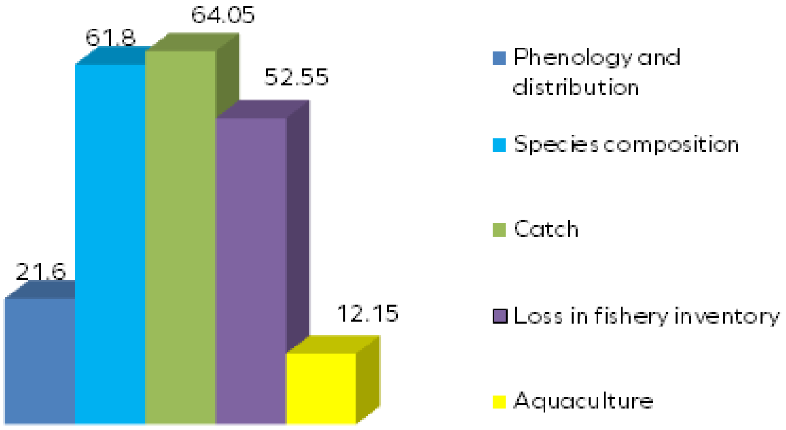

Figure 8: Attribute analysis for Climate Change and Fishery impact

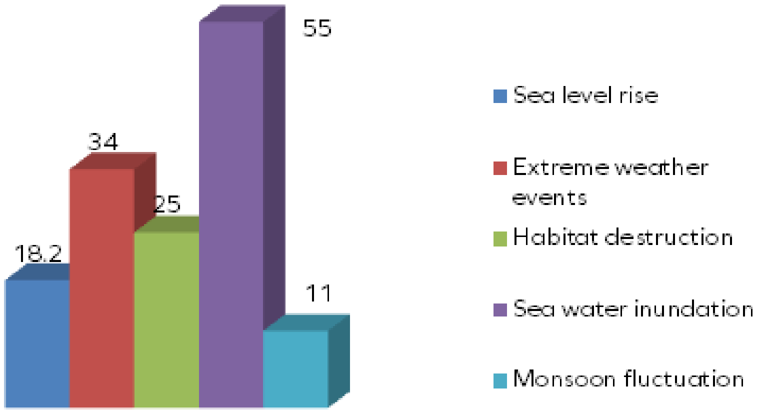

Figure 9: Attribute analysis for Climate Change and Enviromental impact

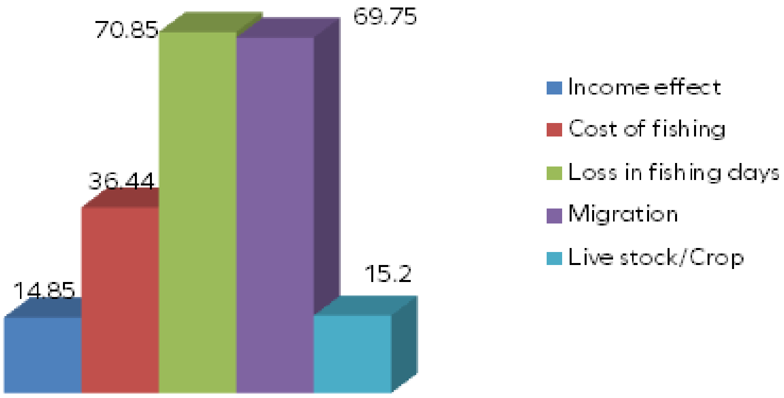

Figure 10: Attribute analysis for Climate Change and Economic impact

Climate change and enviornmental impact ranked fourth with a RBQ value of 60.02. The attribute analysis for this parameter indicated that enviornmental parameter was highly impacted by sea water inundation followed by extreme weather events (Figure 9) Sea water inundation was high in the fishing villages of Udyavara, Paduthonse, Maravanthe and Thenkayermal.

The climate parameter assessment of the composite villages indicated that climate change and economic impact was ranked as last in order with the lowest RBQ value of 50.02. The attribute analysis for this parameter indicated that the economic parameter was highly impacted by the loss in fishing days followed by the phenomena of migration (Figure 10). Fisherfolk believe that there is a considerable economic loss due to the decrease in the number of fishing days owing to extreme weather events. Competiton in fishing has increased due to the increased number of fleets over the years. Coastal Karnataka on the west coast of India has been a witness to inter-sectoral migration. There has been a shift in the occupational mobility and a steady influx of migrants from the agrarian sector of Tamil Nadu, Andhra Pradesh and Odisha to the coastal districts of Karnataka.

The study on climate change and vulnerability indicated that climate change and development driver ranked first among fisher folk. The coastal district of Udupi has been impacted the most with the highest vulnerability index of 0.46. The low lying nature of Udupi coastal zone coupled with significant land reclamation investments and extensive industrial, commercial, residential and tourism activity emphasises that ecological and socio-economic systems are currently facing tremendous pressure due to rapid industrialisation urbanisation and economic development. 59 percent of Udupi's shoreline is classified as being at very high risk due to future Sea Level Rise. This implies that the population living presently in these areas would be displaced. There is an urgent need for incorporating the elevation levels for new settlement areas under the town planning acts so that human life and property are saved form natural hazards/vulnerabilities.

It was observed during the course of the study that the awareness of the fishers about climate change was relatively low. Widespread awareness campaigns on climate change is the need of the hour. The options available for protection of Udupi coast from future sea level rise could be dune afforestation, mangrove restoration and management, periodic beach nourishment and building sea walls and groins. Long term measures should focus on planned and regulated urban development, institutional building and involvement of local fisher folk for disaster preparedness and creation of awareness on a large scale among the coastal fisher folk.

5. Adaptation and mitigation strategies to combat Climate Change in Udupi district

A total of 95 km of the shoreline is ranked in the study area, out of which 59% of the mapped shoreline is classified as being at very high risk due to future Sea Level Rise. The percentage of high and moderate risk is only 11%, and the remaining 30% of the shoreline is under the low risk category. From this it is very clear that the Udupi coast is highly vulnerable for future SLR, and the different LU/LC features under the direct risk of flooding include coastal villages, agricultural land, wetland, salt pans, aquaculture ponds, link roads, beaches and coastal dunes. This implies that the population living presently in these areas would be displaced.

The options available for the protection of the Udupi coast from future SLR could be dune afforestation, mangrove restoration and management, periodic beach nourishment and building seawalls and groins. The construction of seawalls is costly and hence it would be used only for some settlements at high risk of inundation. The performance of properly constructed and maintained seawalls along the undivided Dakshina Kannada coast is satisfactory. The integrated coastal zone management plan, though active in India, is still not fully functional. It must emphasize more on building regulations, urban growth planning, development of institutional capacity, involvement of local community, increasing public awareness and should be based on long-term sustainable developmental programmes.

Adaptive capacity is the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies. The presence of adaptive capacity has been shown to be prerequisite for the design and implementation of effective adaptation strategies so as to reduce the likelihood and the intensity of harmful consequences accruing from climate change. (Brooks et al., 2005) Adaptive capacity also enables sectors and institutions to take advantage of opportunities or benefits from climate change, such as a longer growing season or increased potential for tourism.

Much of the current understanding of adaptive capacity comes from vulnerability assessments. Even if vulnerability indices do not explicitly include determinants of adaptive capacity, the indicators selected often provide important insights on the factors, processes and structures that promote or constrain adaptive capacity (Ericson et al., 2006). One clear result from research on vulnerability and adaptive capacity is that some dimensions of adaptive capacity are generic, while others are specific to particular climate change impacts. Generic indicators include factors such as education, income and health.

Technology can potentially play an important role in adapting to climate change. Efficient cooling systems, improved seeds, desalination technologies, and other engineering solutions represent some of the options that can lead to improved outcomes and increased coping under conditions of climate change. Often, technological adaptations and innovations are developed through research programmes undertaken by governments and by the private sector (Smit and Skinner, 2002). Innovation, which refers to anything perceived as new or the revival of old ones in response to new conditions, is an important aspect of adaptation, particularly under uncertain future climate system (Bass, 2005). Although technological capacity can be considered a key aspect of adaptive capacity, many technological responses to climate change are closely associated with a specific type of impact, such as higher temperatures or decreased rainfall.

In the climate change context, the term 'mainstreaming' has been used to refer to incorporation of climate change vulnerabilities or adaptation plans into some government schemes such as water management, disaster preparedness and emergency planning or land-use planning (Agrawala, 2005). Actions that promote adaptation include integration of climate information into environmental data sets, vulnerability or hazard assessments, broad development strategies, macro policies, sector policies, institutional or organisational structures, or in development project design and implementation. (Burton and Aalst, 1999) By implementing mainstreaming initiatives, it is argued that adaptation to climate change will become an integral part of other well-established programmes, particularly sustainable development planning.

6. Measures for coastal adaptation to climate change

- An effective early warning communication and response system can reduce death and destruction
- Hazard awareness education and personal hazard experience are important contributors to reducing community vulnerability
- Many factors reduce the ability or willingness of people to flee an impending disaster, including the warning time, access and egress routes, and their perceived need to protect property, pets and possessions
- Coastal landforms (coral reefs, barrier islands) and wetland ecosystems (mangroves, marshes) provide a natural first line of protection from storm surges and flooding, despite divergent views about the extent to which they reduce destruction
- Recurrent events reduce the resilience of natural and artificial defenses
- In the aftermath of extreme events, additional trauma occurs in terms of dispossession and mental health

- Uncoordinated and poorly regulated construction has accentuated vulnerability
- Effective disaster prevention and response rely on strong governance and institutions, as well as adequate public preparedness

This assessment shows that the level of knowledge is not consistent with the potential severity of the problem of climate change and coastal zones. Establishing better baselines of actual coastal changes, including local factors and sea-level rise, and the climate and non-climate drivers, through additional observations and expanded monitoring would help to better establish the causal links between climate and coastal change which tend to remain inferred rather than observed and support model development.

- Improving predictive capacity for future coastal change due to climate and other drivers, through field observations, experiments and model development. A particular challenge will be understanding thresholds under multiple drivers of change. Developing a better understanding of the adaptation of the human systems in the coastal zone. At the simplest this could be an inventory of assets at risk, but much more could be done in terms of deepening our understanding of the qualitative trends and issues of adaptive capacity.
- Improving impact and vulnerability assessments within an integrated assessment framework that includes natural-human sub-system interactions. This requires a strong inter-disciplinary approach and the targeting of the most vulnerable areas, such as populated mega deltas and deltas, small islands and coastal cities. Improving systems of coastal planning and zoning and institutions that can enforce regulations for clearer coastal governance is required in many countries.
- Developing methods for identification and prioritisation of coastal adaptation options. The effectiveness and efficiency of adaptation interventions need to be considered, including immediate benefits and the longer term goal of sustainable development
- Developing and expanding networks to share knowledge and experience on climate change and coastal management among coastal scientists and practitioners.

7. Increasing human utilization of the coastal zone

Despite the fact that not all coasts of the world are inhabited, very few of them are devoid of human influence (Buddemeier et al., 2002). Utilization of the coast increased dramatically during the 20th century, a trend that seems certain to continue through the 21st century. The increasing population density harboured by many of the world's deltas, barrier islands and estuaries has led to unprecedented conversion of natural coastal landscapes to agriculture, aquaculture, silviculture, as well as for commercial and residential uses (Wu et al., 2009). It has been assessed that 23% of the world's population lives both within 100 km distance of the coast and <100 m above sea level, and population densities in coastal regions are about thrice higher than the global average (Small and Nicholls, 2003). The attractiveness of the coast has resulted in disproportionately rapid expansion of economic activity, settlements, urban centers and tourist resorts. Migration of people to coastal regions is common in both developed and developing nations. Sixty percent of the world's 39 metropolises with a population of over 5 million are located within 100 km of the coast, including 12 of the world's 16 cities with populations greater than 10 million. Rapid urbanisation has many consequences: for example, enlargement of natural coastal inlets and dredging of waterways for navigation, port facilities, and pipelines exacerbate saltwater intrusion into surface and ground waters. Instances of Increasing shoreline retreat and dangers arising from occurrence of floods in coastal cities in Thailand (Durongdej, 2001, Saito, 2001), India, (Mohanti, 2000), Vietnam (Thanh et al, 2004) and the United States (Scavia et al., 2002) have been attributed to degradation of coastal ecosystems by human activities.

The direct impacts of anthropogenic activities on the coastal zone have been more conspicuous over the last century than impacts that could be directly attributed to observed changes in the climate (Scavia et al., 2002, Lotze et al., 2006). The major direct impacts include drainage of coastal wetlands, deforestation and reclamation, and discharge of sewage, fertilisers and contaminants into coastal waters. Extractive activities include sand mining and hydrocarbon production, harvest of fisheries and other living resources, introductions of invasive species and construction of seawalls and other structures. Engineering structures, such as damming, channelisation and diversions of coastal waterways harden the coast, change circulation patterns and alter freshwater, sediment and nutrient delivery. Natural systems are often affected and changed directly or indirectly by soft engineering mechanisms, such as beach nourishment, and for dune construction (Nordstorm, 2000; Hamm and Stive, 2002). Ecosystem services on the coast are often disrupted by human activities. For example, tropical and subtropical mangrove forests and temperate saltmarshes provide goods and services (they accumulate and transform nutrients, attenuate waves and storms, bind sediments and support rich ecological communities), which are reduced by large-scale ecosystem conversion for agriculture, industrial and urban development, and aquaculture.

8. Conservation and Development of mangroves

The coastal zone in Karnataka contains habitats and ecosystems, such as estuaries, mangroves and coral reefs, which have definite role in the maintenance of ecological balance and economic vitality of coastal region. The diversity and distribution of mangroves along the Karnataka coast indicates the sensitivity to various environmental changes. Increasing anthropogenic pressures in the form of conversion of habitats or pollution are mainly responsible for the decline in species level diversity of mangroves and coral reefs along the coast.

To overcome such problem, it is very essential to formulate an action plan for replanting of mangrove in the area where they have disappeared. Also to be taken up in conjunction with protection of mangroves, is restoration of patches of biodiversity-rich habitats in the coastal, riverine and deltaic belt. The Karnataka State Coastal Zone Management Authority can:

- Develop a viable concept for replanting in terms of extent, timeframe, implementation, monitoring etc. in consultation with a competent re- search institute
- Ensure local communities' participation to protect mangroves
- Promote awareness on the importance of mangrove ecosystems
- Removal of encroachments posing a threat to mangrove ecosystems
- Re-plantation plan to rejuvenate the mangrove ecosystem

The stakeholders would be the Karnataka State Coastal Zone Management Authority, Karnataka Biodiversity Board, the Department of Agriculture, Panchayat Raj Institutions and local non-governmental organizations. It is essential to impart knowledge on mangrove protection to different groups of coastal population. The awareness /user-interaction should be conducted in different regions during different times of the year. Further, skill training programme on mangrove nursery and using of Information and communication tools improves the desired level of awareness.

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Coastal Adaptation

12

Ecological adaptations of Indian mangrove ecosystems to climate change

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ABSTRACT

Mangroves are remarkably adapted to extreme environmental conditions, and play a vital role in disaster risk reduction and climate change mitigation. Mangroves are very efficient in carbon sequestration, due to high photosynthetic rates and a large domain of anaerobic soil to store carbon for millennia. Hence, mangrove conservation and restoration can be a novel counter-measure for global warming as it reduces carbon emission to the atmosphere. This chapter analyses the mangroves in different states and union territories of India, their types, the intensity of vulnerability, factors of vulnerability and resistance/ resilience to climate change. The analysis indicated that mangroves, especially in Andaman & Nicobar Islands and the east coast are highly vulnerable to sea level rise. This calls for more research data on climate change impacts and efficient management of mangroves in those areas.

1. Introduction

Mangroves are one of the first ecosystems to be affected by climate change because of their location at the interface between the land and sea (Kathiresan and Bingham, 2001; Kathiresan and Qasim, 2005; McLeod and Salm, 2006; Kathiresan, 2014; 2017; 2018). The factors of climate change viz., carbon dioxide, and temperature, cyclones/storms, precipitation, and sea level rise, act synergistically upon the mangroves (Figure 1). However, mangroves have the ability of resistance in withstanding disturbances and that of resilience in recovering from disturbances (McLeod and Salm, 2006). This is due to remarkable adaptations of the mangroves, such as green-wall like physical barrier, flexible aerial roots, extensive underground cable roots, and high productivity even in nutrient-poor and saline environment through salt regulation and retention of water and nutrients. The ecological adaptations of mangroves towards climate change in India are discussed here.

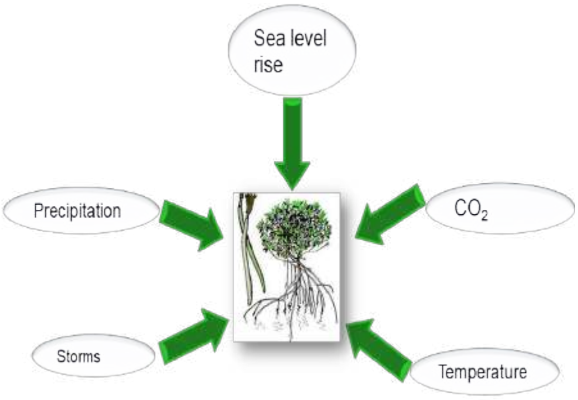

Figure 1: Factors of climate change that act synergistically upon mangrove ecosystems

2. Atmospheric CO2

Atmospheric carbon dioxide has increased mostly from fossil fuels to more than 400 ppm now from 280 ppm in the year 1880. This increase in CO2 is likely to be favourable for mangroves by increasing their net photosynthesis and growth rate. This happens only when the soil salinity is moderate to low. On the contrary, mangroves may be affected if the soil salinity is very high especially in arid regions. It is also believed that the increase in CO2 does not change photosynthesis and growth, but reduces respiration (McLeod and Salm, 2006; Kathiresan, 2014; Figure 2).

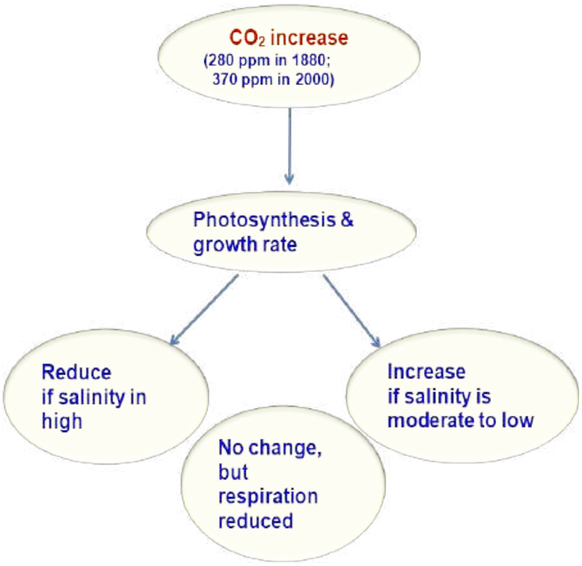

Figure 2: Impact of atmospheric carbon dioxide on mangroves

Mangroves are among the most carbon-rich forests in the tropics. This is because of high levels of photosynthesis, biomass production, and efficient storage of organic carbon in mangrove soils for millions of years due to large domain of anaerobic soil (Bhatt and Kathiresan, 2012; Kathiresan et al., 2013, 2014). Mangrove wetlands are efficient habitats for carbon burial: about 2.4-fold as high as salt marshes, 5.2-fold as high as seagrasses and 4-fold as high as tropical forests (Duarte et al., 2005). However, there is severe lack of spatial data for global mangroves (Taillardat et al., 2018), and hence it is necessary to collect region-wise data to better understand the role of mangroves as carbon sink. This role is well-known in countries with extensive coastlines. In India, for instance, the total biomass in mangrove forests is estimated to be 41.2 million tonnes. This includes 32.68 million tonnes of above-ground biomass and 8.49 million tonnes of below-ground biomass. Total C stock in Indian mangrove forests is 20.59 million tonnes of which, more than 80% of the C stock is present in the mangrove forests of West Bengal, Gujarat and Andaman & Nicobar Islands. Mangroves in India have the potential of sequestering 0.47 ton C.yr^{-1} (Suresh et al., 2017). Covering 4,921 km^2, the Indian mangroves absorb about 9 million tonnes of carbon dioxide daily, valued at around US$ 270 million in the international market (Kathiresan, 2018). Maintaining this carbon sequestration function of mangroves will help to control climate change impacts by reducing atmospheric carbon and temperatures.

Globally, mangrove deforestation generates emissions of 0.02–0.12 picograms of carbon per year, up to 10 % of the total emissions from deforestation (Donato et al., 2011). However, the global mangrove deforestation pattern from the year 2000 to 2012 showed a decreasing trend in many nations being essentially stable, with the exception of the largest mangrove-holding region of Southeast Asia (Hamilton and Casey, 2016). During the same period, mangrove cover in India exhibited an increasing trend from 4,482 to 4,628 km^2 that included around 60% of dense mangrove cover, and 40% of open forest cover. India is witnessing degradation of mangroves (Kathiresan, 2018). Failing to restore mangrove forests is likely to increase in atmospheric carbon and temperatures, and hence mangrove conservation and restoration can be a novel mitigation option against climate change.

3. Atmospheric temperature

Mangrove plants need an ideal temperature of 28-32°C for photosynthesis. Warming of 0.5° C is likely in India by the year 2030. A small increase in temperature may not adversely affect the flowering, but may change their reproductive cycle, and thus may alter the duration between flowering and the fall of ripe seeds. However, temperatures higher than 35°C may alter root structure and seedling establishment, whereas temperatures exceeding 40°C are likely to affect photosynthesis in the mangrove species except in *Avicennia marina* (Kathiresan, 2017).

Temperature and rainfall are important climatic factors influencing the dynamics of mangrove species. In Sundarbans, the trends of change for *Heritiera fomes* and *Sonneratia apelatala* show a strong relationship with temperature and rainfall, while *Ceriops decandra* exhibits a weak relationship. In contrast, *Excoecaria agallocha* and *Xylocarpus mekongensis* do not show any significant relationship with temperature and rainfall (Ghosh et al., 2017).

It has been widely reported that mangroves expand pole ward by replacing salt marshes as a consequence of increasing temperature (Saintilan et al., 2014; Osland et al., 2017a,b; Weaver and Armitage, 2018), but the effects of temperature rise in the core mangrove areas of tropical countries like India remains unknown. However, areas with arid climate in Gujarat, Tamil Nadu and Andhra Pradesh are largely mono-specific with *Avicennia marina*, as this mangrove species is resistant to high temperature of >40°C (McLeod and Salm, 2006; Kathiresan, 2014). Moreover, salt marsh plants that can tolerate high temperature have encroached into the arid mangrove areas. At the same time, increased temperature may increase growth rates of soil bacteria which are likely to increase recycling and regeneration of nutrients. More studies are required on the role of microbes in carbon sequestration of the coastal habitats.

One indirect effect of the increase in temperature is the degradation of coral reefs due to mass bleaching and impaired growth. As a result, the protection function of the coral reefs from wave action will be lost, thereby affecting the mangroves (Kathiresan, 2014). Further, increase in temperature is likely to affect the linkage between mangroves and their associated habitats, such as coral reefs and seagrasses. Mangroves help the adjacent ecosystems by filtering sediments and pollutants from land run-off and improving the water quality for seagrasses, corals and fish communities. Coral reefs reduce ocean currents and waves to create a sheltered environment for mangroves and seagrasses. Mangroves also enhance the biomass of coral reef fish species. It is required to understand the impact of temperature on the physical, chemical and biological interactions of the coastal ecosystems

4. Cyclones and Storms

Tropical cyclones and storms are frequent in the Bay of Bengal. They severely affect the east coast as compared to the west coast of India. According to Koteswaram (1984), there were about 346 cyclones that include 133 severe ones in the Bay of Bengal, whereas the Arabian Sea had only 98 cyclones that include 55 severe ones between the years l891 and l970. Storm surges are expected to increase in intensity by 5–10 % in the world by the year 2050 (McLeod and Salm, 2006). This is evident by more frequent extreme events that have occurred in recent years in 2008 ("Nisha" cyclone) and 2011 ("Thane" cyclone) along the east coast of India. These cyclones with gale force winds hit the coastline and inundated the shores with strong tidal wave (Ayyappan et al., 2016). Increased intensity of cyclones may damage the mangroves through defoliation, uprooting of trees and death of trees. In addition to tree mortality, the nature of soil sediments also gets modified. The cleared mangrove forests may fail to recover due to changed hydrodynamics, salinity and acidity as well as low nutrient levels and poor essential substrates.

According to Sippo et al., (2018), the historical natural events - other than deforestation, land use change and pollution caused mangrove mortality of about 36,000 ha (0.2% of total mangrove cover in 2011) based on published reports from different countries. Such mangrove mortality events go unreported in many countries, and hence it is difficult to assess temporal changes in mortality due to the small number of reports and increasing effort in observations in recent years. Approximately 70% of reported mangrove loss from natural causes has occurred as a result of low frequency, high- intensity weather events, such as tropical cyclones and climatic extremes. Globally, tropical cyclones have caused the greatest area of mangrove mortality, equivalent to 45% of the reported global mangrove mortality area from events over six decades. However, recent large-scale mortality events associated with climatic extremes in Australia account for 22% of all reported historical forest loss. These recent mortality events suggest the increasing importance of extreme climatic events, and highlight importance of mangroves in global climate change. Increasing frequency, intensity and destructiveness of cyclones as well as climatic extremes, including low and high sea level events and heat waves, have the potential to directly influence mangrove mortality and recovery, particularly in mid-latitudes (Sippo et al., 2018).

Generally, mangroves are resistant to cyclones due to the presence of green wall like physical barrier and flexible aerial roots that reduce the speed of waves in addition to the underground cable roots which prevent uprooting. *Avicennia* species exhibit quick regeneration after cyclones, as exemplified by the super cyclone that occurred on the 29th October 1999 with a wind speed of 260 km/h along the Odisha coast in India. This cyclone created havoc, largely in areas devoid of mangroves. On the contrary, practically no damage occurred in the areas with dense mangrove forest. This event killed almost 10,000 people and caused a massive loss of livestock and property. Had the mangrove forests been intact, more than 90% of the human deaths due to this super cyclone would have reduced loss and mortality. In areas affected by storms and cyclones, the protection economic benefits of a hectare of land with mangroves can be nearly two times higher than the economic value of "cleared" land (Das, 2004). Thus, mangrove conservation and restoration can be an economically appropriate policy option and therefore protecting mangroves as storm buffers will generate much more value to society.

5. Precipitation

Precipitation is predicted to show either an increasing or decreasing trend in different areas due to climate change. In India, increased precipitation is likely in the form of more days of extreme rainfall, with increasing amounts of rain in each event leading to significant flooding by the year 2030. In general, the areas with high precipitation are also areas nurturing high biodiversity of mangrove ecosystems. Changes in precipitation pattern may have a marked effect on the biodiversity, growth, productivity, and areal extent of mangroves (McLeod and Salm, 2006; Figure 3). Decreased precipitation results in a decrease in seedling survival, and may change species composition, favouring more salt-tolerant species especially salt marsh species such as *Suaeda, Sesuvium,* and *Salicornia* species. This situation is projected with an increase of hypersaline mudflats especially in Gujarat, Tamil Nadu and Andhra Pradesh. If rainfall improves, as projected in the Northern Hemisphere, vast areas of hypersaline mudflats can be used for mangrove restoration.

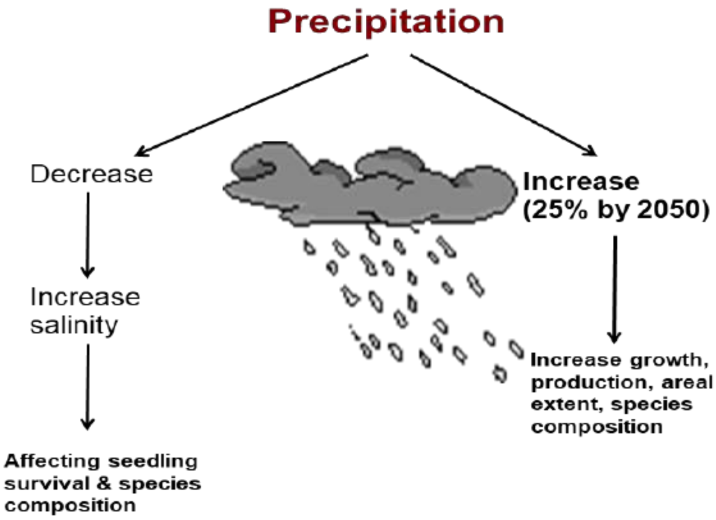

Figure 3: Impact of climate change-induced precipitation on mangroves

Our field observation indicates that low-saline-tolerant species are gradually disappearing, and species like *Avicennia marina* which can tolerate a high and broad range of salinity are becoming dominant, in all the mangrove wetlands of India. In Sundarbans, freshwater-loving species such as *Nypa fruticans* and *Heritiera fomes* ("Sundari") are reducing in population density, and getting replaced with salt-tolerant species such as *Ceriops* species belonging to the plant family Rhizophoraceae (Vyas, 2012). In Muthupet, the true mangrove species belonging to Rhizophoraceae were dominant about 150 years ago but now they are locally extinct. In the Godavari of Andhra Pradesh, dense and tall trees of *Avicennia officinalis, Excoecaria agallocha*, and *Lumnitzera racemosa* constituted nearly 90 % of the population in the 1950s, but now they constitute only 37% of the population and are replaced by salt marsh bushes of *Suaeda maritima* and *S. nudiflora*.

The main reason for such changes in mangrove species composition is the reduction in the periodicity and quantity of freshwater reaching the coastal mangrove environment. This may be attributed to monsoon failure, exceeding of evapo-transpiration to precipitation, and dam constructions in upstream areas for diverting freshwater for irrigation. After the 2004 tsunami, salinity has increased along the east coast of India. Freshwater is required to moderate the salinity of water and also to dilute and disperse pollution in estuaries. Freshwater is required for germination and sprouting of seeds and seedlings of mangroves. Fish stocks of mangrove estuaries are affected due to reduced flow of waters. This reduced flow of freshwater interferes with the migration of freshwater fishes for breeding from upland to coastal waters and also with the migration of marine fishes for breeding from sea to coastal waters as a result of siltation of river mouths due to reduced flow of freshwater in the estuaries.

Reduction in freshwater flow is one of the major threats to mangroves in India especially in West Bengal (Sundarbans), Odisha, Andhra Pradesh, and Tamil Nadu. This situation has made mangrove habitat increasingly saline and favouring colonisation of salt-tolerant species. Moreover, the biomass and growth of the mangroves are also hampered in the areas of increasing salinity. Therefore, an interdisciplinary study should be initiated to find out how much freshwater a mangrove ecosystem requires to sustain itself. The results of this study can be utilised to convince people and policy-makers to allow flow of certain quantity of freshwater into mangroves during certain period in a year. This will ensure a long-term survival of the mangrove ecosystem, at least in its present status.

6. Sea Level Rise

Mangroves exist in the intertidal areas that are influenced by tidal waters. The mangrove habitats are submerged partially at high tide and exposed at low tide. Mangroves can adapt to sea level rise if it happens slowly and if adequate intertidal space exists for expansion (McLeod and Salm, 2006).

Mangroves may tend to shift landward if the sea level rises. In the last 70 years, mangroves that shifted inland 1.5 km (Ross et al., 2000). However, human encroachment at the landward periphery makes this difficult. As a result, the width of mangroves may decrease with the sea level rise. The ability of mangrove migration landward is determined by local conditions, such as coastal slope and man-made structures. The mangrove expansion landward is prevented if the slope is steep and man-made structures such as roads, dykes, urbanisation, seawalls exist.

Tidal range and sediment supply are two critical indicators of mangrove response to sea level rise (McLeod and Salm, 2006; Fig.4). In general, the mangroves with macro-tidal and sediment-rich areas are able to survive sea level rise. Sediment availability can enable the mangrove forests to maintain rates of soil-surface elevation gain that match or exceed that of sea-level rise. However, in most of the mangrove sites, the current rate of sea-level rise exceeds the soil surface elevation gain. It is predicted that the mangrove forests at sites with low tidal range and low sediment supply could be submerged as early as 2070 (Lovelock et al., 2015).

It is predicted that the mangroves of Sundarbans and Gujarat are comparatively less vulnerable to sea level rise than all other mangroves of India. Moreover, Gujarat and Sundarbans are macro-tidal with high range of tides 5–8 m and the mangrove areas here are extensive due to the occurrence of intertidal areas, whereas Tamil Nadu, Kerala, and Karnataka are micro-tidal, and the mangrove areas here are less due to the occurrence of narrow intertidal areas. Besides, the Sundarbans has the highest sedimentation (1130 t. $km^{-2} yr^{-1}$) that helps in extensive colonization of mangroves, whereas Cauvery delta of Tamil Nadu has the lowest sedimentation (115 t. $km^{-2.} yr^{-1}$) with less colonization of mangroves (Kathiresan, 2009). Mangroves of Andaman and Nicobar Islands are likely to be sensitive even to low rate of sea level rise due to small islands, lack of rivers, carbonate settings and tectonic movements. The mangroves of Tamil Nadu and Kerala may also be vulnerable to sea level rise as they are located in low-lying coastal areas. In contrast, Gujarat has extensive hyper-saline mudflats between mangroves and coast especially in the Gulf of Kachchh, and the mudflats may work as barriers against sea level rise. The deltaic region of Sundarbans is likely to adjust and adapt to sea level rise. However, in the absence of accurate regional data on climate change, it is difficult to conclude likely impact on a short and long-term basis.

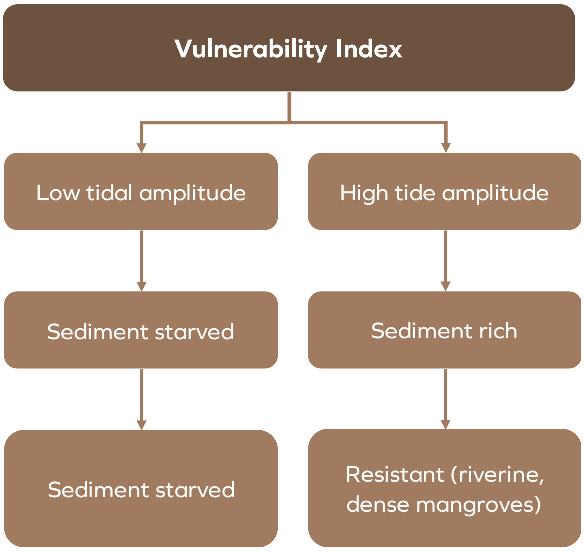

Figure 4: Critical factors of sea level rise that impact mangroves

The mangroves least vulnerable to sea level rise are the dense mangrove forests situated in riverine areas (McLeod and Salm, 2006; Figure 4). Although mangroves of Tamil Nadu are located in Cauvery riverine areas, the mangroves are less dense due to reduction in river water flow and low monsoonal rainfall, and hence the mangrove areas of Tamil Nadu are vulnerable to sea level rise.

The most vulnerable mangroves to sea level change are located in areas with small islands, lack of rivers, carbonate settings, tectonic movements, groundwater extraction, underground mining, coastal development, and steep topography (McLeod and Salm, 2006). The west coast of India has, in general, steep topography and sediment-starved condition. Coastal development and groundwater extraction are widespread all along the Indian coast especially in Maharashtra, Gujarat, Odisha, Andhra Pradesh, and Tamil Nadu.

Avicennia and *Sonneratia* species are more vulnerable than *Rhizophora* species (Figure 5 a,b). This is due to aerial roots of *Rhizophora* species which stand above sea level rise than those of *Avicennia* and *Sonneratia* species which mostly submerge due to the sea level rise. Moreover, aerial roots of *Rhizophora* species trap sediment and facilitate peat accumulation in the mangrove areas.

Sea level rise is the greatest challenge of mangroves to climate change. During the 21st century, mean sea-level is projected to a range from 9 to 88 cm, and this will accelerate over coming decades. The projected sea level rise is 30 cm in the coming 50 years in India (Vivekanandan, 2011). In Indian Sundarbans, two islands, namely, Suparibhanga and Lohacharra, have recently submerged, and a dozen other islands on the western end of the inner estuary delta are under the threat of submergence (http://www.thedailystar.net/2006/12/22/d61222011611.htm).

Figure 5a: Mangroves with tall aerial roots tolerating sea level rise

Figure 5b: Mangroves with short aerial roots getting submerged and affected by sea level rise

7. Mangroves in India & Climate change

India has a mangrove forest cover of 4,921 sq. km, occupying only 3.2% of global mangrove forest. Sundarbans has the most extensive mangrove cover, occupying 43%, while Gujarat has the second largest cover with 23% of total cover in India (SFR, 2017). These two areas alone occupy 66% of the mangrove cover, surprisingly in adverse conditions of high energy tidal coast, experiencing two extreme situations. For instance, Sundarbans is in humid and wet condition with high biodiversity, whereas the mangrove forest of Gujarat is in arid and dry condition with low biodiversity. Interestingly the Andaman and Nicobar islands have the third largest mangrove forest in India, occupying 13% of the total cover, located in low energy tidal coast with rich biodiversity (Kathiresan, 2018). Thus, mangroves of India are highly adapted to extreme environmental conditions including climate change.

Mangroves are dense, healthy and floristically diverse along the east coast of India and Andaman and Nicobar Islands, compared to the west coast of India. The east coast has 57% of total mangrove cover, with 88% of mangrove species in India, whereas the west coast has 30% of cover, with 62% of mangrove species (Kathiresan, 2018). This can be attributed to the mighty rivers (*e.g*. Ganga, Brahmaputra, Mahanadi, Krishna, Godavari and Cauvery) along the east coast that form deltas, rich in sedimentation, upstream water discharge, nutrient-rich alluvial soil, in addition to the smooth topography, which increases the intertidal areas for colonization of mangroves along the east coast. On the contrary, the west coast has narrow intertidal areas due to steep coast, and absence of deltas as a result of funnel-shaped estuaries. The Andaman and Nicobar Islands have 13% of the total mangrove cover, endowed with 75% of mangrove species, colonizing in low energy tidal coast with accumulation of peat and calcareous materials in coastal fringes, tidal estuaries, small rivers, neritic inlets, and lagoons (Bhatt et al., 2013; Kathiresan, 2018).

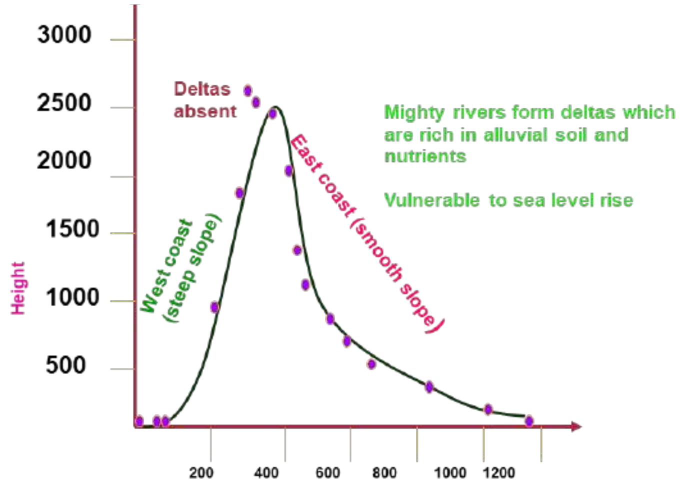

Figure 6: A cross section from Daman and Cuttack showing the gradients along the east and west coasts of India (values not to scale). The east coast with smooth slope may be more vulnerable to sea level rise than the west coast with steep slope (distance from west and east coast (from Daman to Cuttack) (Untawale per. Com.)

It is to be noted here that the east coast is vulnerable to sea level rise as compared to west coast, due to the coast of smooth topography (Figure. 6) and similarly Andaman and Nicobar islands are more sensitive to sea level rise due to the presence of small islands in low lying areas (Kathiresan, 2018). Table 1 depicts the intensity of vulnerability and factors of vulnerability and resistance/resilience to climate change in different states and union territories of India. It is necessary to identify, protect, conserve and manage the mangrove areas, which are vulnerable to sea level rise to mitigate the risk of mangrove loss to sea level rise.

Mangrove areas that are less vulnerable to sea level rise can be identified locally based on the presence of sediment-rich, macro-tidal environments and the availability of freshwater to reduce increasing salinity. The mangrove species can be identified based on their potential of migrating landward in response to sea level rise. The mangrove habitats with abundant mature trees producing a healthy supply of seeds and propagules, along with dense epibiont communities, such as oysters should be protected. This may serve as sources for colonising new areas and repopulating areas damaged by disturbance. Such mangrove areas should be protected under "marine and coastal protected areas" or incorporated into integrated coastal management programs. Currently, there are 31 marine and coastal protected areas in India under the Wildlife Protection Act, 1972, most of which include mangrove forest habitats (Kathiresan, 2017).

Table 1: Mangroves in different states and union territories of India and their types, intensity of vulnerability, and factors of vulnerability and resistance/resilience to climate change (Kathiresan, 2017).

No.	State/ union territory	Type of mangroves	Intensity of vulnerability to climate change	Factors of vulnerability to climate change	Factors of resistance/ resilience to climate change
1	West Bengal	Tide- dominated, deltaic mangroves	Moderate to high	Low lying; increasing salinity; groundwater extraction	Macro-tidal; sediment-rich; Extensive cover area; biologically diverse; increased community participation
2	Odisha	Tide -dominated, deltaic mangroves	Moderate to high	Smooth coastal topography; natural calamities (cyclone); diversion of river water by dam construction; natural calamities (cyclone)	Macro-tidal; sediment-rich; biologically diverse; coastal shelterbelt plantations; community participation
3	Andhra Pradesh	River-dominated deltaic mangroves	High	Much open type of mangroves; micro-tidal and siltation in river mouths; coastal development (aquaculture); increasing salinity; mangroves in private land; natural calamities (cyclone); increasing temperature in summer; groundwater extraction	Biologically diverse; coastal shelterbelt plantations; community participation
4	Tamil Nadu and Puducherry Union Territory	River-dominated deltaic mangroves	High	Much open type of mangroves; micro- tidal; sediment starved; siltation in river mouths; reduced river waterflow; increasing salinity; low lying; natural calamities (cyclone); increasing temperature in summer; groundwater extraction	Coastal shelterbelt plantations; community participation
5	Andaman & Nicobar Islands	Insular mangroves with carbonate plate form on low-energy coast	Low to moderate	Natural calamities (cyclone and earth quake); lack of rivers; small islands; tectonic movement; carbonate setting	Biologically diverse; accretion due to accumulation peat and calcareous materials, which mitigate wave energy; no increasing salinity

Table 1 (Continued): Mangroves in different states and union territories of India and their types, intensity of vulnerability, and factors of vulnerability and resistance/resilience to climate change (Kathiresan, 2017).

No.	State/ union territory	Type of mangroves	Intensity of vulnerability to climate change	Factors of vulnerability to climate change	Factors of resistance/ resilience to climate change
6	Gujarat	Drowned bedrock valley	Low	Much open type of mangroves; biologically least diverse and mostly monospecific	Macro-tidal, increase in mangrove cover due to plantation; community participation
7	Maharashtra	Estuarine backwaters	Moderate	Steep slope of coastal topography; funnel-shaped estuary without deltas; much open type of mangroves; man- grove conversion for urbanization; sewage pollution; mangroves in private land	Active role of Govt. forest department and NGOs
8	Goa	Estuarine backwaters	Low	Steep slope of coastal topography; funnel-shaped estuary without deltas; tourism effects	Biologically diverse; active role of NGOs
9	Karnataka	Estuarine backwaters	Low	Micro-tidal; funnel shaped estuary without deltas; mangroves in private land; lack of people awareness on mangroves	Coastal shelterbelt plantations
10	Kerala	Estuarine backwaters	High	Micro-tidal; low-lying coast; much open type of mangroves; funnel- shaped estuary without deltas; mangroves in private land	Biologically diverse; coastal shelterbelt plantations

The Government of India is efficiently managing mangroves for ecosystem services especially climate change mitigation through promotional, regulatory, and participatory approaches. Under the promotional management, the government is managing the mangroves efficiently in 38 selected areas along the Indian coastline. Under the regulatory management, the mangroves are well protected by strong legal frameworks in the national park or wildlife sanctuary or reserve and protected forests and/or community reserves. Regarding participatory management, Indian mangroves especially in Tamil Nadu, Odisha, West Bengal, and Gujarat are managed through community participation (Bhatt et al., 2013; Kathiresan, 2018).

As a result of such efforts, mangrove forest cover increased by 118 sq. km during 2015-2017 at the rate of 1.9% per year as against global mangroves, which are disappearing at 0.66% (FAO, 2007; SFR, 2017). Maharashtra, Andhra Pradesh and Gujarat mainly contribute this increase in mangrove forest cover. Hence, it is necessary to understand the successful strategies of the states and to replicate them in other maritime states and union territories. However, the open mangrove cover is 40% in the country (SFR, 2017). This deserves attention for its transformation into a dense mangrove cover.

Concluding Remarks

Mangroves are extraordinary ecosystems, providing many goods and services. Their role in disaster risk reduction and climate change mitigation is remarkable. Mangroves are ecologically well-adapted to withstand and recover from the impacts of climate change. However, mangroves of the Andaman & Nicobar Islands and east coast of India are more vulnerable to sea level rise, than the west coast of India. Mangroves of Sundarbans and Gujarat are comparatively less vulnerable to sea level rise than all other mangroves of India especially those in Tamil Nadu and Kerala with low-lying coastal areas. Once the mangroves destroyed or degraded, it may require fairly long periods to recover. This habitat loss might cause a gradual depletion of rich biodiversity of the forest flora and fauna of the mangrove ecosystems. However, there are a few genetically superior organisms in the systems, which can overcome the climatic change. It is therefore, suggested as a long-term plan (i) to identify the mangrove genotypes and fauna which are tolerant to temperature and flooding, (ii) to propagate those genotypes, (iii) to create new hybrid species from those genotypes, for biodiversity enrichment and coastal protection against climate change (Kathiresan, 2017).

Mangrove conservation and restoration can be a novel counter-measure for global warming. It deserves the attention of policy makers in planning for its utilisation in the carbon market and trading as well REDD (Reducing Emissions from Deforestation and Forest Degradation) (Kathiresan, 2018). India has a target to create an additional carbon sink of 3 billion tons of CO_2 equivalent through additional cover of all the forests by 2030. In this regard, mangrove forests would be a promising option as blue carbon sink.

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Mangroves and climate change:

An Indian Perspective

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ABSTRACT

Mangroves are subject to constant changes in environmental micro-parameters, but due to their inaccessible nature, they pose difficulties for measurements and assessments. Climate change is likely to alter structural and functional aspects of mangroves. There is a need for reporting of status of mangrove with concerning its extent, structure, and function, model-ready remote sensing derived databases, policies and activities. Global concern over possible extinction of such areas calls for immediate actions towards planning and conservation. Lack of baseline data on biological, physiological aspects of mangroves and inaccuracies of assessments in carbon assimilation and sequestrations are some of the critical issues that need to be addressed, through multi-institution collaboration at the national level. Though mangroves are considered as resilient ecosystems, preparedness at the national level needs to be significantly strengthened to avoid possible impacts. This chapter presents highlights of studies from mangroves in India, from the perspective of climate change, addressing few critical issues related to climate change, looking into available datasets/ models and gap areas in national-level datasets given the possible impacts of climate change.

1. Introduction

Mangrove forest - a vegetation community formed by a variety of salt-tolerant species growing in the inter-tidal areas and estuary mouths are one of the most productive wetlands on the earth. These habitats are highly loaded with large quantities of nutrients and always share them with adjoining coastal habitats. Mangroves are exposed to wide fluctuations of environmental factors (dissolved oxygen, salinity, organic and inorganic suspended matter). Under such conditions, mangrove flora has evolved with complex range of adaptations. However, a majority of the Indian mangrove habitats are now threatened by various factors such as land use conversion, anthropogenic pressure, reduction in freshwater flow, marine and coastal pollution, siltation, sedimentation and excessive salinity (Bhatt and Kathiresan, 2011, Kathiresan, 2018).

In the Indian context, mangrove studies with direct effect of climate changes- such as effect of changes in temperature, salinity or rainfall regimes on account of global changes, are lacking. Majority of the studies are focused on peripheral issues related to climate change – such as gross primary productivity, carbon sequestration, salinity variations, sediment / nutrient load, pollutants. This chapter highlights some of the key issues on mangrove vegetation that are linked to climate change – starting with significance of mangrove vegetation and the threats, baseline studies including spatial distribution of mangroves in the country, number of species – with highlights of mangrove species maps of selected sites, baseline studies towards climate change such as carbon sequestration through gross primary productivity and mangrove restoration efforts towards climate resilience and as a means to combat climate change.

1.1 Mangroves as Coastal soldiers and the threats

Throughout the tropics, mangroves exist in intertidal areas and are utilised as habitat by thousands of animal species and as fuel, medicine, food and timber by human coastal populations. Mangroves are known for the protection they offer to the coast apart from other biological and socio-economic benefits. Though the benefits of mangroves were well-known, it was the Asian tsunami of 2004 that made the world realise the potential of this habitat. Human populations have grown over recent decades, and increasing pressure is placed on mangrove resources. Several authors have described the role of mangroves in protecting the coast (Blasco, 1975, Costanza et al. 1997, Danielsen et al., 2006, Roy and Krishnan, 2005).

The continuous cycle of low-tide and high-tide in mangrove ecosystems makes it highly dynamic; waves take sediment away and the tides deposit sediment. Aerial roots – the pneumatophores - help to dissipate the impact of waves and also help to capture the sediment. Mangrove ecosystems are also known to amass large amounts of carbon retained by mangrove prop roots, and display intricate nutrient dynamics which are regulated, in part, by tidal fluctuations, salinity variations, and freshwater influx (Alongi, 2008). As 'energy traps' and 'nurse ecosystems' mangroves are primary producers and reproductive zones which shelter and feed juvenile populations of many off-shore species (Redfield, 1982; Tomlinson, 1986). They contribute to the livelihood of coastal folks in terms of forest produce and fishery resources. Although the economic value of mangroves can be difficult to quantify, the relatively small number of mangrove species worldwide collectively provide a wealth of services and goods while occupying only 0.12% of the world's total land area (Dodd and Ong, 2008). From the Indian scenario, it is worth mentioning that 70% Asian population and approximately 20% Indian population depend on coastal habitat for food and as livelihood resource (Costanza et al., 1997; Kathiresan, 2004). Indian mangrove ecosystems are home to 920 plant and 3,091 animal species (Bhatt and Kathiresan, 2011).

Human impacts on mangroves, including climate change, have received much attention of late mainly because mangrove deforestation is occurring at a rate of 1–2 % per year (Alongi, 2002); this implies majority of the forest can be lost in this century. Clearing of mangroves for aquaculture amounts to 52% of mangrove losses, of which shrimp culture alone amounts to 38 % (Elison, 2008). It has been reported that, since 1980, global mangrove losses are 20% to 35% (Upadhyay et al., 2002; FAO, 2003) with 2% to 8 % loss per year (Miththapala, 2008). A detailed review of loss of mangrove species and their respective geographical areas of concern, primarily due to anthropogenic pressure has been presented by Polidor et al. (2010). Although global losses decreased when comparing the rate in the 1980s (≈1.04% per year) to that of the 2000 – 2005 time period (≈0.66% per year), mangrove degradation was three to five times faster than any other forest type (Spalding et al., 2010). In the context of India, over 40% of mangrove area on the western coast has been converted to agriculture and urban development (Upadhyay et al., 2002), with Sunderbans alone facing a loss of 5.5% (Samanta and Hazra, 2017). Ongoing developmental activities and land use conversion are putting mangroves on threat.

Large stretches of land are typically de-notified for development purposes, and sometimes for other aquaculture activities. There is a need to create further awareness amongst society on mangroves vegetation and alternate livelihood options need to be explored for local communities.

2. Mangroves in India- spatial distribution

Influx of salt water and fresh water are essential for mangroves. India is covered along three sides by ocean and the mangrove habitat of India is broadly classified into three categories namely, Deltaic (Eastern and south-east coast Mangroves), Estuarine & backwater (Western Coast Mangroves) and Insular mangroves (Andaman & Nicobar Islands). Deltaic mangroves are found along the east coast within the deltas of the Ganges, Brahmaputra, Mahanadi, Krishna, Godavari and Cauvery rivers. All of these are east-flowing rivers. Estuarine mangroves are found on the west coast in the estuaries, backwaters and creeks of the Indus, Narmada and Tapti Rivers. Insular type of mangroves is found in the Andaman and Nicobar Island (Mandal and Naskar, 2008). Indian mangroves cover is estimated to be 4740 km^2, with 58% is along the east coast (Bay of Bengal); 29% along the west coast (Arabian Sea) and the remaining 13% in the Andaman and Nicobar Islands (FSI, 2015).

In India, first assessment of mangrove vegetation was done at 1: 250,000 scale using IRS data of 1990-93 timeframe (Nayak, 1996; Nayak and Bahuguna, 2001) that showed the use of satellite data for detection and mapping of mangroves in India. Later, advancements in digital technology and sensor systems improved the classification accuracy and mapping capability. Under another national scale project, IRS P6 LISS-3 and LISS -4 data of the year 2005 - 2007 were used for discerning mangrove communities at 1:25,000 scale (SAC, 2012). Another mangrove mapping during similar time was conducted at moderate scale of 1:50,000 under national wetland inventory (SAC, 2011). The outcomes of these national level projects provided seamless map of mangroves at various scales for the entire country. There is a need at present for necessary updation of country-level mangrove mapping; at state-level fine resolution surveys are being conducted in isolation which needs to be synchronised for national-level database preparation.

2.1 Species study

Mangrove environments are typically hostile comprising of high salinity, tidal effects, wind effect, anaerobic conditions and high humidity and moderately high temperature, etc. This is considered to be one of the fragile systems that can likely get affected by threats of warming or climate change and species therein may get altered as an effect. A detailed inventory of species and its distribution are therefore necessary. This section deals with details of species distribution in the Indian context.

On a global scale, mangrove vegetation distribution has been reviewed by a large number researchers and scientists (e.g. Tomlinson, 1986; Ricklefs and Latham, 1993; Duke, 1992; Field, 1995; Duke et al., 1998; Ellison et al., 1999; Saenger, 2002; Wang et al., 2003; Spalding et al., 2010).

Without the adequate knowledge of the exact species composition, it is difficult to identify and implement conservation priorities for the mangroves. Indian mangroves exhibit a distinct pattern in distribution of mangrove species on the East and West coasts. Mangrove cover is larger and more widespread on the east coast compared to the west coast. These differences are attributed to: i) presence of large estuaries, runoff and deposition forming wide delta of sediments on the east coast, while there are funnel-shaped estuaries with an absence of deltas on the west coast; and ii) gentle slopes on the east coast, while there are steep slopes on the west coast (Kathiresan, 2010).

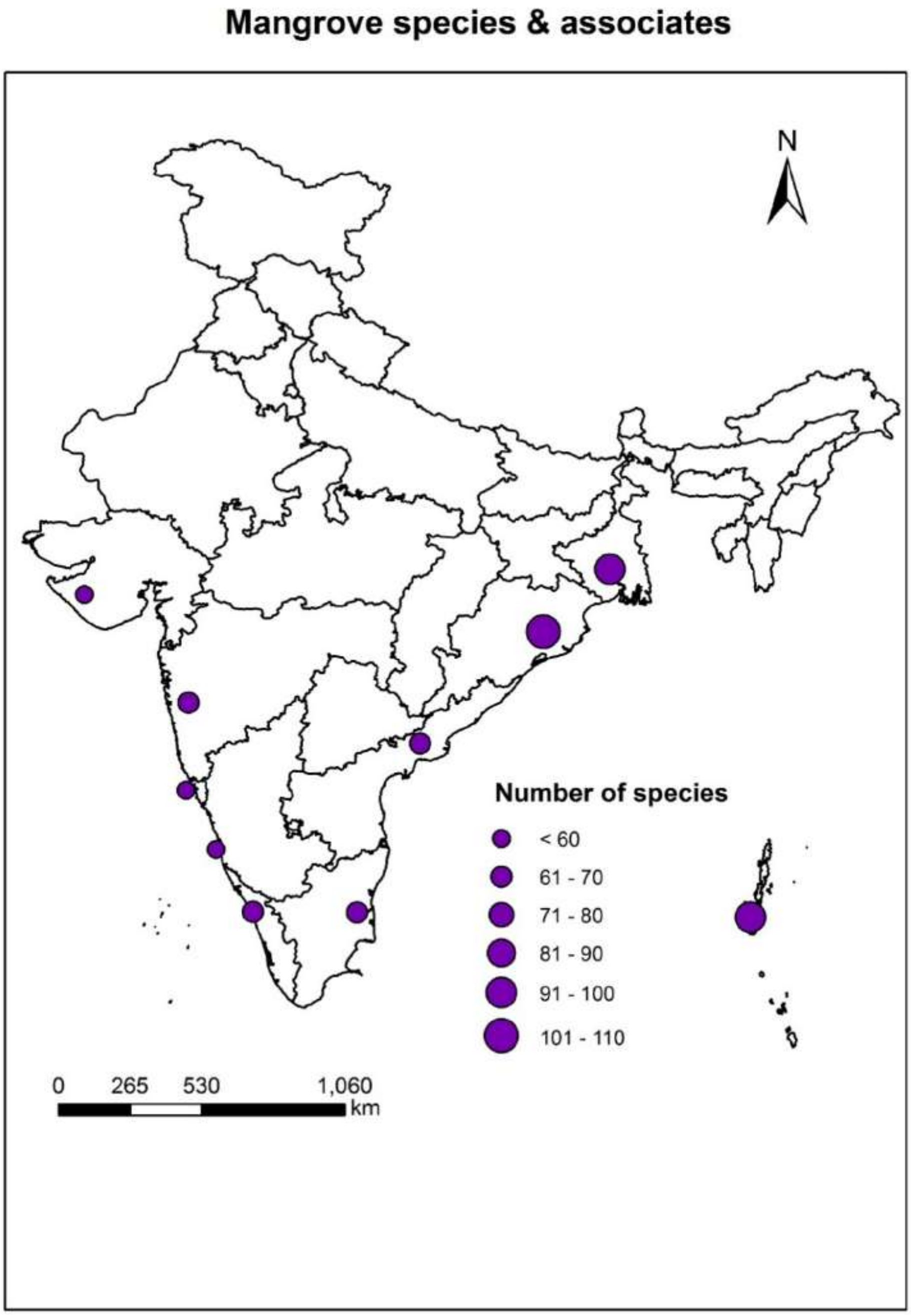

Figure 1: Species diversity - True mangroves and mangrove associate based on Kathiresan (2008)

Indian mangroves are diverse with 125 species, 39 'true' mangroves and 86 mangrove associates (Kathiresan, 2008). Several researchers have detailed mangrove floristics of India (Untawale and Jagtap (1984), Untawale (1986), Naskar and Mandal, 1999, Mandal and Naskar (2008), Swain and Rao (2008), Ragavan et al. (2014), Ragavan et al. (2016)). Mangrove species diversity including associates is the highest in Odisha (101 sp.) state and lowest in state of Gujarat (40 sp.). Diversity is higher in case of states having insular and deltaic mangroves, particularly on the east coast including West Bengal (92 sp.), Andaman and Nicobar Islands (91 sp.), Andhra Pradesh (70 sp.) and Tamil Nadu (70 sp.). States located on the west coast have lower diversity - Kerala (64 sp.), Maharashtra (63 sp.), Karnataka (58 sp.) and Goa (53 sp.) as represented in Figure 1 (Kathiresan, 2008). Recent estimates by Ragavan et al. (2016) listed 46 true mangrove species belonging 22 genera, which include four natural hybrids. The east coast has 40 species, the west coast has 27 species and Andaman and Nicobar Islands have 38 species.

Not many studies have reported dominant species composition map of mangrove habitat. A suite of high- resolution satellite data are now-days available. Satellite remote sensing plays significant role in such type of forests/habitats. Intensive ground information is essential, and vegetation sampling has to be achieved by following sampling method for preparation of species map. In one such study under PRACRITI Programme (PRogrAmmeon Climate change Research In Terrestrial envIronment) of Space Applications Centre (ISRO), three sites viz. Bhitarkanika (Odisha), Chorao (Goa) and Pichavaram (Tamil Nadu) were selected for mapping mangrove species using high resolution Indian satellite data. Typically, mangrove ecosystem is inaccessible due to inundation, presence of mud, pneumatophores, etc. Presence of wildlife such as tigers, crocodiles, wild boars, jackals, numerous poisonous and non-poisonous snakes in majority of mangrove areas in India pose serious threat. Data on dominant species were collected by laying more than 60 sample locations at these sites. Supervised classification algorithm was used to arrive at dominant mangrove community classification (Figures 2 a, b and c) (SAC, 2018).

These studies highlight use of satellite remote sensing, and there is a need to replicate such exercise at other dominant mangrove habitats in other states. Several studies have focused on density-base zonation of mangroves, including biennial assessment done by Forest Survey of India. There is growing concern and demand by scientific community towards dominant community zonation of mangroves which are essential for number of ecosystem-based models.

3. Climate change impact on Indian mangroves

3.1 Natural forcings

Dynamics in mangrove vegetation are directly related to natural forcings, including changes in micro-environmental parameters. Several research studies for example, McIvor et al. (2013), Lu et al.(2013), Krauss et al. (2014) and Alongi (2015), report major issues on impact of climate change and resilience of mangrove system, whether mangrove forests are able to adjust within changing environment or it is adversely affecting the vegetation structure or function.

The International Panel for Climate Change (IPCC) (2013, 2014) has reported a possible increase in sea level rise by 2.0 to 5.4 mm / year in Asia along with increase in temperature and precipitation. Alongi (2008) identified the east coast of India and the Andaman Islands as one of the hotspots vulnerable to future sea level rise, though multispecies forests in both the areas have been suggested to be more resilient to sea level rise due to interspecific facilitation (Huxham et al., 2010). Air temperatures in coastal regions of India are typically near 35°C. Prediction of 2 °C rise in temperature may lead to higher evapotranspiration and may also lead to degradation of biochemical enzymes that are essential for physiological pathways (Cheeseman 2004; Okimoto et al., 2007).

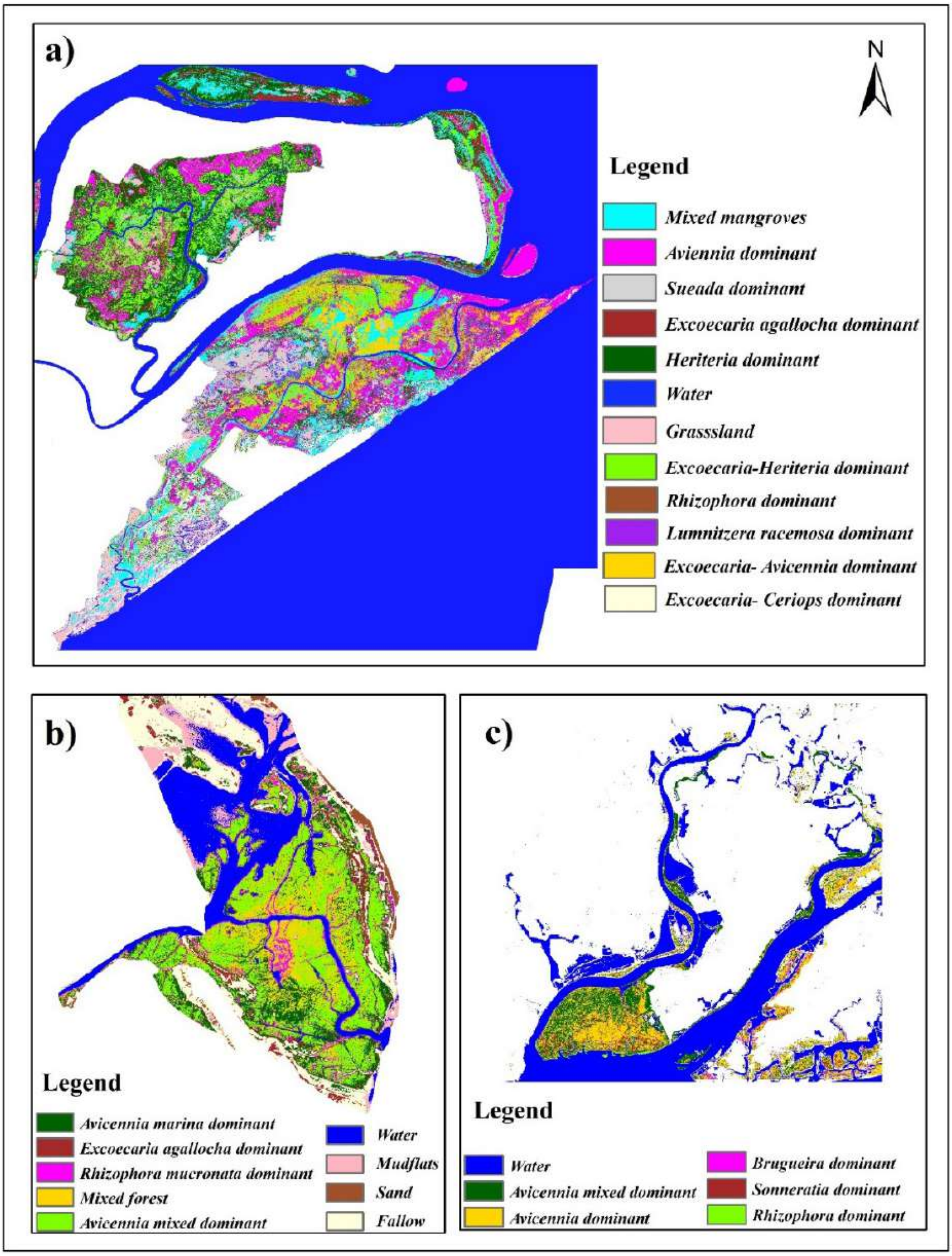

Figure 2: Dominant vegetation species composition at: a) Bhitarkanika (Odisha), b) Pichavaram (Tamilnadu), c) Chorao (Goa), based on IRS Resourcesat-2 LISS IV data during 2015-16.

In the context of Indian mangroves, range of ecological database have been studied, prepared and are widely used for process based modelling for local scale estimations of nutrients and emissions. There are large data gaps and most of the data that are collected are static, whereas models require dynamic type of data where diurnal / seasonal variations can be utilised. There is lack of high resolution, regional level dominant species datasets, which are required to study functional aspects of vegetation in climate change perspective. In addition to satellite data, there are several in-situ observation methods, such as sensor networks, eddy covariance tower, etc., to collect data on local scale remotely. This calls for high computational requirements, apart from technical know-how which are not readily available.

As part of PRACRIT Programme of Space Applications Centre (ISRO), *in-situ* light use efficiency of dominant mangrove species was monitored over three seasons, and was used to estimate seasonal level Gross Primary Productivity estimations (GPP) at various project sites. Light use efficiency of various species indicated the response of leaf-level photosynthesis to changes in diurnal conditions of sunlight, temperature, humidity, atmospheric CO_2, etc. Under PRACRITI programme, 13 mangrove species (*Aegiceras corniculatum, Avicennia alba, Avicennia marina, Avicennia officinalis, Bruguiera cylindrica, Ceriops decandra, Excoecaria agallocha, Heritiera fomes, Kandelia candel, Lumnitzera racemosa, Rhizophora apiculata, Rhizophora mucronata*, *Sonneratia alba* and *Sonneratia apetala*) were studied in detail for their diurnal photosynthetic efficiency – denoted as pE- for three seasons (post-monsoon, winter and summer) at selected locations (SAC, 2018). Variations owing to different response of each species to changing conditions of sunlight, temperature, wind, etc. LICOR Li-6400 instrument was used to measure rate of photosynthesis of each of the species at every 45-minute interval, in sun-exposed and shaded leaves. Total daily amount of CO_2 fixed per day was then analysed to understand amount of fixed on per day basis. Amongst all species, *Excoecaria agallocha* showed highest rate of CO_2 fixation of 6.16 g C /m^2 /day, with maximum light use efficiency of 1.9 g C/mol of sun-light photon. Rates of light use efficiency were further modelled using satellite data and daily amount of solar insolation from geostationary satellite such as INSAT 3-D. Daily insolation data were converted to amount of photosynthetically active radiation to achieve daily gross primary productivity estimation of each site for 3 seasons. Seasonal variations in GPP clearly indicated mangrove vegetation response to daily weather conditions. Table 1 and Figure 3 shows per day GPP estimates for each site and across the seasons. These serve as baseline GPP estimate for mangrove in the perspective of how climate change can impact vegetation distribution and function.

Table 1: Gross primary productivity estimates from IR Resources at-2 LISS-3 and LISS-4 data for mangrove sites

Study sites	GPP (g C m^{-2}day^{-1})		
	Summer	Post-monsoon	Winter
Bhitarkanika	1.2	1.7	5.9
Pichavaram	2.6	3.7	2.7
Chorao Island	7.7	1.2	1.8

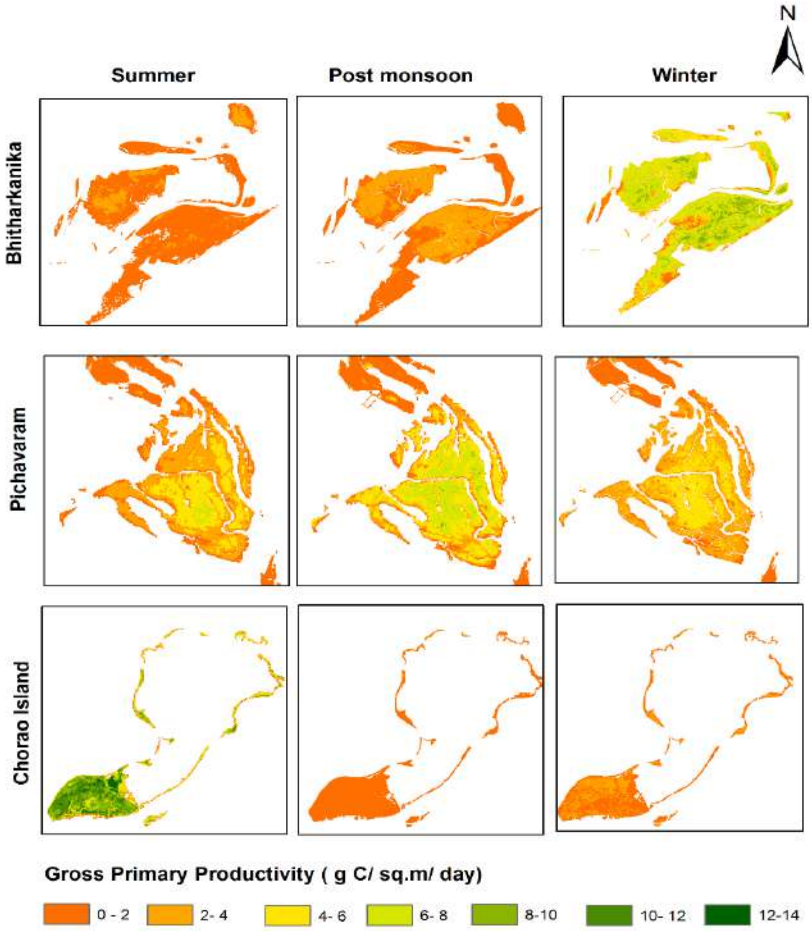

Figure 3: Gross primary productivity in g C $m^{-2}day^{-1}$ at each site for 3 seasons.

Ward et al. (2016) reported important climate change factors and its effect on various regions of the world, including Asia. In India, majority of the climate change related studies have been reported from Sundarbans – being the single largest continuous patch of mangroves in India, the land of Royal Bengal tiger, apart from human population of 4.5 million.

Samanta and Hazra (2017) report typical change from dense mangroves to degraded mangroves and further to saline blanks in Sundarbans, which is one the largest mangrove reserves in the world. Ground evidences and reports suggest a shift in geomorphology of the islands by means of erosion and accretion. Erosion and submergence triggered by climate change and sea-level rise are supposed to be major causes of these changes.

Another *in-situ* experiment carried out by Space Applications Centre (ISRO) conducted simulations using climate scenario datasets for some of the dominant mangrove at Sundarbans, Pichavaram, Chorao and Jamnagar. Sun-exposed and sun-shaded leaves of the canopy were modelled separately at each site and were simulated for photosynthetic behavior using A2, B2 and A1B scenario (SAC, 2015). Kumar et al. (2017) also modeled photosynthetic rates in relation to climatic factors using two models and analyzed responses of photosynthetic assimilation to changing weather parameters.

Some of studies from ground-based experiments, such as Hazra and Bakshi (2003) reported rise in soil temperature during a decade at Sundarbans which was earlier reported to be 0.019 °C and was later reported to be 0.045°C by another follow-up study by Hazra et al. (2010).

Mangrove communities globally are expected to be substantially influenced by climate change-related physical processes in the future. There has been little research conducted on current and changing climate in Indian context and strengthening such studies is required. This necessitates a network of institutions through which coastal changes can be monitored. There is also lot of scope for developing instrumentation for regular automated measurements that are essential for assessment of impact due to climate change.

3.2 Anthropogenic forcings

Several recent habitat specific studies in the eastern coast reveal the conversion of mangrove areas by local communities for coastal agricultural land development and shrimp farming (Ambastha et al., 2010; Pattanaik and Narendra Prasad, 2011; Vyas and Sengupta, 2012). Recent remote sensing based evidence also reveal that conversion to aquaculture ponds remains as a significant threat, especially to the mangroves along the eastern coast (Pattanaik and Narendra Prasad, 2011; Ponnambalam et al., 2012). In addition, increased population pressure poses a significant risk of unsustainable exploitation of mangroves (Mandal et al., 2010). The total forest cover of the Indian Sundarbans as assessed by remote sensing studies for the year 1986 was about 2,247 sq. km., which gradually declined by 2,201 sq. km. in 1996, then down to 2169 sq km in 2001 and to 2122 sq km in 2012. The loss in the mangrove forest in the Indian Sundarbans is about 5.5 % (Samanta and Hazra, 2017).The losses though are partially accounted due to erosion process and natural causes of alteration in river pattern; in addition, there are reports of increasing anthropogenic activities that are posing serious damage to ecosystem at Sundarbans (Chaudhury and Choudhury, 1994; Paul, 2009). As mentioned earlier, overall development along the coast of India is gradually changing into aquaculture farming and expansion of agricultural land as well as encroachment from urbanisation near some of the mega-cities (Upadhyay et al., 2002).

4. Mangrove feedback to climate

Mangrove ecosystems are subject to a wide range of factors, including increasing precipitation, temperature rise, salinity changes, sea-level changes, etc. It is hard to conclude the effect of each parameter, as complex models are essential to understand simultaneous changes in other parameters. The effect on mangrove distribution, physiology, growth and stability are reported due to change in individual parameter in the event of climate change (McKee et al., 2007, Ward et al., 2017), targeting the possible feedback at global scale and also report scenario for mangroves in Asian countries. In context to Indian mangroves, long-term climate records and brief mangroves responses are reported by Rahu, et al. (2012), Kumaran ,(2013), Limaye, et al. (2014).

Solomon et al. (2007) has reported an increase in atmospheric CO_2 from 280 ppm in pre-industrial times to 390 ppm, and predicted to double during 21st century. The effect in CO_2 rise is likely to enhance photosynthetic capability in mangroves. Most of the mangroves have C-3 pathways that are likely to tolerate increase of CO_2 (Bazzaz, 1990; Urban, 2003), yet at the same time, CO_2 increase is expected to reduce marine pH and affect biological organisms responsible for breaking down minerals which in turn affect physiological pathways (Kleypas et al., 1999, Feely et al., 2004). Warmer temperatures are likely to result in extending latitudinal range of mangroves, which are restricted to the tropics and subtropics (Di Nitto et al., 2012). Yet, this does not apply globally as this trend has been observed only at Atlantic and Pacific coast but not reported from Indian Ocean so far.

Sea level rise has been occurring throughout the world due to thermal expansion of ocean water and melting of the polar ice caps. It is estimated that between 1901 and 2010, global mean sea level increased overall by 0.19 ± 0.02 metres (IPCC, 2013). Ellison (1993) – one of the oldest studies in this context, revealed that in Bermuda, mangroves which existed during the Holocene were able to move landward and persist with Sea level rise of 8 – 9 centimetres per 100 years. In developing countries like India, there is limited scope for new habitats due to anthropogenic barriers. Many reports suggest that extreme weather events may increase in scale and frequency in the Indian Ocean region (Dash et al., 2007). It has been reported that various extreme events can significantly affect most of the wetlands species (e.g. Plankton, Benthic animals) and therefore can likely affect mangrove stability and health (Barbier, 2016). Excessive flooding commonly, but not always, inhibits root growth and can enhance stem elongation of some mangrove species (Ye et al., 2010; Lu et al., 2013). A detailed review on how mangroves may adapt to flash flood, elevation changes, sea-level rise and related evidence has been provided by Krauss et al. (2014).

Mangroves are part of coastal wetlands and are frequently inundated giving rise to highly anaerobic conditions. Mangrove habitat contains large contributions of live, dead and decaying organic matter including root mat, pneumatophores, leaf litter, microbial algal and fungal constituents, etc. Some of the green houses gases, particularly CH_4 and N_2O that are biogenic in nature are released during the mineralisation, nitrification process in wetlands and in waterlogged mangrove habitats. CH_4 along with NO_2 released during these processes directly or indirectly affect the present day climate of the Earth (IPCC 2001; WMO (World Meteorological Organization) 2003). Rates of emission also vary depending on mangrove species present, with species of *Avicennia*, *Rhizophora*, *Sonneratia* indicating faster decay. Faster the decay, the more the quantities of the gases liberated to the atmosphere. Average CH_4 flux across mangroves on the east coast of India varied from 2.2 to 77.52 mg m^{-2} day^{-1}. Maximum value of CH_4 flux was noticed at Godavari mangroves (355 mg m^{-2} day^{-1})while moderate values at Pichavaram: 7.4–63.7 mg m^{-2} day^{-1}; Sundarbans indicated varying pattern, sometimes referred as sink or lower values of the order 0.032–2.15 mg m^{-2} day^{-1} (Biswas *et al.* 2007, Chauhan et al., 2008). Another measurement in *Avicennia* dominated Pichavaram mangroves showed annual methane emission rates of 10 g CH_4 yr^{-1} (Purvaja et al., 2004). Typically, it has been observed that degraded or disturbed mangrove forests tend to show higher values of CH_4 emission because most of the time, the disturbance in disturbed or degraded mangrove areas is anthropogenic, and human disturbance of mangrove soils greatly increases the rate of greenhouse gases (GHG) emissions. A similar study was reported from Adyar estuary in South India where high input of organic carbon (largely belonging to domestic waste from urban area) resulted in intense methanogenesis (Rajkumar et al., 2008). A few more observations from (Purvaja and Ramesh, 2000, 2001) indicated that coastal ecosystems of the tropics emit considerable amounts of methane. Transport through leaves and pneumatophores are also important but are difficult to measure. Human activities like cutting of trees, aquaculture practices, waste and pollution from household, etc. increase the emission of GHGs, the major drivers of climate change. There is large scale diurnal and seasonal variability in methane emission - late winters typically show high concentrations owing to low solar intensity and low ambient temperature; also shorter day length would reduce photochemical destruction.

Climate change (IPCC, 2013, 2014) is likely to turn out as a potential threat for mangroves, yet there are limited possibilities of better diversity and growth. On the one hand, mangroves may adapt to new conditions by altering physiological mechanisms, adapting to sea-level rise by vertical growth of canopy or by developing subsurface adaptations, etc.; yet, in terms of distribution and range expansion there is limited scope due to anthropogenic barriers.

Despite so many studies, there is large scale uncertainty and unavailability of the data in spatial and temporal domain. There is still lack of understanding of underlying mechanisms that control spatio-temporal variability of these processes as a function of changes in environmental conditions (Kumar and Ramanathan, 2014) and vegetation distribution. Frequent data updation and long-term studies can be taken up to build a scenario for the entire coast of India. Owing to narrow creeks and narrow mangrove habitats, satellites have limited role to play for retrieval of GHGs in mangrove habitats, yet retrieval of observations from better resolution satellites can be explored for monitoring coastal habitats in the county.

5. Mangrove restoration for climate resilience

From nearly 6000 sq km in the 1960s, mangrove cover in the country has reduced by 21% till 1990s. The rate of degradation over the period 1990-2000 was estimated at 1% per year, a rate twice that of terrestrial rainforests. Global-scale remote sensing studies show that annual rates of mangrove deforestation averaged 0.2–0.7% between 2000 and 2012, with an annual average loss per year of the order of 2.3 km^2 per year in South Asia region. In terms of absolute loss, Southeast Asian countries are profoundly affected, accounting for five of the top 10 countries (Hamilton & Casey, 2016; Feller et al., 2017). Recently, conservation measures and awareness has reduced the rate of mangrove deforestation. In fact, a recent estimate from Forest Survey of India, has indicated substantial increase (112 sq. km) in mangrove cover between 2013 and 2015 assessment, significantly in Maharashtra, Odisha, Andhra Pradesh and, Andaman and Nicobar Islands. Rates of mangrove losses are still higher than restoration efforts leading to net loss of mangroves across the globe. In the context of India, many restoration efforts are underway in all the coastal states after realising the protection it offers to coastal areas and its population, particularly after the 2004 Tsunami.

Although, highly essential and practised, commonly mangrove planting efforts have largely been a failure, due to death of planted seedlings. Mangrove restoration is a complex task, where hydrological regime, soil condition, fresh water inflow, salinity, propagule availability, etc., play an important role. Hoffman (1985), Kairo (2001), Lewis et al. (2005) have recommended essential checks before selecting a site for restoration, that includes: 1) why mangroves are not growing naturally at a place where it should grow, 2) corrections for such defect in ecosystem, 3) local topography and hydrological regime after plantations.

M. S. Swaminathan Research Foundation (Chennai) and the Forest Department demonstrated the 'Canal-Bank Planting' technique with 'fish bone' design, in Muthupet and Pichavaram in Tamil Nadu as well as East Godavari and Krishna districts of Andhra Pradesh (Ramasubramanian et al., 2008). As a result of this, an area of 1978 ha was restored in Andhra Pradesh since 1987, mostly in East Godavari and Krishna districts, one of the largest areas under restoration. In Tamil Nadu state, about 840 ha (Pichavaram, 345 ha., Muthupet 295 ha. and Ramanathapuram 200 ha.) were brought under mangrove plantations (Bhatt et al., 2011). Successful mangrove management requires an effective system of ownership, use and access. Choice of species and local conditions can govern the success of plantations. Typically, locally growing dominant species, in consideration to their salt-tolerance nature are preferred. Land use map, level of water inundation, distance from creek, soil type, are also to be considered. More frequently, it is noted that water-loving species like *Rhizophora apiculata* are preferred towards water-side and other species like *Ceriops*, *Avicennia*, etc., are preferred towards land-side. Furthermore, participation from community and stakeholders are essential as plantations can directly alter their present livelihoods. Pandey et al. (2012) reported one of the high-resolution potential area mappings in Gujarat; this location was later chosen for restoration of mangroves in Gujarat. Another similar study for coast of Maharashtra was carried out by SAC (SAC, 2018) under PRACRITI Programme involved use of high-resolution Resourcesat-2 LISS-4 satellite data for potential area mapping. Taking such examples, site-suitability study based on remote sensing inputs, involving use of advanced algorithms for analysing site suitability are necessary. Efforts are becoming more successful as elements of species biology and hydrological requirements are incorporated into the design and implementation of rehabilitation projects.

Conclusion

From the Indian context, relatively lesser attention has been given to mangrove research, yet mangrove- related studies are in plenty. India has vast diversity in mangroves- right from distribution on the east and the west coast. Each mangrove ecosystem has its characteristics and contributes to the local ecosystem in its own ways. Coastal population in India greatly depend on mangrove habitat for daily livelihoods, including huge dependencies on fish and crab production that in-turn depend on mangrove habitat in direct or indirect ways. Threats to mangroves due to aquaculture and land-sea changes are reported not only from India but across the globe. The global concern of sea-level rise, temperature rise may affect Indian mangroves positively or negatively. There are also speculations that global changes may lead to increase the productivity of mangroves in Asian region and these areas will be able to sequester higher rates of CO_2 from the atmosphere. Though further effect of such adaptations on distribution and physiological changes are not yet known.

Networking of institutions across the coastal region for regular database development, modelling and research are essential to bridge gaps in spatial and temporal domain for Indian mangroves. Climate change adaptation and feedback mechanisms are yet to be clearly understood. Global changes may cause tougher conditions for coastal vegetation and may increase pressure on existing mangrove areas. Restoration of existing areas and afforestation on identified new potential areas of mangroves can certainly build and strengthen our preparedness towards global changes.

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14

Coastal wetlands in India and climate change:

Status, trends and policy response options

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ABSTRACT

Coastal wetlands of India, ranging from intertidal mudflats to vast expanses of mangroves, coral reefs, lagoons, estuaries, and deltas, perform several ecological functions and provide multiple ecosystem services making them a vital component of coastal ecology and risk reduction infrastructure. With the increased incidence of climate change impacts and extreme events, these wetlands are vulnerable to many stresses including rising temperatures, hydrological alterations, geomorphological changes and saltwater intrusion along with human- induced land use and land cover changes. But at the same time, diverse coastal wetlands are capable of responding in different ways to changing climate with mangroves and salt marshes showing high adjustability to climate change and high efficiency in enhancing the resilience of coastal communities to extreme events. International and national policy frameworks have started integration of wetlands towards achieving sustainable development goals (SDGs) and climate change mitigation and adaptation. Towards this mitigation and adaptation mechanisms in India will need to strike a balance between the protection of these ecosystems and their ecological services along with enhancement of other infrastructure. Governance of coastal wetlands in an increasingly uncertain world needs to be collaborative, adaptive and learning based.

1. Introduction

Several climate change assessments predict stresses on wetlands, through atmospheric and sea surface temperature increase, changes in hydrology and sea-level rise (Erwin, 2009; Junk et al., 2013), and deepening of direct and indirect drivers of degradation. Wetlands have a crucial role in buffering society against the impacts of climate change through their role in the carbon cycle, climate adaptation and resilience (Meng et al., 2016; Mitsch et al., 2013). Conservation and wise-use of wetlands and preventing loss and degradation of these ecosystems is essential in meeting climate goals, yet is insufficiently considered in climate policy and planning processes (Moomaw et al., 2018). Of particular significance is the role of coastal wetlands in sequestering carbon (McLeod et al., 2011) and reducing the vulnerability of communities to rising seas and coastal hazards, through their role in sediment capture, vertical accretion, erosion reduction and wave attenuation (Spalding et al., 2014). At the same time, the coastal wetlands face an immense challenge of surviving the destructive effects brought about by high-intensity anthropogenic activities and accelerated climate change (Wu, Zhou, and Tian, 2017).

This chapter aims to present a synthesis of current knowledge on the extent, status and trends in coastal wetlands of India, the likely impacts of climate change on these ecosystems, and opportunities for integrating wetlands conservation and wise-use in climate change response strategies. The first part of the chapter includes a discussion on the status and trends of coastal wetlands and critical drivers of degradation. The second part maps available projections of climate change for India with a specific focus on coastal wetlands, carbon accumulation and GHG emissions, sea-level rise, extreme events and disaster risks. A review of policy and management strategies for coastal wetlands in the context of changing climate is discussed in the third section. Recommendations for integrating coastal wetlands within climate change mitigation and adaptation policies and programmes are drawn in the final part.

2. Coastal wetlands in India: Status, trends and threats

Wetlands are located at the interface of terrestrial and aquatic ecosystems and typically arise when inundation by water produces soils dominated by anaerobic processes, forcing the biota, particularly rooted plants to adapt to flooding (Keddy, 2010). The Ramsar Convention (having 170 Contracting Parties todate, including India which ratified the Convention in 1982) defines wetlands as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres'(Ramsar Convention Secretariat, 2016). Article 2.1 of the Convention provides that wetlands 'may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands'(Ramsar Convention Secretariat, 2016).

Varied definitions of 'coastal wetlands' are in vogue, ranging from wetlands located in coastal watersheds (https://www.epa.gov/wetlands/coastal-wetlands#whatAre), sub-tidal and inter-tidal wetlands falling within estuarine subclass (Cowardin et al., 1979) and as wetlands located between sub-tidal depths to which light penetrates to support photosynthesis, till the landward edge where sea passes its hydrological influence to groundwater and atmospheric processes (Wolanski et al., 2009). Coastal wetland types recognised within the Ramsar Convention include deltas, tidal marshes and mudflats, mangrove swamps, coastal lagoons, rocky shores and coral reefs. Also, there are human made coastal wetlands such as fish and shrimp ponds, salt pans, and wastewater treatment ponds and canals. This chapter uses the wetland types mentioned as the basis for further discussion.

2.1 Distribution, extent and trends

The remarkably varied and diverse rock, sediment and coral based landforms of India's eastern and western coast and islands (Mukhopadhyay and Karisiddaiah, 2014), differences in geomorphology, climate and coastal processes underpin high diversity of coastal wetlands. The 100-130 km wide eastern coastal plain, placed between the Eastern Ghats and the Bay of Bengal, has wide and extensive delta formations of the major east flowing rivers and has seaboards comprising long stretches of sandy beaches backed by coastal dunes. The Sunderbans tidal delta spans over 10,000 km^2, is fed by sediments and water from Ganges and Brahmaputra Rivers and has the world's largest contiguous mangroves situated within a maze of creeks, sinuous tidal channels and inlets, dune complexes, estuaries, beaches and islands (Raha et al., 2012). The complex delta of Mahanadi and Baitarani have complex-spit with a number of hooks, prominent being Hukitola Bay and Jatadhar Muhan, estuaries formed by the rivers Devi, the Mahanadi, the Brahmani, the Baitarani, and the Rushikulya; mangroves dominated tidal swamps of Bhitarkanika, and a sizeable brackish lagoon, Chilika (Kumar and Patnaik, 2016). Predominant wetlands along the ~ 300 km long Andhra coastline include the Godavari-Krishna delta complexes and prominent sand spit enclosing Kakinada Bay (Rao et al., 2012). Within the Coromandel coast, the Gulf of Mannar region has a diverse wetlands regime, notably mangroves, coral reefs and seagrass beds (ENVIS, 2015). Pulicat Lagoon, the swamps of Vedaranayam, coastal dunes along Mahabalipuram, and the Kaveri Delta are some significant coastal wetlands in this stretch.

The west coast is narrower, 50-100 km wide sandwiched between the Western Ghats and the Arabian Sea, fed by short and swiftly flowing rivers with hardly any delta formation, and is more indented with rocky headlands, pocket beaches and many estuaries (Kumar et al., 2006). The saline flats of the Rann of Kachchh are the most extensive wetlands regime along the Gujarat coast (Baba and Nayak, 2002; Juyal, 2014). The Gulf of Kachchh and Khambhat have extensive mangroves, with the presence of coral reefs around the former. The rocky Konkan coastline has intertidal mudflats, with patches of mangroves along Thane Creek and Malvan coast. The Malvan coast also has a well-developed patch of corals (Raj et al., 2018). The coastline of Goa has bays and headlands with estuaries of Mandovi and Zuari Rivers. Kerala's Malabar Coast has a series of backwaters and floodplain complexes aligned parallel to the coast, Vembanad-Kuttanad-Kol complex and Ashtamudi Estuary being significant wetlands regimes (Kumar et al., 2013). Andaman & Nicobar, Lakshadweep Islands, Gulf of Mannar and Gulf of Kachchh have coral reef formations embracing all the three major reef types, i.e. atoll, fringing, and barrier (Venkataraman, 2011).

Environmental and geomorphic factors have a distinct influence on coastal wetlands. Mangroves of the west coast, owing to lesser freshwater and sediment input as compared with the east coast, are smaller in size, less diverse and less complicated in terms of tidal creek network (Selvam, 2003). High volumes of freshwater and sediment discharged by the Ganges and Brahmaputra within the Bay of Bengal create an unfavourable environment for the development of coral reefs, thus explaining their absence from the region.

The shoreline is a dynamic entity, being continuously modified by the geomorphic processes of erosion, sediment transport, deposition and sea-level changes. This makes a comprehensive assessment of coastal wetlands extent an arduous task and subject to uncertainties. Nonetheless, efforts to create an inventory of wetlands and assess their extent in the country have been made since the 1980s, wherein an All India Wetland Survey was initiated by the Government of India (Kumar, Bhatt and Goel, 2017). Since the eighties, advances in remote sensing techniques have made it possible to publish national scale assessments of wetlands (Garg, 2015). The mapping of Indian coastal habitats, using IRS LISS II and Landsat TM data of 1989–1991 generating maps and spatial data on high tide line and low tide lines and various wetland features therein, stands out as the first inventory of coastal wetlands in the inter-tidal stretch and coralline shelf (Nayak, 2017). Since then, a number of assessments have been carried for the Indian coast, results published in the form of National Wetlands Atlas based on analysis of satellite images of 2006-07 (Panigrahy et al., 2012), land use land cover assessment of coastal zones (SAC, 2011), shoreline change assessment reports (SAC, 2014), atlas of mangroves (Chauhan et al., 1996), coral reefs (Chauhan and Nayak, 2005; Deshmukh et al., 2005; Mahendra et al., 2010; Bahuguna et al., 2013), status reports on estuaries (ENVIS, 2002) and lagoons (ENVIS, 2001) and seagrasses (Geevarghese et al., 2018; Jagtap et al., 2003). A summary of extent of coastal wetlands drawn from various assessments is given in Table 1.

Table 1: Recent estimates of the extent of select coastal wetlands types in India (km^2)

Wetlands type	West Coast	East Coast	Islands	Total	Data Year
Natural					
Lagoon (a)	608	1,615	237	2,460	2006-07
Creek (a)	1,917	132	18	2,067	2006-07
Sand/Beach (a)	164	359	108	630	2006-07
Intertidal Mud Flat (a)	22,886	937	124	23,947	2006-07
Salt Marsh (a)	1,449	102	60	1,611	2006-07
Coral Reef (f)	353	76	1955	2384*	2004-07
Mangrove (a)	1492	2812	617	4,921	2015
Pond/Lake (a)	272	389	2	663	2004-06
Bay (e)	-	8,731	-	8,731	2004-06
Estuary (e)	298	11	-	309	2004-06
Rocky Coast (e)	59	3	-	62	2004-06
Deltas (d)	-	96,540	-	96,540.00	Various years
Seagrasses (c)	17	484	15	517**	2014-16
Human-made					
Salt Pan (a)	1,017	472	na	1,489	2006-07
Aquaculture Pond (a)	117	2,729	na	2,846	2006-07
Reservoir/Tank (e)	208	1,387	na	1,595	2004-06

*overall accuracy range 77-92%; ** overall accuracy range 64-83.5%

Data Source: (a) Panigrahy et al. (2012); (b) FSI (2017); (c) Geevarghese et al. (2018); (d) Mukhopadhyay and Karisiddaiah (2014); (e) SAC (2011) and (f) Bahuguna et al. (2013)

Varying resolutions and mapping methods prohibit discerning comprehensive trends, yet several assessments indicate a decline in extent of natural coastal wetlands. Most of the lagoons have undergone shrinkage due to changes in land use and other anthropocentric stresses (Kumar and Chackacherry, 2017; Kumar et al., 2013; Venkataraj, 2007). The current extent of mangroves is a remnant of nearly 6000 km2 recorded in the nineteen sixties (FAO, 1981) to just 4,046 km2 in 1985 and subsequently increasing to 4,921 km2 in 2015 (Forest Survey of India, 2017). Of the current cover, 30% is under very dense cover, and an equal proportion under moderately dense cover, with rest being open (FSI, 2017). Significant conversion of mangroves for aquaculture (Hein, 2000) and settlements (Vijay et al., 2005) has taken place during the sixties and the seventies. There is also a high likelihood that the recent increase in area under mangroves has been on inter-tidal mudflat areas aided by plantation efforts. Tidal mudflats along the northern regions of Gulf of Kachchh have shown signs of extensive erosion with the loss of around 28.66 km2 within three years from 2014-2017 caused by strong tidal currents pushing the tidal channels further landward (Bhatti et al., 2018). While the seagrass patches of Palk Bay, Gulf of Mannar and Chilika are large and meadow forming, the decline has been observed in the Gulf of Kachchh (Geevarghese et al., 2018). The corals have also suffered extensive damage due to bleaching events specially since 2002 (Bhatt, Kumar, and Edward, 2012; Edward et al., 2018, Krishnan et al., 2013).

2.2 Biodiversity and ecosystem services

A recent compilation of species richness in coastal and marine ecosystems has indicated presence of at least 14 species of seagrasses, 69 species of mangroves (including associates) , over 200 species of diatoms, 512 species of porifera, 1042 species of cnidaria, 55,525 species of molluscs, 2394 species of crustaceans, 2629 species of pisces, 37 species of reptiles, 243 species of birds and 24 mammalian species (Sivakumar et al., 2012). As many as 925 floristic and 4107 faunistic species are known to be inhabiting Indian mangroves (Kathiresan, 2018). Scleractinian corals of India have richer diversity as compared to other tropical reefs with at least 478 species thriving in significant reef areas of the country (George and Jasmine, 2015). Several coastal wetlands due to their particular hydro-geomorphological settings support a unique assemblage of marine, freshwater and brackish biodiversity such as Chilika, which is an abode to at least 1247 faunistic species (Mishra and Mohapatra, 2017). Similarly, the mangrove swamps of Sunderbans biosphere reserve serve as a habitat for as many as 2626 faunistic species (ZSI, 2017). A total of 885 faunistic species belonging to six different phyla (porifera, coelenterata, athropoda, mollusca, echinodermata, fishes, reptiles and mammals) have been accorded protection under the Wildlife (Protection) Act, 1972 due to increasing threats and high endemism (Sivakumar et al., 2012). Several coastal wetlands support charismatic species such as Royal Bengal Tiger *Panthera tigris tigris* in the Sundarbans, Irrawaddy dolphin *Orcaella brevirostris* in Chilika (largest resident population), a large rookery of Olive Ridley turtles and estuarine crocodiles *Crocodylus porosus* in Bhitarkanika, dugongs *Dugong dugon* in Gulf of Mannar, Leatherback sea turtle *Dermochelys coriacea* in Andaman and Nicobar Islands and large breeding population of Lesser Flamingos *Phoeniconaias minor* in the Rann of Kachchh.

Hundreds of thousands of birds migrating along the Central Asian Flyway descend upon the coastal wetlands of India in search of food and refuge annually flying nearly 18,000 km (Balachandran, 2012). The Indian coastal wetlands are known to serve as habitats for at least 243 taxa of birds including 90 trans-continental migrants and 37 resident migrants (Gopi and Hussain, 2014). Chilika, Point Calimere, Gulf of Mannar and Pulicat on the east coast and Vembanad-Kol, Kadalundy estuary and Great Rann of Kachchh on the west coast support large congregations of water birds (Sivaperuman & Venkatraman, 2015). The wetlands of Andaman and Nicobar Islands provide feeding and resting sites for many migratory shorebirds (Sivaperuman & Venkatraman, 2015).

Coastal wetlands provide a range of ecosystem services such as food and fibre, shoreline stabilisation and sediment accretion, habitat for wildlife, carbon sequestration, a buffer for extreme events and cultural and recreational avenues (Millennium Ecosystem Assessment, 2005). Annual economic benefits derived from the diverse ecosystem services of coastal wetlands in terms of 2007 Int.$ were assessed to range between 164 to 1.08 million per hectare, amongst the highest of the ecosystems evaluated (Russi et al., 2013).

Several studies have brought out quantitative estimates of benefits societies derive from coastal wetlands. The contribution of mangroves to fish production in Indian coastal states has been estimated to be worth 23% of commercial marine fisheries output in 2011 (Anneboina and Kavi Kumar, 2017). The annual flow of benefits from Chilika through fisheries, aquatic vegetation, inland navigation and tourism were assessed to be INR 4.8 billion at 2014 prices (Kumar et al., 2017). The benefits from fisheries, husk retting, inland navigation, recreation, and carbon sequestration services of Ashtamudi estuary have been assessed to be worth INR 1,924 million (Anoop et al., 2008). The Vembanad – Kol backwaters provide sustenance to 0.2 million households through backwater tourism, inland navigation, clams, shellfish and finfish, besides buffering urban settlements of Cochin and Ernakulum from floods (Kumar et al., 2013). The bivalve-based economy of Aghnashini Estuary was estimated to have an annual turnover of INR 57.8 million per year, generating direct employment for about two thousand people, and nutritional security of millions more along the Karnataka coast and also in neighbouring states (Boominathan, Chandran and Ramachandra, 2008). The values of ecosystem services emanating from the coral reefs of Gulf of Kachchh including fisheries, recreation, protection of coastal aquifers from salinity ingress, erosion control and biodiversity were estimated to be equivalent of INR 2200.24 million based on 2007 prices (Dixit et al. 2010, Dixit et al., 2012). The annual recreational value derived from Indian Sundarbans has been estimated to be worth US$ 377,000 (Guha and Ghosh 2009).

Mangroves and salt marshes have high value for coastal hazard mitigation and climate change adaptation (Shepard, Crain, and Beck, 2011). Storm surges can be slowed down by vast mangrove tracts, rates of surge height reduction have been recorded at between 4 and 48 cm per km of passage through mangrove (McIvor, Spencer and Möller, 2012; Zhang et al., 2012). Bhitarkanika mangroves form the base of resilience and sustainability of local economy, contributing nearly 14.5% of the total household income (Hussain and Badola, 2010). Das and Vincent (2009) estimated the opportunity cost of saving a life by retaining mangroves to be INR 11.7 million per life saved. A study on ecosystem degradation and biodiversity loss in Indian Sunderbans assessed the damage to be worth INR 6.2 billion annually at 2009 prices, equivalent to 4.8 per cent of the region's Gross Domestic Product (The World Bank, 2014).

2.3 Threats

Located within the highly concentrated human population and economic assets, coastal wetlands are subject to a range of anthropogenic threats. Foremost amongst these is an alteration of hydrological regimes. Water and sediments set the physical templates in which wetlands, including coastal wetlands, evolve and function (Ramsar Convention Secretariat, 2010). With the rapid intensification of water use in the upstream stretches, there has been a significant reduction in water and sediment availability to the coastal wetlands leading to several adverse changes in their structure and functioning. In the last four decades, the sediment flux of ten large Indian peninsular rivers declined by over 75%, impeding the delta building processes (Gupta, Kao and Dai, 2012). Environmental flow analysis for Pichavaram mangroves (Tamil Nadu) indicated that the minimum freshwater flow required for maintaining healthy mangroves was available only for 12% of the period during 1977 – 2008, resulting in loss of species diversity and ecosystem degradation (Sathyanathan, Thattai and Selvam, 2014). In the Sundarbans, alterations in salinity due to a reduction in freshwater flows into mangrove have impacted the aboveground biomass of the endangered and steoecious mangrove species *Heritiera fomes* (commonly known as Sundari) (Banerjee, Gatti and Mitra, 2017). In Ashtamudi Estuary, over 50% decline in freshwater inflows from Thenmala Dam has been observed to be one of the causative factors for increasing salinity and reduction in the haitat of freshwater fish species (Kumar and Chackacherry, 2017).

Coastal wetlands have also been subject to intensive landscape alteration. Development of intensive aquaculture in coastal areas (Krishnan and Birthal, 2002) led to the conversion of large swathes of mangroves and occupation of estuarine shorelines (Hein, 2000). In Vembanad, the floodplains of Periyar draining into the estuary were intensively reclaimed during the sixties and seventies through polders for agriculture (Kumar et al., 2013), and mangroves along Ashtamudi shoreline cleared for development of tourist infrastructure and industries (Kumar and

Chackacherry, 2017). Extensive conversion of sandy beaches, foredunes and other associated landforms within the near shore areas to built-up areas have been reported from Kanyakumari coast (Kaliraj et al., 2017).

Invasive species are a significant threat to the native diversity and ecosystem processes of coastal wetlands. A modelling of plant invasion hotspots in India delineated through the intersection of ecoregions, multi-species ecological niche model consensus, and anthropogenic biomes have indicated west coast, Sundarbans and Coromandel coast to be one of the high invasion risk areas (Adhikari, Tiwary and Barik, 2015). *Kappaphycus alvarezii,* a commercially important red alga and a source of worldwide kappa carrageenan believed to have been introduced in Gulf of Mannar in the 1990s, its escape from culture areas paved way for invasion, and eradication efforts thus far have had limited success (Kamalakannan et al., 2014). Eighteen species of exotic animals and plants have been documented along the Indian coasts which have been introduced through ballast water and maybe potentially invasive (Anil, 2006). Island diversity is particularly vulnerable to species invasion (Kiruba-Sankar et al., 2018). The occurrence of invasive snowflake coral (*Carijoa riisei)* in the reef systems of India has raised significant concerns regarding its impacts on the indigenous biota (Venkataraman et al., 2013).

Coastal wetlands and seas end up being receptacles of pollution from inland and densely populated coastal stretches. With over 250 million people living within the 50 km of the coastline, as many as 130 cities, and the sewage treatment infrastructure having the capacity to treat less than half of the grey water it is evident that the coastal wetlands become sinks to a large amount of untreated effluents. Increased accumulation of heavy metals in the Sundarbans has become a significant cause of concern (Nobi et al., 2010; Sarkar et al., 2002). Industrial pollution has been identified as a major threat to the mangroves of Uran (Navi Mumbai) (Pawar, 2013). Naqvi et al., (2000) reported an intensification of one of the largest low-oxygen zones developing naturally over the western Indian continental shelf. Backwater tourism once hailed as a hallmark of Kerala, has ended up being an ultimate threat to these wetlands due to the insignificant treatment of waste (Kumar et al., 2013). A summary of significant direct and indirect drivers of adverse change in coastal wetlands, synthesised from various sources is presented in Table 2. Institutions and governance were excluded from the purview of assessment and are discussed in section three of the paper.

Table 2: Drivers of adverse change in Indian coastal wetlands

Coastal wetland Type		Adverse Drivers of Change									
		Direct Drivers							Indirect Drivers		
		Freshwater input reduction	*Sediment deprivation*	*Invasive species*	*Pollution*	*Encroachment and conversion*	*Extreme events*	*Sea level rise*	*Climate Change*	*Unsustainable Tourism*	*Unplanned Urbanization*
Natural wetlands	Deltas	+++	+++		+++	++	+++	+++	+++	+	+++
	Intertidal marshes (Seagrasses)	++	++	+++	+++		++	+++	+++	++	+
	Mudflats	+++	++	+	+++	+++	++	+++	++	+++	++
	Coral reefs		+++	+++	+++		+++	+++	+++	+++	
	Mangroves	+++	+++	++	+++	+++	+++	++	+++	++	+++
	Lagoons	+++	+++	++	+++	++	++	+++	++	+++	+++
	Creeks	++		++	+++	++	+++	+++	++	++	+++
	Estuaries	+++	+++	++	+++	+++	+++	+++	+++	+++	+++
	Rocky shores			+	++	+++	+	+	++	++	++
	Sand and Beaches			+	+++	+++	+++	++	++	+++	+++
Human made wetlands	Shrimp and Fish ponds	++	+	+++	+++		++	++	++		
	Salt pans			+	++	++		+++	++		
	Reservoirs/ Tanks	++		+++	+++		++	++	++		

🟥 Strong impact 🟧 Medium impact 🟨 Low impact ⬜ Not applicable/ Data not available

3. Coastal wetlands and climate change

Climate change projections for India indicate increase in atmospheric temperature (Bal et al., 2016; Chaturvedi et al., 2012; Kumar et al., 2006; Kumar et al., 2013), sea-surface temperature (Arora et al., 2016), intensifying rainfall (Kumar et al., 2006 and Bal et al., 2016), sea-level rise (Unnikrishnan, Kumar and Sindhu, 2011), and increasing extreme events (Mishra, 2014; Rajeevan, Bhate and Jaswal, 2008). Coastal wetlands are vulnerable to all these changes through impacts on ecosystem structure, function and processes. Deepening of anthropogenic drivers of change is likely to accentuate adverse changes in coastal wetlands further.

3.1 Carbon accumulation and GHG emissions from coastal wetlands

Coastal wetlands have a role in stabilization of CO_2, CH_4, N_2O and other GHG concentrations through their influence on two pathways namely, preventing climate and land use mediated release of GHGs and increasing the capacity to actively remove CO_2 from the atmosphere and sequester carbon for a long time (Moomaw et al., 2018). For several coastal wetland types, the bulk of sequestered carbon is in the soils as compared with plant communities, due to limitations on decomposition imposed by water saturation and lack of oxygen (Wolanski et al., 2009). The coastal blue carbon soaked by mangroves, salt marshes and seagrasses via photosynthesis and stored in wet anaerobic soils has received considerable attention recently in the context of climate change (Chmura et al., 2003; Tollefson, 2018).

A 2010 assessment of above ground carbon in Indian Sunderbans indicated carbon storage in mangroves to range between 21.44 – 25.24 tonnes per ha in various sectors (Raha et al., 2013). Carbon sequestration rates have been estimated to range between 53.95 – 123.30 tonnes per ha in mangroves of Gujarat (Pandey and Pandey, 2013). Assessments on seagrass meadows of Palk Bay and Chilika indicated that these wetlands acted as a net sink of atmospheric CO_2, annually capturing 8.44 – 15.9 Mg CO_2 per hectare (Ganguly et al., 2018). The economic value of carbon sequestration service of the seagrass meadows, up scaled for the total cover of the country, was estimated to be $1.02 - $ 3.65 million annually (Ganguly et al., 2018).

Several coastal wetlands can also be a net source of GHGs and emissions are further elevated by anthropogenic disturbances and alterations to these ecosystems (Pendleton et al., 2012). Anthropogenic disturbances have been observed to increase methane emissions from mangroves (Purvaja, Ramesh and Frenzel, 2004). Methane emissions from the coastal wetlands of South India were found to vary between 3.10 $mg/m^2/hr$ (Bay of Bengal) to 21.56 $mg/m^2/hr$ (Adyar River), with emissions increasing with the levels of perturbance (Purvaja and Ramesh, 2001). Tidal flooding induced anoxic conditions in mangroves have been observed to make these wetlands potential sources of GHGs including CH_4 and N_2O (Krithika, Purvaja and Ramesh, 2008). Studies on spatial and temporal variations of methane emissions in Hoogly-Matla estuary indicated higher levels of methane emission from the adjacent forest as compared to water within mangroves (Biswas et al., 2007). In Chilika, the CO_2 flux was observed to be influenced by the maintenance of brackish water conditions and phytoplankton density (Muduli et al., 2012). Similarly, methane flux assessments in Vembanad indicated the wetland to be a net source, with high influence of salinity gradient and anthropogenic influence (Verma, Subramanian and Ramesh, 2002).

3.2 Impacts on coastal wetland dependent species

The effect of global climate change on biodiversity of coastal wetland systems is projected to take place at several landscape spatial scales ranging from habitat units, ecological types, geomorphologic types to global distributions (Day et al., 2008). Many of these changes are expected to be mediated by deepening of drivers of wetlands degradation such as reduced freshwater and sediment input, increased nutrient loading, conversion of natural shoreline and species invasion.

The northern Indian Ocean is identified as one of the 17 climate change hotspots (areas that will warm faster than 90% of the oceans) (Hobday and Pecl, 2014). Long-term climate change is likely to impact coastal ecosystems and their capacity to sustain fish stocks, exacerbate stress on fish stocks thereby affecting the fisher communities along the Indian coastline. Increased sensitivity to climatic fluctuations has been observed in several overfished species such as Bombay duck, tuna, pomfret, various shrimp and catfish (Rao and Vivekananda, 2008; Zacharia et al., 2016). Many tropical fish stocks are already exposed to high extremes of temperature tolerance and face regional extinction, with some others moving towards higher latitudes (Zacharia et al., 2016). Shifts in spawning periods have been observed in several commercially important fish stocks, such as threadfin breams *Nemipterus japonicus and N. mesoprion* (Zacharia et al., 2016).

Coral reefs of Indian Ocean had experienced as many as 29 widespread bleaching events with intense bleaching around 2002 when observed sea surface temperature was higher than the summer maxima forcing dependent communities to search for other food and breeding sites (www.reefbase.org). During the third global coral bleaching event between 2014 and 2017, corals in the Gulf of Mannar faced high mortality with reduction of live corals to only one-fifth area, fast growing coral forms including Acropora, Montipora and Pocillopora being the most-affected not only by bleaching but also by severe mortality (Edward et al., 2018).

Future sea surface temperature changes are also likely to induce adverse impacts on populations of several endangered species such as female skewed sex ratios at many rookeries of sea turtles (Poloczanska, Limpus and Hays, 2010; Witt et al., 2010). This risk is superimposed on the adverse trends in the loss of available nesting sites and flooding of turtle nests (Witt et al., 2010).

3.3 Sea-level rise

A key determinant of the vulnerability of coastal wetlands is whether their surface elevation can keep pace with rising sea level (Webb et al., 2013). Salt marshes and mangrove swamps are known to accumulate soils vertically mainly through three synergistic processes: a) below ground growth adding volume to the soil and the above ground portion helping trap inorganic sediments of tidal waters, b) increasing soil volume resulting in raised surface elevation of the wetland enabling it to roughly track sea-level rise, and c) increase in elevation accompanied by lateral expansion over tidal flats in the lower intertidal zone and inland over adjacent terrestrial ecosystems (Moomaw et al., 2018). Areas surrounded by urbanised wetlands are expected to lead to a coastal squeeze in the face of sea-level rise ultimately leading to wetland loss (Torio and Chmura, 2013; Webb et al., 2013). Availability of accommodation space, which is strongly influenced by the building of anthropogenic infrastructure in the coastal zone and how such infrastructure changes in response to development dynamics is likely to have a bearing on actual magnitude of loss or even gain in coastal wetlands (Schuerch et al., 2018).

With the rapid intensification of water use in the upstream stretches, there has been a significant reduction in water and sediment availability to the coastal wetlands (Gupta, Kao and Dai, 2012). Intensive coastal infrastructure built up in major parts of Indian coastline may, thus, deprive coastal wetlands of the much-needed accommodation space. For lagoons, rising sea-level along with a reduction in freshwater flows may tend the system to marine processes domination and reduced ecological productivity as compared with brackish water state as observed in Ashtamudi (Kumar and Chackacherry, 2017).

3.4 Extreme events and disaster risks

Assessments on extreme weather events for India indicate a trend of enhanced cyclogenesis (Mishra, 2014) and increasing extreme rainfall events (Rajeevan, Bhate and Jaswal, 2008) exposing the coast to the risk of floods, storm surges, tsunamis and tropical cyclones. Impacts of extreme events on coastal wetlands are known to range from changes in hydrological characteristics in lagoons (such as prolonged freshwater conditions in Chilika after cyclone Phailin (Barik et al., 2017)) to extensive physical damage (mangrove destruction during great Indian tsunami (Ramachandran et al., 2005)). Reef areas of Andaman and Nicobar Islands were devastated entirely during the 2004 tsunami, and in Gulf of Mannar, the delicate branching corals (Acropora and Montipora) needed more than ten years to recolonise (Venkataraman, 2006). Santhanam and Natarajan (2018) observed short-term desalination in Pulicat during the 2015 floods. On the contrary, coastal wetlands as mangroves have buffered communities against the impacts of tropical cyclones (Das and Vincent, 2009; Das and Crépin, 2013; Kathiresan and Rajendran, 2005). Careful stewardship of sediments and reduction in human induced land subsidence is critical to reducing the vulnerability of coastal areas to flooding (Woodruff, Irish and Camargo, 2013).

4. Policies and management strategies

4.1 National settings

Systematic efforts for conservation and integrated management of coastal wetlands can be discerned as shaping up in India with its ratification of Ramsar Convention in 1982 and establishment of a separate Ministry of Environment and Forest (currently known as Ministry of Environment, Forest and Climate Change) in 1985. Before this, management was largely based on production values, such as rotational felling of mangroves (DasGupta and Shaw, 2013) by the erstwhile landlords and allocation of fishing rights to the traditional fishers on payment of revenues in Chilika (Sekhar, 2007). Mangroves were considered as part of forests and subject to policy interventions of the sector (DasGupta and Shaw, 2013). Towards the seventies, concerns on declining biodiversity led to high biodiversity value landscapes, including several wetlands being designated as protected areas under the Indian Wildlife Protection Act (1986) and state wildlife laws. Point Calimere was perhaps the first coastal wetland to be accorded a protected status in independent India in 1967 (under the Madras Forest Act, 1882). Presently, as many as 131 coastal wetlands have been covered within the national terrestrial and marine protected area network, including two transboundary protected areas (Sundarbans National Park and Gulf of Mannar Biosphere Reserve) designated under the IUCN cross-border protected area programme (Sivakumar, 2012).

The degradation and pollution of wetlands were identified as one of the significant environment challenges by the MoEFCC and reflected in the National Conservation Strategy and Policy Statement on Environment and Development (1992). The Ministry institutionalised conservation programming for wetlands in the form of a National Wetlands Conservation Plan in 1986. The programme centred around the creation of a network of well-managed wetlands by providing support to state governments in the design and implementation of management plans and providing complementing support to research, capacity development and outreach programmes. A National committee on wetlands, mangroves and coral reefs was constituted by the Ministry in 1992 to advise the government on appropriate policies and action programmes, recommending priority sites, research and training and collaboration with International agencies (WWF and MOEF, 1992). While the initial set up of the scheme included all inland and coastal wetlands, mangroves and coral reefs were soon carved into a separate scheme entitled 'National Programme for Conservation of Mangroves and Coral Reefs', albeit with similar functions as the parent scheme. In 2001, considering the need to address pollution issues in wetlands located with urban and peri-urban settings, a separate scheme by the name 'National Lake Conservation Programme' was introduced. Wetlands located within protected areas continue to receive financial support for conservation actions through a separate scheme 'Integrated Development of Wildlife Habitats'. The National Environment Policy of 2006 laid down specific policy elements for wetlands with recommended actions including integration in developmental planning, management based on prudent use strategies, promotion of eco-tourism and implementation of a regulatory framework (Ministry of Environment and Forests, 2006).

Provisions of the Indian Forest Act, 1927 and the Indian Wildlife (Protection) Act, 1972 defined the regulatory framework for wetlands located within forests and designated protected areas. Similarly, coastal wetlands are protected under the Coastal Regulation Zone (CRZ) Notification (2011) and the Island Protection Zone (IPZ) Notification 2011. These Notifications recognise coral reefs, mangroves, mud flats, and salt marshes as ecologically sensitive and categorise them as CRZ-I which implies that these areas are accorded protection of the highest order. The Indian Fisheries Act, 1897, The Water (Prevention and Control of Pollution) Act, 1974, The Environment (Protection) Act, 1986 and The Biological Diversity Act, 2002 provide substantive legal and regulatory framework for conservation of Indian wetlands. The Coastal Aquaculture Authority Act, 2005 prohibits the conversion of natural coastal wetlands. In 2010, the Ministry notified the Wetlands (Conservation and Management) Rules as the regulatory architecture for wetlands, which was superseded by the 2017 notification, entrusting the state governments with responsibilities of notifying wetlands, ensuring that activities prohibited in notified wetlands do not take place, and management is based on wise use principles.

The regulatory aspect of coastal zone management has recently been complemented with efforts towards integrated coastal zone management (Nayak, 2017). Through a World Bank assisted project on Integrated Coastal Zone Management initiated in 2010, vulnerability mapping, delineation and demarcation of the hazard lines, and delineation of coastal sediment cells all along the mainland coast of India are being carried out and integrated approaches being piloted in three states namely Odisha, Gujarat and West Bengal.

The linkages of national policy settings for wetlands with climate change are primarily through inclusion in the National Action Plan for Climate Change. Wetland conservation and sustainable management is included in the National Water Mission. Similarly, the National Mission for Green India has a target of 0.1 Mha for wetlands conservation and an additional 0.1 Mha for mangroves. Recently, the blueprint of a National Coastal Mission has been developed which will further strengthen conservation and management of coastal wetlands.

4.2 International wetlands and climate policy

International climate policies have of late taken steps to incorporate wetlands. In 2013, the Wetlands supplement was released by the Intergovernmental Panel on Climate Change guiding the countries on how they can explicitly include emissions from land use change in freshwater wetlands including peatlands in their national carbon inventories. Opportunities for including coastal blue carbon ecosystems and other wetlands exist in Reduced Emissions from Deforestation and Degradation Plus (REDD+), Clean Development Mechanisms (CDM) and nationally appropriate mitigation actions (Gordon et al., 2011). Ramsar Convention on Wetlands calls for 'conservation and wise use of all wetlands' through local and national action and international cooperation, as a contribution to achieving sustainable development throughout the world. Towards its commitment under the Ramsar Convention, India has designated 26 Ramsar sites including six coastal wetlands.

Elements pertaining to conservation of coastal wetlands are also contained in the programmes of Convention on Biodiversity (CBD), Convention on Migratory Species of Wild Animals (CMS or the Bonn Convention), Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES), World Heritage Convention, Intergovernmental Panel on Climate Change (IPCC) and the United Nations Convention on the Law of the Seas (UNCLOS), the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) and the Stockholm Convention on Persistent Organic Pollutants (Bhatt et al., 2012). The Sendai Framework on Disaster Risk Reduction and the Sustainable Development Goals, clearly recognise that nature-based solutions for reducing disaster risk are vital for a sustainable and secure world. The Sendai Framework explicitly recommends taking into account the role of ecosystems, including wetlands, within disaster planning (Kumar et al., 2017).

In line with the CBD Strategic Plan 2011–2020, India has formulated 12 National Biodiversity Targets. Wetlands find direct reference under Target 3 (Strategies for reducing rate of degradation, fragmentation and loss of natural habitats are finalized and actions put in place by 2020), Target 6 (ecologically representative areas on land and in inland waters, as well as coastal and marine zones, especially those of particular importance for species, biodiversity and ecosystem services, are conserved effectively and equitably), and Target 8 (by 2020, ecosystem services, especially those related to water, human health and livelihoods and well–being are enumerated and measures to safeguard them are identified).

4.3 Gaps and Challenges

India, through its national programmes and complementing multilateral environmental agreements, has put in place a robust policy framework and action programme for conservation and wise use of coastal wetlands. There has been a significant improvement on the status and trends in these ecosystems, supporting efficient policy targeting. Measures such as Joint Mangroves Management and basin scale restoration of Chilika have demonstrated stakeholder led ecological restoration pathways. The institutional architecture for conservation has been made robust through creation of state level wetlands authorities, and knowledge centres.

However, the effectiveness of the programmes above has been limited by some factors, of which sectoral approaches, in-effective governance mechanisms, ad-hoc implementation of management plans and insufficient capacity for integrated management remain prominent. Barring mangroves, the extent and quality of which have indicated a positive trend since the devastating Indian Ocean Tsunami of 2004, much of the coastal wetlands are bearing adverse trends. With a multiplicity of national programmes, each guided by sectoral priorities, a unified policy framework for wetlands remains elusive.

5. Integrating Coastal wetlands within Climate Change response actions

This chapter documents recent research on the status and extent of wetlands, biodiversity and ecosystem service values, drivers of adverse change and the role coastal wetlands can play in moderating climate change impacts. Available evidence underlines the vulnerability of coastal wetlands to the changing climate and resultant effects. Avoidance of impacts to wetlands and associated carbon stocks and processes are likely to be the most effective management strategy for preventing increases in GHG emissions from wetlands, and securing climate resilience functions (Moomaw et al., 2018). The climate related functions of wetlands remain highly undervalued.

A network of conserved and well-managed wetlands underpins India's resilience to climate change. As discussed in the previous section, a need of pragmatic policy and programming to secure integrated management of coastal wetlands and their integration in coastal zone management has emerged in the last decades. There is a pressing need to build on the current policy frameworks and programmes to ensure that climate risks are factored at all levels. Current wetlands management planning approaches are based on business-as-usual scenarios and do not consider vulnerabilities imposed by climate change. Wetland monitoring frameworks, despite recent innovations such as ecosystem health report card (CDA, 2017), are not geared towards identification of climate risk indicators and trends thereof. Wetlands, coastal ones, in particular, are also exposed to the risk of maladaptation – the likelihood of adverse impacts on these ecosystems in response to adaptation actions in other sectors. For example, the construction of hydraulic structures to increase freshwater storage in upstream stretches, may further accentuate the risks of salinisation in downstream coastal wetlands. With coastal blue carbon receiving increasing attention of late, it is essential to ensure that conservation action is not led by the role of wetlands in carbon cycles alone; instead takes into account the full range of ecosystem services and biodiversity values. Governance of coastal wetlands in an increasing uncertain world needs to be collaborative, adaptive and learning based.

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15

Climate Change Challenges on Indian marine fisheries sector

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ABSTRACT

Climate change can have a significant influence on terrestrial and aquatic biodiversity at all system levels – ecosystem, species and genetic. Marginalised sections of communities will further be pushed due to the impacts of climate change. The effect on the marine ecosystem will be multipronged affecting the environment, the resources and the resource users, affecting the sustainability. Primary strategies and policies will have to be sensitive to all the components separately, yet complimenting each other. This chapter is part of the studies undertaken for the Belmont Forum funded project titled `Global Learning and Understanding for Local Solution' (GULLS) to reduce the vulnerability of marine-dependent coastal communities in two marine fishing villages in Kerala, southwest India by attempting to test a climate resilient village adaptation and mitigation plan (CReVAMP) for vulnerable coastal communities with the understanding that overall vulnerability could be mitigated only by increasing the adaptive capacity of the population. Blue economy emerges as a commonly acceptable development paradigm which will effectively blend economic growth with sustainable development. Policies on adaptation need to consider multiple scales of climate change effects. Integrating adaptation and mitigation will increase the local legitimacy of the plan, as adaptation emphasizes on local needs.

1. Introduction

Climate change has been a topic of growing concern in terms of its reality and its acceptability as a reality. The ongoing debate around the world about climate change, actions to be taken and responsibility sharing dilemma between developed and developing nations are adding to the trouble. Climate change impacts can be seen on the environment and the most vulnerable communities, and if appropriate adaptation and mitigation measures are not considered, it will have - reaching negative outcomes at a huge cost.

Climate change is expected to have a significant influence on terrestrial and aquatic biodiversity at all system levels – ecosystem, species and genetic diversity. The changing climate will stimulate species-level changes in range and abundance, life cycle and behaviour, and, over time, genetic evolutionary responses. These changes will in turn be linked with changes in natural disturbance patterns and changes in ecosystem structure and function.

The most concerning factor regarding climate change is that the marginalised sections of the society are at the frontlines of facing the impacts of climate change, pushing them further to the edge. Climate change is going to strike at the root of these sections of the society already grappling with the constant problem of poverty and unemployment. Farmers and fishers who heavily depend on natural resources for their livelihood are going to find it difficult to survive this impending disaster if not given appropriate and effective support. Shifting rainfall patterns, recurring floods, stronger cyclones and droughts or soil erosion are exacerbating the challenge of poverty eradication and necessitate the allocation of scarce national resources for preventing loss of human life.

Scientists have been observing a change in the climate since the beginning of the 20th Century that cannot be attributed to any of the 'natural' influences of the past. Global warming has occurred faster than any other climate change recorded by humans and so is of great interest and importance to the human population. Various anthropogenic (human caused) factors responsible for climate change includes greenhouse gases, aerosols and changed land use patterns. It is high time that every country whether developing or developed, realises this threat and makes comprehensive adaptation and mitigation (A& M) plans for the common good of humanity.

Global warming as a result of Climate change has increased the vulnerability of social and biological systems to relatively sudden changes, which will last many years. So, climate change adaptation is necessary to offset the effects of global warming. Adaptation strategies are needed at all levels of administration to make them more effective. Successful adaptation not only depends on governments but also on the active and sustained engagement of stakeholders including national, regional, multilateral and international organisations.

Mitigation is an intervention to reduce emissions sources or enhance the sinks of greenhouse gases. Mitigation addresses the causes of climate change (accumulation of greenhouse gases in the atmosphere), whereas adaptation addresses the impacts of climate change.

Both approaches are needed. On the one hand, even with strong mitigation efforts, the climate would continue changing in the next decades and adaptation to these changes is necessary. On the other hand, adaptation will not be able to eliminate all negative impacts and mitigation is crucial to limit changes in the climate system.

Adaptation and mitigation differ in terms of spatial scales: even though climate change is an international issue, adaptation benefits are local and mitigation benefits are global. Mitigation is a priority in the energy, transportation, industry and waste management sectors whereas Adaptation is a priority in the water and health sectors and in coastal or low lying areas.

Climate change, more particularly harsher weather conditions, will have impact on the quality, productivity, output and viability of fish and aquaculture enterprises, thereby affecting fishing community. The small-scale fishers may be faced with greater uncertainty as availability, access, stability and use of marine food and supplies would diminish and work opportunities would dwindle. Aquaculture development opportunities will increase in particular in tropical and sub-tropical regions. The climate change in warmer regions offers new opportunities as production in warmer regions will increase because of better growth rates, a longer growing season and the availability of new fish farming areas where it was once too cold.

Climate change will affect individuals, populations and communities through the individuals' physiological and behavioral responses to environmental changes (Boesch and Turner, 1984). Extremes in environmental factors, such as elevated water temperature, low dissolved oxygen or salinity, and pH, can have deleterious effects on fishes (Moyle and Cech, 2004). Suboptimal environmental conditions can decrease foraging, growth and fecundity, alters metamorphosis and affects endocrine homeostasis and migratory behaviour (Barton and Barton, 1987; Donaldson, 1990; Portner et al., 2001). These organismal changes directly influence population and community structure by their associated effects on performance, patterns of resource use, and survival (Ruiz et al., 1993; Wainwright, 1994). Climate affects the distribution and abundance of species in ecosystems around the world. In the face of rising temperatures, the ocean may experience variations in circulation, water temperature, ice cover, and sea level (McCarthy et al., 2001). Climate-driven fluctuations in regional temperature can further affect growth, maturity, spawning time, egg viability, food availability, mortality, and spatial distribution of marine organisms (Ottersen et al., 2001; Perry et al., 2005; Nye et al., 2009). Also affected by climate change are the size and timing of plankton blooms, a major driver of marine ecosystem function with a direct impact on recruitment success and population sizes (Walther et al., 2002; Fischlin et al., 2007).

2. Impact of climate change on Marine Ecosystem and its components

The marine ecosystem is affected in many ways and the major components that get affected due to climate change are illustrated in Figure 1. The three major components that have to bear the brunt of climate change include the environment, the resources and the resource users. Each component is equally important for maintaining the balance and sustainability of our existing marine ecosystem. Major strategies and policies need to be developed considering all the components separately, yet supporting each other.

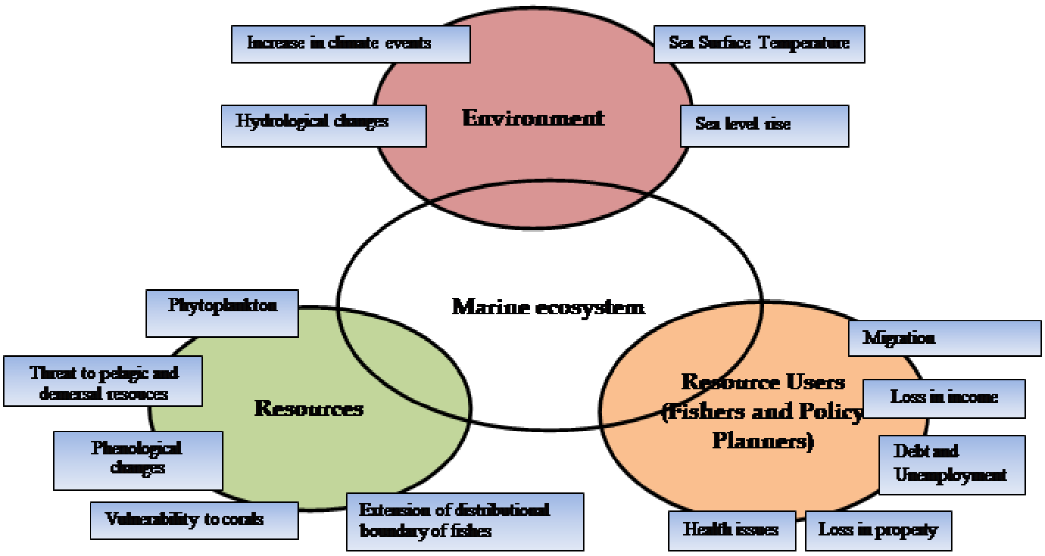

Figure 1: Impact of climate change on Marine Ecosystem and its components

3. Impactof climate change on Environment

Global warming is expected to have the potential to increase the atmospheric temperature by 1.3°C by 2040 compared to 1850-1900. A 1.5°C average rise may put 20-30% of species at risk of extinction. The atmospheric concentration of CO_2 reached 400 ppm for the first time in human history, up from pre-industrial levels of 280 ppm.Annual mean Arctic sea-ice extent decreased from 1979 to 2012, approximately at a rate of 3.5-4.1 % / decade. Sea level is predicted to rise between 0.24 - 0.3 meters by 2065 compared to mean levels for 1986-2005. Increased sea surface temperature, ocean acidification, coral bleaching, tree-lines shifting pole ward and upward are other major consequences of climate change.

4. Impactof climate change on Resources

Studies on the impact of climate change on fisheries (fish species, stock distribution etc.) have been carried out mainly by CMFRI, Kochi. Investigations carried out by CMFRI show that different Indian marine species will respond to climate change as follows: (i) Changes in species composition of phytoplankton may occur at higher temperature; (ii) Small pelagic may extend their boundaries; (iii) Some species may be found in deeper waters as well; and (iv) Phenological changes may occur.

a. *Indian mackerel is getting deeper:* Besides exploring northern waters, the Indian mackerel *Rastrelliger kanagurta* has been descending deeper as well during the last two decades (CMFRI, 2008). The fish normally occupies surface and subsurface waters. During 1985-89, only 2 percent of the mackerel catch was from bottom trawlers, the remainder was caught by pelagic gear such as drift gillnet. During 2003-2007, however, an estimated 15 percent of the mackerel has been caught by bottom trawlers along the Indian coast. It appears that with the warming of sub-surface waters, the mackerel has been extending deeper and downward as well.

b. *Small pelagics extend their boundaries:* The oil sardine *Sardinella longiceps* and the Indian mackerel *R. kanagurta* accounted for 21 percent of the marine fish catch in 2006. These small pelagics, especially the oil sardine, have been known for restricted distribution – between latitude 8^{0}N and14^{0}N and longitude 75^0 E and 77^{0}E (Malabar upwelling zone along the southwest coast of India) where the annual average SST ranges from 27 to29^{0}C. Until 1985, almost the entire catch was from the Malabar upwellingzone, there was little or no catch from latitudes north of 14^{0}N. During the last two decades, however, catches from latitude 14^{0}N - 20^{0}N are increasing. In 2006, catches in this area accounted for about 15 percent of the all-Indian oilsardine catch. The higher the SST, better the oil sardine catch. The surface waters of the Indian seas are warming by 0.04^{0}C per decade. Since the waters in latitudes north of 14^{0}N are warming, the oil sardine and Indian mackerel are moving to northern latitudes. It is seen that catches from the Malabar upwelling zone have not gone down. It can be inferred that the sardines are extending northward, not shifting northward. The Indian mackerel is also found to be extending northward in a similar way. According to CMFRI, the catch of oil sardines along the coast of Tamil Nadu has gone up dramatically, with a record landing of 185877 tonnes in 2006. The presence of the species in new areas is a bonus for coastal fishing communities. Assessing their socio-economic needs will greatly help in developing coping strategies for adaptation to climate impacts. WWF is currently documenting community perceptions and experiences in relation to the oil sardine fishery of the eastern coasts.

c. *Spawning:* Fishes have strong temperature preferences so far as spawning goes. The timing of spawning, an annually occurring event, is an important indicator of climate change. Shifts in the spawning season of fish are now evident in the Indian seas. The thread fin breams *Nemipterus japonicas* and *N. mesoprion*are distributed along the entire Indian coast at depths ranging from 10 to 100 m. They are short-lived (about 3 years), fast growing, highly fecund and medium-sized fishes (35 cm). Data on the number of female spawners collected every month off Chennai from 1981 to 2004 indicated wide monthly fluctuations. However, a shift in the spawning season from warmer to relatively cooler months (from April-September to October-March) was discernible (Vivekanandan and Rajagopalan, 2009).These changes may have an impact on the nature and value of fisheries (Perry et al., 2005). If small sized, low value fish species with rapid turnover of generations are able to cope up with changing climate, they may replace large-sized high value species, which are already declining due to fishing and other non-climatic factors (Vivekanandan et al., 2005). Such distributional changes might lead to novel mixes of organisms in a region, leaving species to adjust to new prey, predators, parasites, diseases and competitors (Kennedy et al., 2002), and result in considerable changes in ecosystem structure and function.

d. *Vulnerability of corals:* In the Indian seas, coral reefs are found in the Gulf of Mannar, Gulf of Kachchh, Palk Bay, Andaman Sea and Lakshadweep Sea. Indian coral reefs have experienced 29 widespread bleaching events since 1989 and intense bleaching occurred in 1998 and 2002 when the SST was higher than the usual summer maxima. By using the relationship between past temperatures and bleaching events and the predicted SST for another 100 years, Vivekanandan et al. (2009a) projected the vulnerability of corals in the Indian Seas. They believe that the coral cover of reefs may soon start declining. The number of decadal low bleaching events will remain between 0 and 3 during 2000-2089, but the number of decadal catastrophic events will increase from 0 during 2000-2009 to 8 during 2080-2089. Given the implication that reefs will not be able to sustain catastrophic events more than three times a decade, reef building corals are likely to disappear as dominant organisms on coral reefs between 2020 and 2040. Reefs are likely to become remnant between 2030 and 2040 in the Lakshadweep Sea and between 2050 and 2060 in other regions in the Indian seas. These projections take into consideration only the warming of seawater. Other factors such as increasing acidity of seawater are not considered. If acidification continues in future as it does now, all coral reefs would be dead within 50 years. Given their central importance in the marine ecosystem, the loss of coral reefs is likely to have several ramifications.

Fresh research studies have found out new areas of concern for fisheries due to increased global warming. Scientists from Indian National Centre for Ocean Information Services (INCOIS), a Ministry of Earth Sciences body and US National Oceanic and Atmospheric Administration (NOAA) have found that global warming is driving proliferation of Noctiluca algae (commonly known as sea tinkle), a harmful algae in Arabian Sea responsible for glowing of Mumbai's beaches in dark.

Noctiluca algae are parasites and compete with fish for food and choke their supply. It devours one of the most important planktonic organisms at base of fish-food chain, namely diatoms. It also excretes large amounts of ammonia, which causes massive fish mortality.

Warming of oceans due to global warming is increasing temperature difference among layers of sea water. This temperature differences has slowed the upward transport of nutrients like silicate from the ocean bottom, lowering its concentration at surface. Diatoms growing in surface water which need both sunlight and silicate to build their glass skeletons,fail to thrive when silicate is in short supply. On the other hand, Noctiluca algae remain unaffected by these changes and prey on remaining diatoms. Thus, the study shows that intensifying global warming conditions will disrupt fish-food chain and cause the decline of fisheries in the region.

Such newly emerging findings are adding to the concern and exposing the multifaceted effects of climate change which are yet to be ascertained and taken into account..

5. Impact of climate change on resource users

Climate change poses a significant threat to resource users, in particular, the fisher communities who are emotionally attached to their living environment as their livelihood is heavily dependent on sea.The impact of climate change in marineresource users includes, displacement of family members, food security issues, migration of fisher folk, fall in income level, seasonal employment, change inemployment pattern, increased fishing cost, reduction of fishing days etc.

a. *Demography and Social standards*: Displacement of family members increased over the years, the young generation has a tendency to move out of fishing. Food security issues increased rapidly in recent years. Disguised unemployment is rampant in all sectors since earnings from marine fisheries are not proportionate to the increase in fishers. This has instigated labour migration induced by the earning potential in the distant waters coupled with limited resources in their vicinity.

b. *Infrastructure sensitivity*: Increased frequency and severity of storms orweather, and sea conditions are unsuitable to fishing as well as damaging to communities on shore through flooding, erosion, and storm damage. Proximity to hazard areas makes the fisher households highly prone to disasters resulting in substantial property losses.

c. *Income Effect*: The income levels of fishers decreased substantially over the years. The employment pattern has been mostly seasonal, and alternate avocation options are minimal, there is also economic loss due to loss in number of fishing days. Changed fishing ground caused increased cost of fishing andfish storage. The fuel cost, the cost of fishing gear and boat are increasing significantly over the years.

The study conducted in the most climate change vulnerable marine hotspots of Kerala (Elamkunnapuzha and Poonthura) by Shyam et al. 2014 explains the problems and prospects of the inhabitants in the sector and the importance of Alternative Livelihood Options (ALOs) for climate change adaptation. Based on the assessment, it was understood that climate change has impacted coastal communities, mainly fisher communities. Around 70 per cent of them needed alternative livelihood option supports. The preferred alternative livelihood means include daily wages jobs, service industry, small scale industries etc. Coastal communities (75.95 %) are willing to participate in adaptation and mitigation programmes against climate change and majority (61 %) of the respondents would like to take part in individual climate change adaptation activities followed by household and social roles.

To tackle this problem of climate change it is imperative that the coastal communities be aware of its repercussions and are willing to participate at every stage of the planning process. To be effective, every climate change adaptation and mitigation strategy should be specific according to the needs of the community members. Climate change is an issue affecting large sections of the society and needs integration of plans at different levels viz., international, national, state, district, panchayat etc. Co-management of adaptation and mitigation strategies involving community members is going to have long term and sustainable effects in compacting climate change. Science and civil society must share their expertise, knowledge and capacity of action to be even stronger and more efficient to protect the ocean.

Coasts are experiencing the adverse consequences of hazards related to climate and sea level, extreme events, such as storms, which impose substantial costs on coastal societies (Shyam and Manjusha, 2015). The coastal regions around the globe are more prone to the impacts of climate change than the mainland. Fishing being one of the primary occupations of the coast, the fishermen community is the most vulnerable group to be affected by climate change. Adaptation for the coasts of developing countries will be more challenging than for coasts of developed countries, due to constraints on adaptive capacity. Climate change has the potential to affect all natural systems thereby becoming a threat to human development and survival socially, politically and economically. Beyond basic findings of levels of concern, awareness and belief in human impact on the climate, some recent studies have attempted to delve deeper into public attitudes about climate change. Furthermore, awareness of climate change is a prerequisite for adaption and mitigation plans and programs in any community. In addition, it is quite relevant to take advantage of the key informants within the community to disseminate the need for long term and short term adaptation and mitigation options to combat the climate change impacts and thereby making the community more resilient to climate change issues.

A study was carried out to assess the level of awareness of vulnerable fishing communities of Ernakulam district of Kerala, about climate change and to identify the level of adaptation and mitigation strategies available and adopted by them (Shyam et al., 2015). Njarackal (highly vulnerable village) and Ochanthuruth (moderately vulnerable village) were selected for the study. Across the villages, it was found that 98% of the respondents have heard about climate change at a time or the other however it was found that awareness about climate change was less than 40 percent. There is a discrepancy between hearing and awareness about climate change; hearing means only superficial knowledge about climate change. The significant sources of information were found to be different media, friends, and relatives. But awareness involves in depth understanding about climate change which indicate that the people know the causes, impacts, consequences, the societal need and commitment towards its preparedness, adaptation measures *etc*. The perception of the visible features consequent to climate change is the extent of their agreement to the variables such as sea level rise, temperature increase, change in wind pattern, extreme weather events, sea water intrusion, water scarcity, property loss, erratic weather, diseases etc. that affect them.

Knowledge on climate change among the respondents of both these villages was very shallow and pertained to short term happenings. Awareness on climate change is a prerequisite to initiate steps in combating negative impacts of climate change. Though changing climatic condition is a global concern, the possible mitigation options for improving adaptive capacity needs to be local. An integrated approach comprises of actions for addressing long term and short term concerns of the community, through grass root level actions which would have to be initiated in materialising local solutions to compact the cumulative impact of climate change.

GULLS (Global understanding and learning for local solutions), a four-year project that began in 2014 looked at the low-level of awareness on climate change among fishers in Kerala owing to the fact that such change issues were entangled with other developmental issues; thereby the community could not decipher anything other than loss in fishing days and extreme weather events that could be related to climate change.

A strategy was conceptualised for planning and implementing village level adaption and mitigation plan through sensitizing and improving the resilience of community towards climate change and initiating a multi stakeholders platform for developing a climate knowledge and information systems; CReVAMP' – "Climate Resilient Village Adaptation and Mitigation Plan". This is facilitated using a multi stakeholder governance model by bringing different stakeholders together to participate in the dialogue, decision making, and knowledge sharing and there by instigating knowledge generation process within the community during the process. This then is directed to create a village information system within the community, enable green fishing practices and prepare adaptation and mitigation plan for the community. This would, in turn, help in community empowerment, thus enabling in building resilient community /Climate Change Informed Fisher Community (CCIF). Through this process, they are expected to influence the society and government in decision making and actions related to climate change mitigation and would eventually be able to influence the policy- making process (Figure 2)

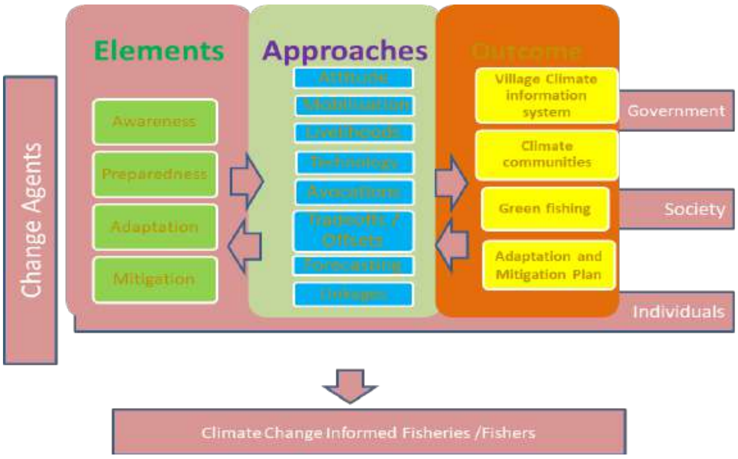

Figure 2: CReVAMP Framework

Two marine fishing villages in Kerala have been chosen to test a climate resilient village adaptation and mitigation plan (CReVAMP) for vulnerable coastal communities in tropical countries. Twenty four climate change hotspots, regions warming faster than the global average, have been recognised around the world. Each of these has a unique suite of species which inhabit them, and all are important to the countries surrounding them in supporting fisheries, tourism and in hosting important ecosystems.The hotspot area of south -west India comprises of four coastal districts (South Zone: Thiruvananthapuram & Kollam and Central zone: Ernakulam and Alapuzha), and the rationale behind the selection of this particular location is i) It falls within the upwelling ecosystem of the south-west coast of India, ii) this region has rich diversity and supports substantial marine and estuarine fisheries iii) identified as major spawning gyre of many pelagic species based on fish and larval surveys iv) has extensive system of backwaters.

The study titled GULLS covered spatial scales across southern Africa, western and southern Australia, Mozambique Channel and Brazil in addition to South India. The climate change vulnerability of over 1,000 fishermen households in two major fishing villages of Kerala (Elamkunnapuzha in Ernakulam and Poonthura in Thiruvananthapuram) was assessed. Exposure, sensitivity and adaptive capacity were the pertinent factors that determine the vulnerability. The method used was a structured household questionnaire. The coastal population was categorized as low, moderate, high and very high on their vulnerability scores and a geospatial analysis was attempted.

A composite vulnerability index approach was used in this study to evaluate relative exposure, sensitivity, and adaptive capacity. The mean values of the three sub-indices of Exposure (E), Sensitivity (S), and Adaptive Capacity (AC) were combined to develop a composite vulnerability index by using the following additive (averaging) equation.

Vulnerability (V) = Exposure (E) + Sensitivity (S) - Adaptive Capacity (AC)

The salient finding of the study was that the overall vulnerability could be reduced only by increasing the adaptive capacity of the population.It is against this backdrop that 'Blue economy' has emerged as a commonly acceptable development paradigm which has effectively blended economic growth with sustainable development.

Blue economy refers to marine-based sustainable economic development which leads to improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. Integrating climate change and blue economy can open up fresh opportunities and solutions which will help these vulnerable coastal communities to become resilient to climate change impacts (Figure 3).

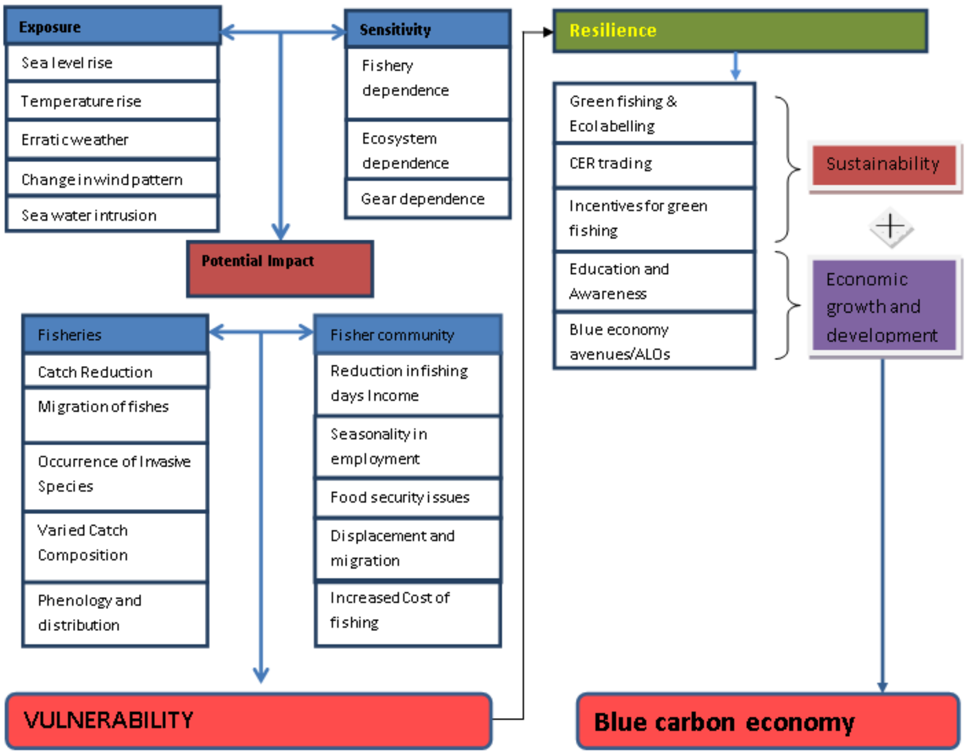

Figure 3: Integrating climate change and Blue Economy in Marine fisheries

6. Blue Economy Avenues

Blue economy is going to be the source of many alternative and climate change resilient avenues that is going to lift the environment, resources and the resource users out of the unsustainable ecosystem that exists today. Blue economy guarantees a green perspective to the maritime economy which is presently seen as a means of free resource extraction and waste dumping. It seeks to take into cognisance the cost of all negative externalities including environmental degradation and ecological imbalance. In short, it postulates a complementary apparatus to the existing brown model of ocean economy (WWF, 2015).

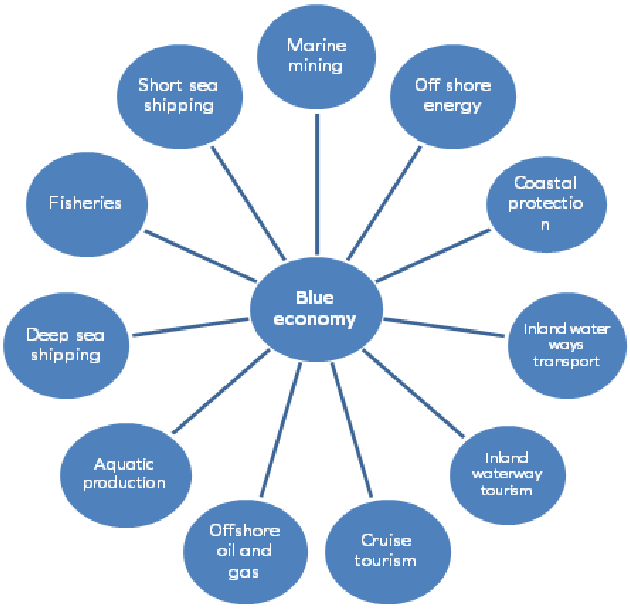

Figure 4: Blue Economy Avenues

The Way Forward

Climate change as a phenomenon should not get restricted as subjects of discussions for scientists and researchers and a topic of debate for the political and environmental bodies. It should be considered as a serious issue having enormous repercussions, many of which are yet to be found out. Concerning mitigation, the distinction enshrined in the Convention between Annex I (Developed) and non Annex I (developing) Parties must be maintained in accordance with the principles of Equity, CBDR (Common but Differentiated Responsibilities) and other provisions of the UN Conventions. The 'developing versus developed country' schism needs to be diluted at the earliest and Developed Countries should avoid watering down the CBDR principle envisaged in earlier agreements.

Politics and power struggle to control resources need to be set aside so that the most vulnerable sections in the society, who are get affected more by climate change impacts, are assured that they will be safe to pursue their lives and livelihoods. Mechanisms to anticipate and deal with climate change should be jointly developed by all the countries in the world and incorporated well in advance. Measures to prevent elite networks to capture and misuse land, water and other resources should be identified. Equity issues are primary to address the vulnerabilities and costs while framing policies and strategies to tackle climate change. Policies on adaptation should also consider the multiple scales of effects. Integrating adaptation and mitigation will increase the local legitimacy of the plan, as adaptation puts emphasis on local needs.Climate change is no unidirectional issue; it has effects on both the resources and resource users. Thus the adaptation to climate change impacts should ensure that the multifarious impacts it brings along can be tackled.

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16

Climate change and freshwater security in coastal ecosystem

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ABSTRACT

Water is the primary medium through which climate change impacts trickle-down to the people. In many regions, changing precipitation or melting snow and ice are altering hydrological systems and affecting water in terms of quantity and quality, which influences almost all aspects of the economy including drinking water, sanitation, health, food production, energy generation, industrial manufacturing, and environmental sustainability. Coastal areas which are already facing multiple anthropogenic-related environmental challenges are more vulnerable. Floods, rising sea levels and other coastal calamities contaminate freshwater sources, damaging water infrastructures for drinking water supply, wastewater collection and treatment systems. In coastal areas when more freshwater is removed from rivers and aquifers, saltwater will move farther upstream into the river mouth and the aquifer. All these challenges are putting high pressure on the limited freshwater available on the coast and forcing water managers to seek costly alternative options including desalination plants. Water resources in the South and South East Asian coast, including Indian coast, are vulnerable to climate change. India has come up with climate change adaptation and mitigation strategies and appropriate policy measures for managing its coastal ecosystems. However, effective policies for preserving scarce resource like freshwater in the coast in an era of climate change needs to be appropriately framed and implemented with the support of local government and public.

1. Introduction

Water is an important natural resource essential for human existence, social wellbeing and stability of ecosystems. Water is required to sustain our life and health, agriculture (food security), energy production, navigation, recreation, and manufacturing different consumer products. Competing uses for water put more pressure on the available resources in a country. These stresses may be exacerbated further by climate change induced events. In many areas, climate change is likely to increase the demand for water while simultaneously shrinking the water supplies. This shifting balance (water deficit) might be a challenge to water resources managers to frame appropriate allocation strategies or simultaneously meet the needs of the growing numbers of users. In some areas, increases in rainfall/runoff may lead to flooding and adversely affect water quality and even damage water infrastructure and water supply systems.

Water cycle is a delicate balance of precipitation, evaporation, and all processes in between. Warmer temperatures increase the rate of evaporation of water into the atmosphere, in effect increasing the atmosphere's capacity to "hold" water. Increased evaporation may dry out some areas and fall as excess precipitation on other areas. According to the USEPA (2018), changes in the amount of rainfall during storms provide evidence that the water cycle is already changing. Over the past 50 years, the amount of rainfall during very heavy precipitation events has increased. Warming winter temperatures cause more precipitation to fall as rain rather than snow. Furthermore, rising temperatures cause snow to begin melting earlier in the year. This alters the timing of the stream flow in rivers that have their sources in mountainous areas. When the atmospheric temperatures rise, people and animals need more water to maintain their health and thrive. Besides, many important economic activities, like raising livestock, growing food crops, and producing hydropower energy are also require more water. In other words, the amount of water available for various activities may be reduced when global warming continues and competition for water resources increases at an alarming rate.

Even if climate change impacts on water persist, their magnitude may vary from place to place, based on the geographical locations and the level of population density; and coastal areas is one of these zones categorized as more vulnerable to climate change impacts. Coastal zone comprises a continuum of aquatic systems and a continental shelf is the most taxonomically rich and productive of ecosystems (buffer-zone) on earth. It contains a wide diversity of assets including human, physical and biological ones. In view of the rich resources, the coast has attracted human settlements and various economic activities from time immemorial. A number of mega cities and other urban settlements and industries are located on the coast. However, due to population growth, urbanization, industrial development, and trade and capital flow, coastal zones are facing multiple environmental challenges which impact the coastal ecosystem significantly. Freshwater security is one of the major challenges.

In the coastal zones, locally available freshwater is inadequate for meeting various demands. Since coastal zones are more vulnerable to climate change impacts, freshwater resources along the coastal and island regions face risks from sea level rise. Rising sea level and the occurrence of drought can increase the salinity of both the surface water and groundwater through saltwater intrusion. This may force water managers to seek other sources of freshwater, or go for desalination plants. In addition, when more freshwater is removed from rivers for human use, saltwater will move farther upstream in the river mouth. Water infrastructure in coastal cities, including drinking water supply, sewer systems and wastewater treatment facilities are under serious risks from rising sea levels and various other coastal calamities. Climate change induced unexpected floods also contaminate the freshwater sources in coastal areas.

As coastal zones are more sensitive and vulnerable to climate change, freshwater issues in the coastal areas must be emphasized in the climate change adaptation strategies and coastal zone management programs. This chapter examines the freshwater issues in coastal areas in the context of climate change, with emphasis on the changes in the hydrological cycle and freshwater vulnerability. Further, appropriate strategies for water security in the context of climate change are also proposed.

2. Impact of Climate Change on Hydrological Cycle and Water Sector

According to Intergovernmental Panel on Climate Change (IPCC, 2013), warming of the climate system is unequivocal and since the 1950s, many of the observed changes are unprecedented over decades to millennia. During this period, atmosphere and ocean have warmed, amounts of snow and ice have diminished, sea level has risen, and concentrations of greenhouse gases have increased. Water is an integral component of climate change and the primary medium through which climate change impacts manifest. Climate change directly affects water cycle and the quantity and quality of water resources available to meet human and environmental demands. It can lead to both floods and drought.

Many countries are already facing multiple water challenges compounded by climate change. Rising sea levels have a serious effect on coastal aquifers, a major source of fresh water. Increasing water temperatures and changes in the rainfall pattern exacerbate the water crises further. Even if greenhouse gas concentrations stabilize in the coming years, some impacts from climate change (increasing water stress, more extreme weather events and population migration) are unavoidable. One can consider that, carbon is a measure of the anthropogenic causes of climate change and water is a measure of its impacts (United Nations, 2009).

Water and its availability in various forms is the result of the complex natural process known as the water/hydrological cycle. From time immemorial this cycle was in equilibrium, where anthropogenic pressure on nature was nil/limited. However, recent decades have witnessed tremendous population growth and economic development. Global warming, which leads to climate change, is one of the outcomes of the excessive emission of greenhouse gases into the environment.

Changes in the atmospheric concentration of Global Green House Gases (GHG) and aerosols, land cover and solar radiation alter the energy balance of the climate systems and are drivers of climate change. According to an IPCC (2007) report, GHG emissions have grown by 70% between 1970 and 2004. Global warming had critical effects on the hydrological cycle, altering the amount, distribution, timing, and quality of the available water, which in turn, has affected the fresh water requirements of various sectors (domestic, industrial, agriculture, and ecosystems) and its socio-economic repercussions are numerous.

Due to climate change, water cycle is expected to undergo significant change. A warmer climate causes more water to evaporate from both land and oceans; in turn, a warmer atmosphere can hold more water, roughly four percent more water for every 1°F rise in temperature (**Union of Concerned Scientists,** 2018). These changes are expected to lead to negative consequences on the water sectors, with increased precipitation and runoff (flooding) in certain areas and less precipitation and longer and more severe scarcity of water (droughts) in other areas. Hence, wet areas are expected to become wetter and dry areas drier.

Wetlands (rivers and lakes) and aquifers are the major sources of water, affected by the regional climate change. Warming of lakes and rivers in many regions affects thermal structure and water quality. Wetlands cover around 6% of the earth's terrestrial areas and provide invaluable services and benefits for the human population in multiple ways. Increased temperatures would adversely affect sensitive plants and animal species in the wetlands. Decreased precipitation in wetland areas would result in the shrinking of wetlands that will release more carbon into atmosphere due to decay of organic matter. Variations in the water flow may lead to a shift in the geographical distribution of wetlands, and the water availability/level will influence the nature and function of wetlands (Tiwana et. al., 2010).

According to IPCC (2013), changes in the global water cycle in response to the warming during the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions. Globally, about one-third of the top 200 rivers (ranked by their river flow) show statistically significant trends (during 1948–2004), with more rivers having reduced flow than rivers with increased flow.

Declining water quality is another consequence of climate change and is a major concern in the coastal zone, where freshwater availability is limited. Due to greenhouse gases, as air temperature rises, the water temperature will also rise in streams, lakes, and reservoirs. This tends to lead to lower levels of dissolved oxygen in water and increase stress on the aquatic animals. Further, high precipitation led runoff in certain regions can wash more pollutants into waterways. This includes: sediments, nitrogen from agriculture, disease pathogens, pesticides, and herbicides. Naturally, the pollution load carried by streams and rivers will be deposited largely in downstream water bodies (lakes, ponds, estuaries etc.,) in coastal areas and the ocean. Heavy runoff can produce harmful algae and bacteria in the coastal zones (**Union of Concerned Scientists,** 2018). The ultimate impact of pollution in coastal areas is freshwater bodies losing their drinking water function.

Groundwater is another source of freshwater, which plays a dominant role in coastal areas. A UNESCO study revealed, that throughout history groundwater has been integral to human life and livelihoods, and for stable agricultural production in the face of water resources' variability. But groundwater stock (aquifer) is only a small fraction of the overall water available, and is not evenly distributed around the world. Of the total annual precipitation of 577,000 cubic kilometres (km^3) per year, 79% falls in the ocean, 2% in the lakes and 19% on land. Most of it evaporates or runs-off into streams and rivers. Only 2,200 km^3 (2%), infiltrates into aquifers as groundwater (UNESCO, 2009).

However, in recent decades use of groundwater is increasing, and in South Asia the subsidized rural electrification to meet irrigation demands, has been a key driver of groundwater use, especially in dryland areas with no surface water services. Apart from irrigation, groundwater is also a major source for domestic (both rural and urban) and industrial water supply around the world. In India, at present, more than 85% of the domestic water supply in rural areas, about 50% of the water requirements in urban areas (domestic and industries) and more than 55% of the irrigation water requirements are being met from groundwater (Romani, 2007). But our groundwater sources are under threat due to rainfall variations. Persistent drought leads aquifers to get drier, and high precipitation- induced flash floods (rather than moderate run in longer durations) will reduce the possibilities of water percolation.

According to Foster and Chilton (2003), the development of the power-driven pump in the mid-20th century led to the emergence of many groundwater-dependent economies, and recently to warnings of the potential adverse impacts of excessive abstraction and aquifer pollution. Over-extraction of groundwater is a serious concern, particularly in coastal areas, where other freshwater sources are limited. Local aquifer studies concluded that where groundwater services are in heavy demand, much of the good quality groundwater has already been used up.

According to Cramer et.al, (2014), regional water balance is the net result of gains (precipitation, ice and snow melt, river inflow, and groundwater recharge) and losses (evapotranspiration water use and river outflow, and groundwater discharge). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of solar radiation, surface temperature, vegetation cover, soil moisture, and wind, is affected not only by the changing climate, but also by changing vegetation processes and land cover. Generally, climate change drivers have increased the frequency and the magnitude of flood leading to loss of property and life, water pollution by way of overflow of sewage systems and damage to agricultural areas and livestock. Rising temperatures and lack of rainfall increase the frequency and magnitude of droughts. The overall impacts could be scarcity of drinking water, decreased food production, loss of ecosystem and biodiversity.

3. Climate Change Vulnerability in Coastal Zones

Geographical locations of coasts (fag end of land and areas adjacent to the sea) make them more vulnerable to any climate change impacts. Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010. It is virtually certain that the upper ocean (0–700 m) warmed from 1971 to 2010. The rate of sea level rise since the mid-19thcentury has been higher than the mean rate during the previous two millennia. Over the period 1901 to 2010, the global mean sea level rose by 0.19 m. The global oceans will continue to warm during the 21stcentury. Heat will penetrate from the surface to the deep ocean and affect ocean circulation. The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in the last many years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions, and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification (IPCC, 2013). Broadly, coastal systems are influenced by many anthropogenic and natural processes. Among these, climate-related drivers are changes in ocean temperature, salinity, pH and sea level.

Cramer et.al, (2014), also stated that the frequency of extreme temperature events in coastal waters has changed in many areas. Seawater pH spans larger ranges and exhibits higher variability near the coastlines, and anthropogenic ocean acidification can be enhanced or reduced by coastal geochemical processes. The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of sea water by about 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes. These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as a result of human activities. Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions.

Global sea levels have risen between 17 to 21 cm during the period 1901 to 2010, and are predicted to rise a further 26 cm to 98 cm by 2100 (IPCC, 2014). The rate of relative sea level rise in the Bay of Bengal (between 1977 and 1998) was 4.0 to 7.8 mm/year which is much higher than the global average of 1.8 ± 0.3 mm/yr. The rate of sea level rise is generally higher along the India–Bangladesh–Myanmar coast (> 4 mm/yr) compared to the Thailand–Vietnam coast (ca. >1.5 mm/yr) (Church et al., 2004). The coastal region of South and South Eastern Asia is vulnerable to sea level rise, and could lose around 10 % of the land area by 2100 (Nicholls and Mimura, 1998), which would increase the risk of drinking water salinization to a considerable extent.

Throughout the world, the rate of shoreline erosion is increasing. Coastal lagoons and estuaries, as well as deltas, are highly susceptible to alterations of sediment input and accumulation. Ocean warming has contributed to observed range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (Cramer et al., 2014). Any changes in coastal wetlands and mangroves have a direct impact on freshwater availability, as wetlands act as a source of freshwater and mangroves save the freshwater bodies and/ aquifers from seawater intrusion.

Total damages from coastal flooding have increased globally over the last decades.

Recent global and regional studies have found that the increasing frequency of extreme water levels affecting coastal infrastructures observed so far, are related to the rising mean sea level rather than to changes in the behavior of severe storms. While the vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well documented, there is a shortage of studies discussing the role of climate change in observed impacts on coastal systems. Cramer et.al, (2014) stated that increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and small islands, though the contribution of climate change to this is not clear. But, both climate change impacts on the physiological and ecological properties of fish and vulnerability of coastal communities and fisher-folk to climate fluctuations and change are well established in the literature.

It is very clear that the global mean sea level will continue to rise during the 21st century, and the rate of sea level rise will very likely exceed that observed from 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. The occurrence of coastal calamities (cyclone, wind, tsunami, tidal waves etc.) is frequent along the coast and its implications are multifold and become alarming threats to coastal communities' life, infrastructure (buildings, roads, etc.), economic activities and ecosystems. When sea levels rise, more saltwater will be driven into the freshwater sources, creating problems for the coastal communities and the administration. Farmers are sacrificing their agriculture. Households are compelled to find alternative sources of water for drinking and other domestic purposes. The local administration is forced to import freshwater from distant sources or treats the contaminated water, which is a cost-intensive process. In future, climate-driven changes will affect the water sector and human lives, in coastal areas to a greater extent.

4. Water Resource Scenarios in the South and South East Asian Coast

Generally, coastal regions, where land and sea-water meet, are ecologically dynamic and sensitive with high resource potential and tremendous scope for economic development. Hence, population in coastal areas, particularly cities, is increasing. Major economic/commercial activities (ports, jetties, trade, ship building/breaking, export based manufacturing, oil refinery, petroleum based industries, agriculture, salt production, tourism, fisheries, fish processing, aquaculture etc.) are attracted to the coast. However, all these activities may impose tremendous pressures on the coastal ecosystems and the demand for freshwater is one of them.

According to Villholth (2013), in South and South East Asia, groundwater is the dominant source of drinking water, frequently providing >50 % of the total demand, with the remainder coming from surface water bodies and harvested rainwater. Generally, the Asian coast has a high potential for groundwater resources due to its unconsolidated to semi-consolidated Quaternary sediments in multi-aquifer settings. However, relatively shallow groundwater (depths <150 metres below ground level -mbgl) is generally impacted by high natural salinities and naturally occurring arsenic, while in some areas, deep groundwater (>150 mbgl) is fresh and arsenic free. Due to high groundwater salinity, the coastal population relies on multiple sources to meet its drinking water demands. Harvested rainwater *stored in large jars, communal tanks and surface water ponds* at the ground level, plays a vital role in coastal areas. However, once the stored rainwater is used up, or when pond water becomes too saline and/or resource-limited from evaporation losses, people then inevitably rely on relatively saline tube-well and/or river water sources (Hoque et al., 2016).

In coastal and rural settings, freshwater, particularly for drinking purpose, is provided by multiple sources (rainwater, surface water, or groundwater) and managed at the individual or local community level. According to Hoque et al. (2016), the coastal and near-inland drinking water resources in South and South East Asia are vulnerable to contamination from seawater, in particular during episodic inundation events. Such events include: storm surges (mostly due to cyclonic tropical storms); tsunamis (undersea earthquake); inland flooding (due to excessive rainfall), and shallow coastal flooding (due to extreme tide). The severity of inundation events is often determined by the elevation and geomorphology of the associated coastal segment. Broadly, the impacts by inundation are more in the areas where the population density is high. Hence, the availability of fresh/drinking water in coastal areas depends on multiple factors such as: volume of rainfall, availability of fresh groundwater and population density. Studies reveal that climate change is likely to further intensify these impacts due to sea level rise, increased sea-surface temperature, and more intense rainfall (Karim and Mimura, 2008).

Hoque et al. (2016) assessed the spatial vulnerabilities to salinisation of drinking water sources due to meteorological variability and climate change along the coastline of South and South East Asia. The risks of increasing climatic stresses were considered, and then maps of relative vulnerability along the entire coastline were developed, using data from the global scale land surface models, along with an overall vulnerability index. The inferences of the study include:

- There is a high risk of salinisation of drinking water in more than 35,000 km^2 near-inland and coastal areas. Consequently, it is estimated that more than 25 million people, within 30 km from the coast, are living in highly vulnerable areas, while another 30 million people are living in moderately vulnerable areas.
- The “surface and near-surface drinking water in the coastal areas of the mega-deltas in Vietnam and Bangladesh-India” are the most vulnerable, putting more than 25 million people at risk of drinking ‘saline’ water. Climate change is likely to exacerbate this problem, with adverse consequences for health, such as prevalence of hypertension and cardiovascular diseases.
- The relative vulnerability assessment indicates that the vulnerability of drinking water to salinization is the highest along the deltaic segments, and this is primarily due to low coastal elevation, and the associated geomorphology.
- The upstream withdrawal of water in Asian rivers has increased substantially since the 1950s and has already resulted in increased river salinity and landward intrusion of saline water in the Bengal delta.
- Around 80% of its coastal mangrove-forest has been replaced by rice paddies and shrimp farms.
- Economic activities in coastal and upstream areas have a direct link to coastal hazards, in particular, the construction of dams or major abstractions of water for irrigation.

5. Indian Coast: Economic Scope and Freshwater Issues

India has about 7517 km. of coast line located in 9 states and 4 union territories spread over 75 districts; that is 35% of the total districts in the country (Figure 1). Gujarat and Andhra Pradesh have the longest coastline, followed by Tamil Nadu, Maharashtra, Kerala, Odisha, Karnataka, Goa and West Bengal. India has an exclusive economic zone (EEZ) area of 2.02 million sq. km, comprising 0.86 million sq. km on the west coast, 0.56 million sq. km on the east coast and 0.6 million sq. km around the Andaman and Nicobar islands (Sanjay, 2011).

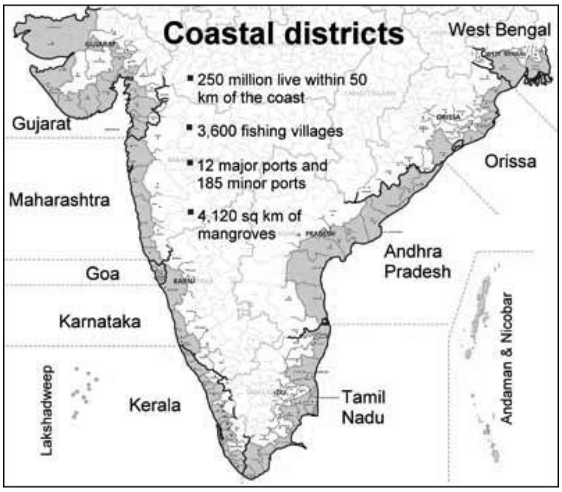

Figure 1: Coastal Area (Districts) in India
Source*:* Resources Research (2018)

Indian coastal ecosystems, comprising of mudflats, sandy beaches, estuaries, creeks, mangroves, coral reefs, marshes, lagoon, sea grass beds, sandy and rocky beaches, extend to 42,808 sq. km. They are also known for their high biological productivity, which provides a wide range of habitats for many aquatic flora and fauna. India has 31 established Coastal and Marine Protected Areas and several species have been listed under the Wildlife (Protection) Act 1972 (MoEFCC and GIZ, 2014). Coastal zones are continuously changing because of the dynamic interactions between the ocean and the land. Erosion and accretion, inundation due to sea level rise and storm surges, and shifting of shoreline caused by natural or anthropogenic forces, such as construction of artificial structures, ports and harbours lead to changes in the coastal zone and its environment (MoEFCC, 2015).

According to Sanjay (2011), "most coastal states in India have not been able to maintain the balance between economic growth and ecosystem quality, with the result that they are facing serious problems with respect to life and livelihood of coastal population on one hand and sustainability of the coastal activities on the other hand". The Indian coast has been experiencing rapid urbanization and industrialization, which has long historical roots. From the 15th century onwards, different European nations established their colonies and / or settlements on the Indian coast (Figure 2). Later, these settlements emerged as important cities in India. Currently, some of these have become mega cities. Their progress has been substantial during the post independent era, particularly during the post-liberalization period.

However, the country's coastline is facing various anthropogenic induced challenges including climate change. Even if the precise demarcation of the climate change impacts on coastal ecosystems is difficult, one can attribute the climate change impacts in the light of increasing coastal calamities in recent decades. According to MoEF&CC and GIZ, (2014), the major human-induced drivers of coastal ecosystem degradation include, habitat (coastal fragile land) conversion to other forms of land use, overexploitation of resources and associated destructive harvesting practices, spread of invasive alien species, pollution from agricultural, domestic and industrial effluents and climate change. Most of these issues are affecting the freshwater sources in coastal areas and freshwater availability has become an emerging challenge. The freshwater issues in Chennai, one of the age-old coastal cities in India, flag interesting insights.

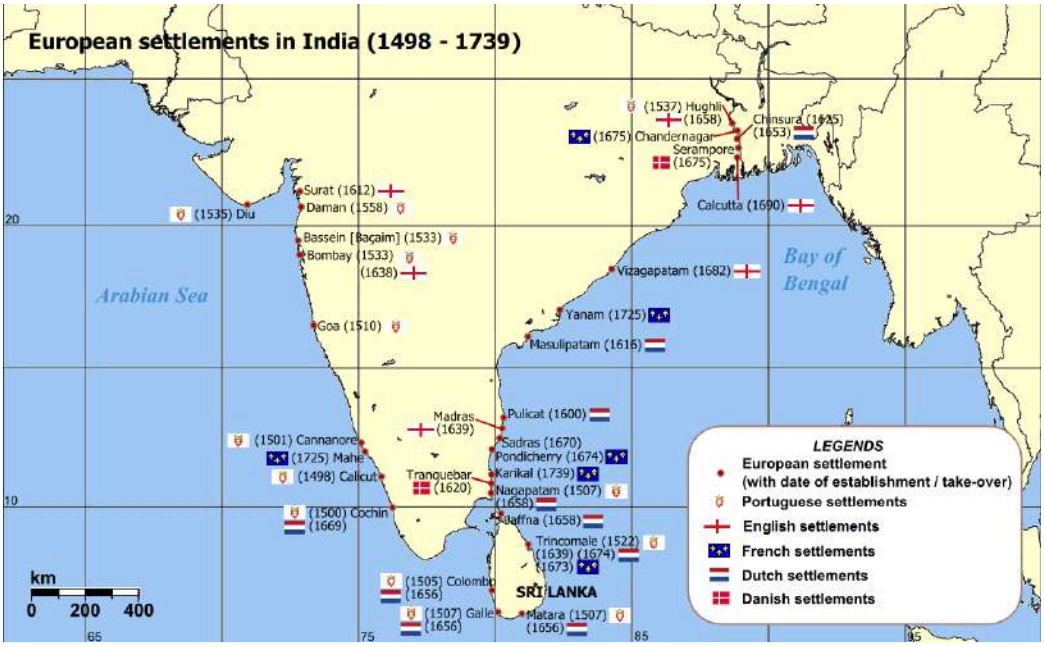

Figure 2: European Settlements in Indian Coast Source: Wikipedia (Colonial India), (2018)

Figure 3: Chennai Metropolitan Area
Source: Discover Ideas about City Maps (2018)

The Chennai Metropolitan Area's (Figure 3) growth has been rapid since the 1970s. Its population has increased from 3.5 million (1971) to 5.8 million (1991) to 9.8 million (2011). Besides the permanent residents, the number of migrants and floating population is also high in Chennai. The estimated population of Chennai during 2026 will be 12.6 million. The provision of water for the ever growing urban population is a challenge to the city administration. Rapid urbanization, with the expansion of residential, industrial and business establishments, has put significant pressure on the water sector of the city and its periphery. Chennai gets an average annual rainfall of 1290 mm. In the urban areas, only about 5% of the rainfall seeps into the ground (Nelliyat, 2016b). Chennai receives about 985 million liters per day (mld) from various sources against the required amount of 1200 mld. The average availability of water in the city (90 litres/capita/day - lpcd), is the lowest compared to the other Indian cities (270 lpcd in Delhi, 220 lpcd in Pune). Each summer, when the stock in the storage reservoir reduces, the city faces severe scarcity problems.

There are huge supply-demand gaps in the Chennai water supply and the deficit during the period from 2005 to 2008 ranged from 38% to 58%. The deficit is primarily met through either extraction from the local aquifer or through transported groundwater from the sub-urban areas of Chennai (Nelliyat, 2016b). Ground water extracted from sub-urban areas is being supplied by private tankers to different users in the city. Private operators have agreed to fix Rs. 2,200/- as a rate to supply.

20,000 litres of water and Rs. 1,200/- for 12,000 litre tankers (The Hindu, 2015a). The projected water requirement for the Chennai Metropolitan Area during 2026 will be 2,248 MLD. Based on the present scenario, meeting such a huge demand is a great challenge. Now, the government is also considering costly options, like seawater desalination devices and has set up two plants, with 100 MLD capacities each at Minjur and Nemmeli.

Studies done by the Centre for Water Resources, Anna University (as part of the Crossing Boundary Programme on IWRM) in the coastal city of Chennai, reveal the following insights:

- Unplanned urbanization with unscientific land use changes has created enormous impacts on Chennai's water sector. Mobilizing huge quantities of water for meeting the increasing urban need is a big challenge. The public water supply system is unstable as the sources are highly uncertain.
- Freshwater sources in most parts of the city are severely contaminated. The deterioration of groundwater and surface water sources in the city and its suburbs is due to the indiscriminate discharge of sewage, industrial effluents and poor disposal of solid wastes.
- The groundwater quality analysis indicates that water is often not suitable for domestic purposes, particularly drinking. However, socially vulnerable communities are compelled to use this water and as a result are exposed to various water borne diseases.
- Solid wastes are disposed in low-lying public lands and groundwater pollution in the surrounding areas is severe due to leachate transfer.

- The multi-functionality of the socio-ecological services (including the freshwater provision) of water bodies has diminished considerably. Many of them have been filled for various developmental purposes and the urban poor are the ones who suffer the most from these developments.
- Urbanization with rigorous land use changes has significant impacts on storage structures and drainage canals, which have historically discharged flood water to the sea.
- The Pallikaranai marsh (with its cascading tanks) and the Buckingham canal used to play a significant role in moderating the floods in South Chennai. Recently, the marsh has been considerably encroached upon and only 10% of its original area exists. Its storage capacity has reduced from 55.78 Mm^3 to 14.73 Mm^3.
- The reduction in the natural recharge options not only increases the runoff in the city but also reduces the scope of the groundwater recharge. In areas where public water supply is not sufficient or does not exist, people depend on peri-urban groundwater transferred through tankers and packaged cans (where the access depends on the consumers' ability to pay).
- This informal water market has led to excessive exploitation of groundwater in the suburban areas, including the coastal belts. In many areas, the groundwater table has diminished and water quality has deteriorated, which adversely affects the livelihoods of marginal farmers and agricultural labourers.
- The coastal areas of the city are experiencing sea water intrusion even up to 10 km from the coast (See Box 1).

The Chennai case clearly revealed the freshwater issue of the coastal city from anthropogenic perspectives. However, the influence of climate change on the city's water crisis is not specifically assessed. In brief, the freshwater scenario in coastal India should be considered seriously in the light of climate change and should be integrated in various coastal programmes and policies.

India has come up with appropriate policy measures for managing its coastal ecosystem and ensures the welfare of coastal communities. The Coastal Regulation Zone (CRZ) Notification, 2011 and Island Protection Zone (IPZ) Notification, 2011 have been issued under the Environment (Protection) Act, 1986. The Coastal Regulation Zone (CRZ) Notification, 2011 was issued with three specific objectives: (a) to ensure livelihood security to fishing communities and other local communities living in coastal areas, (b) to conserve and protect coastal stretches, their unique environment and the marine area, and (c) to promote sustainable development based on scientific principles taking into account the dangers of natural hazards in the coastal areas, and sea level rise due to global warming (MoEFCC, 2015).

Box 1:
Seawater Intrusion Plagues Minjur

Overexploitation of groundwater has led to increased salinity in areas around Minjur and Panchetti at North Chennai. Farmers in the region struggle to cultivate crops. Public water supply is the only source for drinking and other domestic purpose as groundwater has been saline for years now. A three-year-study made by the Department of Geology, Anna University, in the Minjur-Ponneri belt reveals that the seawater had intruded up to 14.7 km into land this (2015) May. However, during 2007 the seawater intrusion was recorded till 10 km into land near Minjur belt. More salt pans, which were confined to areas closer to the coast, have come up in the region as salinity has increased in the groundwater. As per the study; "even if there is over-exploitation of groundwater sources in Poondi located about 50 km away from the coast; it will have an impact on Panchetti and Minjur belt and increase seawater ingression in Araniar-Kosasthalaiyar river basin. This is because the aquifer formation is the same in the region. The government may increase the number of check dams, increase the level of existing check dams and also encourage farmers to create percolation ponds to mitigate impact of seawater intrusion and recharge groundwater".

Source: The Hindu (2015b)

6. Climate Change Impacts on the Indian Coast and Water Security

India's initial National Communication 2004 (NATCOM 1) to UNFCCC has observed the following changes in climate parameters:

1. At the national level, an increase of 0.4°C has been observed in surface air temperatures over the past century. A warming trend has been observed along the west coast, in central India, the interior peninsula, and north-eastern India. However, cooling trends have been observed in the north-west and parts of south India.
2. Regional monsoon variations have been occurring in the country. A trend of increasing monsoon seasonal rainfall has been found along the west coast, northern Andhra Pradesh, and north-western India (+10% to 12% of the normal over the last 100 years), while a trend of decreasing monsoon seasonal rainfall has been observed over eastern Madhya Pradesh, north-eastern India, and some parts of Gujarat and Kerala (-6% to -8% of the normal over the last 100 years).
3. More frequent droughts have been observed (in multi-decadal periods), followed by less severe droughts.
4. There has been an overall increasing trend in severe storm incidence along the coast at the rate of 0.011 events per year.
5. An analysis of the daily rainfall data revealed: (i) a rising trend in the frequency of heavy rain events and (ii) a significant decrease in the frequency of moderate events over central India from 1951 to 2000.
6. An analysis based on the records of coastal tide gauges in the north Indian Ocean for more than 40 years revealed that the sea level rise was between 1.06-1.75mm per year. (These rates are consistent with the 1-2mm per year global sea level rise estimates of the IPCC).
7. The Himalayas possess one of the largest resources of snow and ice and its glaciers form a source of water for perennial rivers such as the Indus, the Ganga, and the Brahmaputra. Glacial melt may impact their long-term lean-season flows, with adverse impacts on the economy in terms of water availability and hydropower generation (Prime Minister's Council on Climate Change, 2008).

While considering the increasing trend of the GHG emissions in the country, the Prime Minister's Council on Climate Change, (2008) made some projections on climate change for the 21st Century. More warming is expected in the northern parts of India, The possibilities of increasing summer monsoon intensity has been derived for the period beginning from 2040 and by 10% by 2100. The possibilities of changes in frequency and/or magnitude of extreme temperature and precipitation events are high. The Ganga and the Indus benefit from melting snow in the lean season, but it is likely to be affected by the decrease in snow cover. A decline in run-off by more rivers - more than two-thirds - is also anticipated. Due to sea level rise, the fresh water sources near the coastal regions will suffer saline intrusion.

Changes in temperature and rainfall have significant effects on the productivity of agricultural and related sectors (lower yields from dairy cattle and decline in fish breeding, migration, and harvests). Changes in climate may alter the distribution of important vector species (for example, malarial mosquitoes) and may increase the spread of such diseases to new areas. 77% of the forest areas in the country are likely to experience a shift in forest types.

Heavily populated regions such as coastal areas are exposed to climatic events, such as cyclones, floods, and drought and large declines in sown areas in arid and semi-arid zones occur during climate extremes. About 40 million hectares of land are in flood prone areas and may affect about 30 million people on an average each year. A mean Sea Level Rise (SLR) of 15-38cm is projected along India's coast by the mid-21st century and of 46-59 cm by 2100. The intensity of tropical cyclones may increase, which poses a heavy threat to the populated coastal zones in the country (Prime Minister's Council on Climate Change, 2008).

In this context, the Government of India took some adaptation and mitigation actions and the steps taken in the water sector and coastal areas are summarized below. The National Water Policy (2002) stresses that non-conventional methods for the utilization of water, including inter-basin transfers, artificial recharge of groundwater, and desalination of brackish or sea water, as well as traditional water conservation practices like rainwater harvesting, including roof-top rainwater harvesting, should be practiced to increase the utilizable water resources. Many states now have mandatory water harvesting programmes in several cities.

In coastal regions, restrictions have been imposed in the area between 200m and 500m of the HTL (high tide line) while special restrictions have been imposed in the area up to 200m to protect the sensitive coastal ecosystems and prevent their exploitation. This simultaneously addresses the concerns of the coastal population and their livelihood. Some specific measures taken in this regard include construction of coastal protection infrastructure and cyclone shelters, as well as plantation of coastal forests and mangroves. Generally mangroves protect the coastal aquifer, an important source of freshwater, from the sea water intrusion (Prime Minister's Council on Climate Change, 2008).

7. India's National Action Plan on Climate Change and National Water Mission

India is one of the rapidly developing economies of the world. The country possesses around 18% of the world population with only 2.4% of the world's geographical area and 4% of renewable water resources. Indian economy is closely linked to its natural resources and climate sensitive sectors, such as agriculture, water and forestry. Hence, the possibilities of climate change impacts to the economy and livelihoods of people are huge. Achieving economic growth by controlling the greenhouse gas emissions is an emerging challenge. In this context, India has come up with its National Action Plan on Climate Change (NAPCC) with the intention of adapting to climate change and enhancing the ecological sustainability of the country's developmental path. Recognizing that climate change is a global challenge, India is engaging actively in multilateral negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) in a positive, constructive and forward-looking manner. According to the Prime Minister's Council on Climate Change (2008), the objective of NAPCC is to establish an effective, cooperative and equitable global approach based on the principle of common but differentiated responsibilities and respective capabilities, enshrined in the UNFCC. India is determined that its per-capita greenhouse gas emissions will at no point exceed that of developed countries even as it pursues the country's developmental objectives.

For dealing with the complex challenges like climate change, one must act on several fronts in a focused manner simultaneously. In this context, eight National Missions have been designated in different areas and the focus will be on promoting the scientific understanding of climate change, adaptation and mitigation, energy efficiency, and natural resource conservation. While several of these programmes have already become a part of India's current actions, they may need some changes in direction, enhancement of scope and effectiveness and accelerated implementation of time-bound plans.

The National Water Mission is one among the eight actions, ensuring Integrated Water Resource Management (IWRM) helping to conserve water, minimize wastages, and ensure more equitable distribution both across and within states. According to the Prime Minister's Council on Climate Change, (2008), the mission will take into account the provisions of the National Water Policy and develop a framework to optimize water use, by increasing water use efficiency by 20% through regulatory mechanisms with differential entitlements and pricing. It will seek to ensure that a considerable share of the water needs of urban areas is met through recycling of wastewater, and ensuring that the water requirements of coastal cities with inadequate alternative sources of water are met through the adoption of new and appropriate technologies, such as low temperature desalination technologies for purifying sea water.

The National Water Mission proposes that, the National Water Policy would be revisited in consultation with states to ensure basin level management strategies to deal with climate change induced variability in rainfall and river flows. This will include enhanced storage both above and below the ground, rainwater harvesting, coupled with equitable and efficient management structures. The Mission seeks to develop new regulatory structures, combined with appropriate entitlements and pricing. It will seek to optimize the efficiency of existing irrigation systems, including rehabilitation of systems that have run down and also expand irrigation, where feasible, with a special effort to increase the storage capacity. Incentive structures to be designed to promote water-neutral or water-positive technologies, recharging of underground water sources and adoption of large scale irrigation programmes which rely on sprinklers, drip irrigation and ridge and furrow irrigation are some of the schemes proposed (Prime Minister's Council on Climate Change, 2008). In brief, most of these devices are important in the climate change vulnerable coastal belts, which accommodate huge populations with limited fresh water sources.

8. National Water Policy (2012) and Climate Change Adaptation Strategies

India's National Water Policy (2012) has been designed to consider the growing population, rising water needs for economic development, impact of climate change, and water conflicts faced by the country in recent years. Low public consciousness about the scarcity of water and its economic values, pollution of water bodies, reduction of flows below minimum ecological needs, and lack of a unified perspective in planning, management and use of water resources are the major concerns highlighted in the Water Policy. The objective of the policy is to take cognizance of the existing situation, to propose a framework for the creation of a system of laws and institutions and a plan of action with a unified national perspective.

The National Water Policy (2012) laid a special emphasis on climate change impact and stated that, "climate change is likely to increase the variability of water resources affecting human health and livelihoods. Therefore, special impetus should be given towards mitigation at the micro level by enhancing the capabilities of the community to adopt climate resilient technological options". Further, the anticipated increase in variability in the availability of water because of climate change should be dealt with by increasing water storage in its various forms, namely, soil moisture, ponds, groundwater, small and large reservoirs and their combination. States should be incentivized to increase water storage capacity, which inter-alia should include revival of traditional water harvesting structures and water bodies.

The climate change impact adaptation strategies could also include better demand management, particularly, through the adoption of compatible agricultural strategies and cropping patterns and improved water application methods, such as land levelling and/or drip / sprinkler irrigation as they enhance the water use efficiency, as also, the capability for dealing with increased variability because of climate change. Similarly, industrial processes should be made more water efficient. The policy proposed multi-stakeholders' collaboration and emphasised to promote stakeholder participation in land-soil-water management with scientific inputs from local research and academic institutions for evolving different agricultural strategies, reducing soil erosion and improving soil fertility. The specific problems of hilly areas like sudden run off, weak water holding capacity of soil, erosion and sediment transport and recharging of hill slope aquifers should be adequately addressed. Further, planning and management of water resources structures, such as, dams, flood and tidal embankments should incorporate coping strategies for possible climate changes. The acceptability criteria with regard to new water resource projects need to be re-worked in view of the likely climate changes.

The policy also laid special emphasis on averting water related disasters like floods and droughts, through structural and non-structural measures as well as conservation of rivers, river corridors, water bodies and infrastructure, and should be implemented in a scientifically planned manner through community participation. In brief, the National Water Policy (2012) gives adequate importance for water resource management strategies in the event of climate change; however, its effective implementation is the key.

9. Climate Change Adaptable Water Resource Management Strategies

The National Water Mission of India's NAPCC and the National Water Policy (2012) have come up with a number of strategies, programmes and policies for adapting to the climate change impacts on the water sector. The devices, which are extremely significant for coping with the water resources vulnerability induced by climate change in coastal areas are summarised below.

9.1 Rainwater Harvesting

India receives an average rainfall of about 1170 mm which corresponds to an annual precipitation of about 4000 billion cubic meters (BCM) including snowfall. After accounting for evaporation and evapotranspiration, the average annual water availability in the country is 1869 BCM. It is estimated that owing to topographic, hydrological and other constraints, the utilizable water is 1121 BCM which comprises 690 BCM of surface water and 431 BCM of replenishable groundwater resources. As per the assessment made by the Central Water Commission and Central Ground Water Board in 2009, about 450 BCM of water was utilized out of 1121 BCM and the balance water could be considered to be flowing down to the sea (Ministry of Water Resources, 2013). For utilizing these resources, the government promotes rain water harvesting and artificial recharge in the country. Roof top rain water harvesting has been made mandatory to reduce the depletion of groundwater in most of the states/union territories. Further, the Central Ground Water Authority (CGWA) has issued appropriate advisories on rainwater harvesting in the different building environments of the country.

In an era of climate change effective rainwater harvesting may have dual advantages: (a) reduce the magnitude of flooding during extreme precipitation, and (b) improve the water availability through better groundwater stock during a drought. As coastal areas are rapidly urbanizing, mandating roof water harvesting and storm water recharge will be an effective strategy of water management and will ensure water security to the communities, especially when the climate change impacts are acute.

9.2 Desilting Water Bodies

Desilting natural water bodies and reservoirs makes a significant contribution towards flood management and tackling drought situations. Desilting will increase the storage capacity of the water bodies as well as improve the aquifer recharge and the groundwater table. According to the Ministry of Water Resources (2018), desilting of water bodies and dams is the prime responsibility of the owners of water bodies and dams who are generally under the control of state governments or Central Public Sector Undertakings, like the Bhakra Beas Management Board (BBMB), National Hydroelectric Power Corporation Ltd. (NHPC) etc. In order to supplement the efforts of the state governments, the Ministry of Water Resources, River Development and Ganga Rejuvenation provide technical and financial assistance to encourage sustainable development and efficient management of water resources through various schemes and programmes such as Repair, Renovation and Restoration (RRR) of water bodies' scheme and Dam Rehabilitation and Improvement Programme (DRIP).

Generally, state governments are engaged in desilting and restoration of water bodies with financial assistance from the central government and external agencies.
The Government of India, with financial assistance from the World Bank, started DRIP in 2012 for the rehabilitation of 223 dam projects. The Tamil Nadu Irrigated Agriculture Modernization and Water Bodies Restoration and Management Project Phase-I has received external funding of $ 335 million from the World Bank in 2007 and completed the project in 2016.

9.3 Desalination Plants

As the present surface and groundwater sources of the country have become increasingly stressed, the possibility of an acute drinking water shortage is high in the future. The per capita annual water availability of the country is expected to fall from 1860 cubic metre per year in 2001 to 1140 cubic metre per year by 2050 (Malavika, 2017). In this context, the Government is seriously thinking of seawater desalination in the coastal states. Desalination means removing salt and other minerals to make the water fit for drinking and/or other purposes. The filtration of saline water can be done through thermal desalination technology or membrane technology like reverse osmosis.

Seawater desalination plants in Minjur with 100 million litres per day (mld) capacity started in 2010 (cost Rs. 515 crore) and Nemmeli with 100 mld capacity commenced in 2013 (cost Rs. 533 crore) are the two successful desalination plants in Chennai. Three desalination plants based on the Low Temperature Thermal Desalination (LTTD) technology (which makes use of the temperature gradient of two water bodies to evaporate the saline water and condense it), indigenously developed and demonstrated by the National Institute of Ocean Technology (NIOT), have been successfully commissioned at Kavaratti, Minicoy, and Agatti islands of the Union Territory of Lakshadweep with expenditures of Rs. 5 crores, Rs. 10.4 crores and Rs. 16.4 crores, respectively. The capacity of each of these plants is 1 mld. An experimental LTTD plant using condenser waste heat from a power plant was set up at North Chennai thermal power station at the cost of Rs. 4.5 crore. The work for a prototype LTTD plant with a capacity of 2 mld at the Tuticorin thermal power station, Tamil Nadu, has been initiated at an initial cost of Rs. 42.14 crores. Further, the Lakshadweep Administration requested NIOT for setting up similar plants in six islands (Amini, Chetlet, Kadamath, Kalpeni, Kiltan and Andrott) and NIOT have sent a detailed project report with a fund requirement of Rs. 280.01 crores to the Lakshadweep administration (Ministry of Earth Science, 2016).

In brief, the desalination plants are emerging as an effective alternative for managing the freshwater crises in the coastal states and the islands of the country. Now, the government is attempting to develop a Desalination Mission. However, these technologies are extremely expensive and also require costly infrastructures. The Concerned scientific agencies need to develop cost effective desalination technologies.

9.4 Recycling and Reuse of Wastewater

About 29,000 mld of wastewater is generated from India's class-I cities and class-II towns, out of which about 45% (about 13,000 mld) is generated from 35 metro-cities alone. A collection system exists for only about 30% of the wastewater through sewer lines, and the treatment capacity exists for about 7000 mld (CPCB 2007). Thus, there is a large gap between the generation, collection and treatment of wastewater. Most of the un-collected, un-treated wastewater finds its way into either nearby water bodies or cesspools. The industrial sector discharges around 30,730 million cubic meters of effluents, without proper treatment, into water bodies (CPCB 2006). A CAG (2011) report revealed that, only about 10% of the wastewater generated from the domestic and industrial sectors in India is treated; the rest is discharged as it is into water bodies and land. In almost all urban centres, cesspools exist, which are the breeding grounds for mosquitoes. Further, the wastewater accumulated in cesspools gets percolated into aquifers and pollutes the groundwater. Coastal cities in India are under the looming threat of pollution (Nelliyat, 2016a).

In the absence of proper waste management in the upstream part of the river, there are enough possibilities to transfer the pollution load to the downstream areas or the coast, particularly in times of heavy precipitation and flooding, and to contaminate the freshwater sources. Recycling and reuse of wastewater in the domestic and industrial sectors can considerably reduce an additional fresh water demand. In these contexts, the promotion of recycling and reuse of wastewater in the domestic and industrial sectors is important. However, wastewater (sewage and effluents) recycling and re-use in India is in the preliminary stage. Wastewater recycling and reuse should be encouraged by the government through providing adequate technical and financial support as it has huge scope in tackling the country's water crises.

9.5 Maintain the Environmental Flow

Due to the increasing extraction of water for agriculture, domestic and industrial purposes and the land use changes with deforestation in the catchments, most of the Indian rivers do not have flows in most parts of the year. However, 'environmental flows' are necessary for the healthy status of the river and to sustain its aquatic ecosystems. It is a method and an option for the sustainable use of water resources. According to Jain and Pradeep (2014) in the past, environmental flows in India have usually been understood as the minimum flow to be released downstream from a dam as compensation for riparian rights, without considering the impacts on the river's ecosystem. However, flows are needed for maintaining the river regime, making it possible for the river to purify itself, sustaining aquatic life and vegetation, recharging groundwater, supporting livelihoods, facilitating navigation, preserving estuarine conditions, preventing the incursion of salinity, and enabling the river to play its role in the cultural and spiritual lives of the people.

As coastal areas are at the extreme end of the river basin and vulnerable to climate change impacts, the ecological services of environmental flows, particularly purifying the water, recharging into aquifers, resisting the sea water flow in to the upper part of the river etc. are critical for ensuring freshwater security.

10. Discussions and Way Forward

There is evidence that the global climate is changing significantly. IPCC reports have clearly stated that in recent decades, changes in climate have caused impacts on natural and human systems in all the continents and across the oceans. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality. Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to the ongoing climate change. Climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of ecosystems and humans. The negative impacts of climate change on crop yields have been more common than the positive ones. Climate-related hazards often end up with negative outcomes for livelihoods, especially for people living in poverty.

Water is the primary medium through which climate change impacts the earth's ecosystem and people. Climate change impacts alter water availability which influences almost all aspects of the economy including domestic water supply, sanitation, health, food production, energy generation, industrial product manufacturing, and environmental sustainability. Climate variability water resource management and economic development are intricately linked. Hence, the vulnerability to natural disasters affecting water supply hampers economic performance and undermines poverty reduction goals and achievement of the SDGs.

Drinking water sources along the coastal plains are at risk from salinisation due to episodic storm surges. These risks are likely to increase over the coming century due to climate change induced rising sea levels and more frequent and/or intense tropical cyclones. Hence, many millions of people living along the coast are at risk of being exposed to salinity and its associated health impacts.

The Least Developed Countries are the most vulnerable, as their present water resource management technologies and capacities are inadequate. In this context, water resource management must be a priority area and an inescapable part of reducing vulnerability and promoting adaptation to climate change.

In brief, since freshwater is a precious and scarce resource in coastal areas, and is getting degraded due to anthropogenic and natural reasons, its preservation is important. Unfortunately, the freshwater available in the coastal areas are not considered as 'coastal resources', since it is available in all other terrains also (Nelliyat et. al., 2009). However, an adequate quantity of fresh water is essential in coastal areas for the progress of the economy and environment. Otherwise, the overall sustainability of the coastal ecosystem is under jeopardy. Hence, freshwater management issues also need to be incorporated in the Coastal Zone Management Programmes. Further, fresh water in the coastal areas should be considered as a "critical resource" and more scientific studies should be done to examine its linkages with economic development, water resources conservation and sustainable use, ecosystem management, and climate change.

Management Strategies: Comprehensive water resources management strategies with emphasis on the multiple aspects of water and climate change are required for the coastal areas. In this regard, the following methods are proposed:

- Detailed and accurate vulnerability assessments along the coasts are crucial for planning the targeted adaptation programmes. In the most vulnerable (to climate change and salinisation) areas, appropriate strategies for avoiding/decreasing the climate change impacts must be implemented with the support of the local officials and the public.
- Vulnerability mapping should be done with more detailed and scientific information, including previous inundation history, the condition and elevation of polders, the availability and quality of local infrastructure, and also any potential influences of upstream water related and other economic activities.
- In coastal areas where salinisation of drinking water exists, along with the emergency efforts to supply interim drinking water (bottled water and portable water plants), long - term solutions are required. Adaptation to these measures would require modification of the natural environment, people's practices and appropriate engineering devises. Devices must be identified and strengthened with consideration to the hydro-geological and ecological conditions of the coast. Large-scale communal rainwater harvesting would also help to reduce inundation risks.
- For sound water resources management planning, at national levels, water governance must be integrated with, non-water sectors. The technological knowhow and science based hydrological information should be increased. The Government should follow an "Integrated Water Resources Management" policy, and the climate change adaptation strategies proposed in India's National Action Plan on Climate Change and the National Water Policy, with the collaboration of all the stakeholders in the coastal areas.
- At the regional levels, collaborative water management should be emphasized. At the international and global level, financing for water-related investments (infrastructure and technology) should be increased.
- Desalinisation plants could also be developed as an option to produce fresh water from saline/brackish water. Cost effective reverse osmosis technology must be developed.
- Strict policy initiatives should be enforced on groundwater over-extraction, pollution management and preservation of the existing water bodies and maintaining the environmental flow. Efforts should be undertaken for the reclamation of aquifers through rainwater harvesting. Wastewater recycling and reuse should be encouraged in the appropriate sectors.

- Mangrove plantation (which protects the aquifer from seawater intrusion and coastal disasters must be extended to wider areas of the coast.
- Mass awareness generation about the criticality of freshwater in coastal zones with respect to the changing climate, and its judicious use and management is the need of the hour.

In brief, climate change is a gradual process, and its implications are highly uncertain and occur in different magnitudes. Generally, renewable natural resources like water in coastal areas may get depleted due to multiple anthropogenic reasons and natural phenomena. Now, the climate change factors are also influencing the water availability and quality. Here, a water resources management strategy, exclusively to tackle the climate change induced problem in the water sector cannot have much scope. What is needed is that water resources planning, particularly in the vulnerable areas like the coast, must give due consideration to the existing and predicted climate change impacts.

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Climate Mitigation

17

Fluxes of carbon dioxide from Indian coast and their role in climate mitigation

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ABSTRACT

Estuaries are generally the *source* whereas shelf regions are the *sink* for the atmospheric CO_2 due to dominant heterotrophy and autotrophy respectively. However, several local processes such as coastal upwelling, river discharge, and atmospheric deposition of pollutants modify the general pattern of CO_2 source/sink in the coastal regions. The annual emission of CO_2 from the Indian estuaries and shelf regions is estimated to be ~2 TgC and 6.33 TgC to the atmosphere. Though CO_2 fluxes from the Indian estuaries are smaller than the developed countries, by order of magnitude, the emission from the coastal regions is higher. Both natural and anthropogenic processes cause such high fluxes from the coastal regions. Natural processes such as coastal upwelling, winter convective mixing and high respiration rates of organic matter due to the tropical climate enhance pCO_2 levels in the surface waters. On the other hand, anthropogenic processes, such as atmospheric deposition of acidic pollutants, modifications in river discharge and release of sewage into the coastal oceans increases pCO_2 levels and their fluxes to the atmosphere. Moderately reduced flow of water from the dam reservoir to the estuary, limited release of excess fertiliser inputs to estuary, and a decrease in atmospheric pollutant release may decrease pCO_2 in the Indian Coastal waters. Fertilisation using natural nutrients may be attempted to increase primary production, and therefore atmospheric CO_2 removal. However, this must be done with caution as there are possibilities of formation of oxygen minimum zones.

1. CO_2 fluxes from the Global coastal regions

The global oceans are a net sink for the atmospheric CO_2 (Gruber et al., 2009; Takahashi et al., 2009), however, the role of coastal bodies on global CO_2 fluxes remains unclear due to lack of data (Borges et al., 2005; Cai et al., 2006; Chen and Borges, 2009; Laruelle et al., 2010). The coastal ocean, by definition, includes estuaries and near-shore up to the shelf region. The estimated absorption of CO_2 from the continental shelves is estimated to be 200TgC y^{-1}(1 Tg = 10^{12}g; Cai et al., 2006; 2011; Chen et al., 2013; Borges et al., 2005; Laruelle et al., 2010; 2014; Wanninkhof et al., 2013), whereas CO_2 emission by estuaries to the atmosphere is estimated to be 270TgC y^{-1} (Laruelle et al., 2010). These estimations were made based on the data available in the coastal regions in the developed countries and the data from the Indian coastal regions are rather scarce. In contrast, the coastal oceans in the subtropics, such as the northern South China Sea, were found to be a weak source to the atmospheric CO_2 (Zhai et al., 2005; 2013; Dai et al., 2013). Coastal oceans are known to be notorious for variability in CO_2 fluxes due to the influence of various physical processes, such as upwelling, river inputs, submarine groundwater injections and discharge of anthropogenic pollutants. Hence, extrapolation of data collected in some regions to the entire global coastal regions is challenging.

On the other hand, estuaries are known to be a strong source of CO_2 to the atmosphere due to the existence of dominant heterotrophy. Added to this, these regions receive pollutants directly from various sectors that further enhance CO_2 fluxes to the atmosphere. It has been estimated that European estuaries emit CO_2 in the tune of 30 to 60 TgC (1 Tg = 10^{12}g), which represents 5 to 10% of present anthropogenic CO_2 emission for Western Europe due to high pollution in these estuaries (Frankignoulle et al., 1998). Due to lack of data, Frankignoulle et al. (1998) hypothesised that the emission from the estuaries in the developing countries, such as India and China, may be an order of magnitude higher than that of European estuaries. Several efforts have been made in the past decade to estimate fluxes of CO_2 from the Indian estuaries and coastal waters around India and the potential reasons responsible for their variability in fluxes with reference to space and time have been evaluated. This chapter is structured in the following way: variability in pCO_2 and their fluxes to the atmosphere from the Indian estuaries and the processes responsible for such fluxes are examined followed by discussion of the same in the coastal regions. Then the recent trends in coastal pCO_2 are discussed followed by possible mechanisms that may be adopted to reduce the CO_2 fluxes from these regions to the atmosphere.

2. Variability in pCO_2 levels, and their fluxes from the Indian estuaries

The pCO_2 in the Indian estuaries showed wide variations from ~300 to 18492 μatm with relatively higher levels in the estuaries located along the west than the east coast of India (Sarma et al. 2012). The pCO_2 levels observed in the Indian estuaries are in the range of the world's estuaries. The pCO_2 values showed a significant linear relation with a magnitude of discharge with low pCO_2 levels in the low discharge and vice versa. Close to or >10,000 μatm of pCO_2 was observed in highly polluted estuaries such as Haldia, Ponniyaar, Mahanadi etc. Enhanced organic carbon load, either due to discharge of freshwater that brings terrestrial organic matter or pollutants, and subsequent microbial decomposition is responsible for higher pCO_2 levels in the Indian estuaries. It is further supported by low oxygen saturation, higher nutrient concentration and low production to respiration ratio (P: R; Sarma et al., 2009) in the Indian estuaries indicating dominant heterotrophy. Based on the isotopic composition of organic matter, it was estimated that about 40-80% of the organic matter originates from terrestrial sources in the Indian estuaries (Sarma et al., 2014). In addition to this, nitrification also acidifies the estuarine waters resulting in enhanced levels of pCO_2 and fluxes to the atmosphere (Billen, 1975; Frankingnoulle et al., 1996). Relatively lower nitrification rates were measured in the Indian estuaries (Rao and Sarma, 2013) suggesting that the contribution from this process may not be very significant. The annual flux of CO_2 from the Indian estuaries is estimated to be ~2 TgC (1 Tg=10^{12} g) to the atmosphere (Sarma et al., 2012) which is an order of magnitude less than that of from the European estuaries (30-60 TgC/y; Frankignoulle et al., 1998). In addition to this, the mangrove regions are also a significant source of pCO_2 to the atmosphere. The pCO_2 in the Indian mangrove regions ranged between 420 to 510 µatm and the range of pCO_2 is always above the atmospheric value. The water-to- air emission of CO_2 from the Indian mangrove regions amounted to 2 x 10^{-3}TgC y^{-1} to the atmosphere.

3. Variability in pCO_2 levels, and their fluxes from the Indian coastal waters

The pCO_2 levels in the coastal waters ranged between 200 and 680 µatm along the Indian coast and showed significant spatial and seasonal variability. The higher pCO_2 levels (350 to 680 µatm) were observed during the southwest monsoon period along the west coast of India and higher pCO_2 levels were attributed to the occurrence of coastal upwelling (Sarma et al., 1996; 1998). In contrast, lower pCO_2 levels were observed during the southwest monsoon period in the northern coastal Bay of Bengal (200-250 µatm), but it is increased toward the south (400-650 µatm) due to occurrence of mild coastal upwelling (Sarma et al., 2012). In contrast, pCO_2 levels during non-monsoon period were relatively lower (400 to 480 µatm) compared to the southwest monsoon in the Indian coastal waters (Sarma et al., 1998; 2015a, b). The flux of CO_2 from the Indian coastal water is estimated to be in the tune of 6.33 TgC/y in which 1.3 TgC is emitted from Bay of Bengal and it is four times higher in the Arabian Sea coastal region (5.03 TgC/y). Relatively lower fluxes from the Bay of Bengal were caused by strong stratification due to river discharge as freshwater from the Ganges contains relatively lower dissolved inorganic carbon (Kumar et al., 1996) and stratification inhibits vertical mixing of pCO_2 rich subsurface waters. On the other hand, strong coastal upwelling enhances pCO_2 levels in the west coast region, whereas winter convective mixing increases pCO_2 during winter. On the other hand, microbial decomposition of organic matter contributes significantly during non-monsoon seasons (Sarma et al., 2000). Recently Sarma et al. (2018) found that pCO_2 variation along the coastal Bay of Bengal is mainly controlled by change in the direction of the East India Coastal Current (EICC) as it flows from pole to equator during October to January. This brings surface water from the northern Bay, which is influenced by high pH and low pCO_2 Ganges River water, to the east coast of India, in contrast to that observed during March to September, when EICC flows towards the pole. It is further noticed that biological effect is more important than mixing effect in the coastal Bay of Bengal on pCO_2 levels in the surface (Sarma et al., 2018); and it is in contrast to that in the coastal Arabian Sea (Sarma et al., 2000) due to strong mixing resulting in the injection of pCO_2 rich waters to surface in the latter basin. In addition to this coastal circulation and mixing, DIC rich waters are also received through submarine groundwater discharge (SGD) to the estuarine and coastal waters. It was recently estimated that ~54% of the riverine DIC flux to the Godavari estuary is contributed by SGD flux (Rengarajan and Sarma, 2015). Recently we have measured DIC in the groundwater along the Indian coast and it was found to be 1.5 to 3 times higher in the groundwater than adjacent coastal waters. The estimation of SGD rates along the coast suggested that ~20-30% of the coastal water DIC is contributed from these fluxes. In addition to this, nutrients are also brought to the coastal waters through SGD. The net effect on coastal water pCO_2 (or DIC) is yet to be determined.

4. Recent changes in pCO_2 levels in the Indian coastal waters

Long-time-series coastal observatories are lacking in the Indian coastal waters to examine the long-term variability in pCO_2 levels and growth rate of CO_2 in the surface waters. However, Sarma et al. (2015) compared the pCO_2 levels during 2011 with 1991 in the coastal Bay of Bengal during winter-spring and found that the rate of increase in pCO_2 (5.4 - 6.7µatm/y) is higher than elsewhere in the open ocean regions (1.2 to 1.6 µatm/y; Dore et al., 2003; Church et al., 2013; Astor et al., 2013; Metzl, 2009). The rapid increase in pCO_2 levels in the coastal Bay of Bengal was mainly attributed to the deposition of atmospheric pollutants. It has been noticed that sea-salt corrected component of SO_4 (nss-SO_4) was higher in the marine atmosphere boundary layer over the Bay of Bengal than over the Arabian Sea (Kumar et al., 2008). The relatively higher abundance of nss-SO_4 over the Bay of Bengal suggests the greater influence of anthropogenic sources to the aerosol loading. As a result, surface waters of the coastal Bay of Bengal are acidified more rapidly than elsewhere in the world, resulting in faster growth of pCO_2 levels (Sarma et al., 2015a). On the other hand, the long-term variations in the pCO_2 levels in the coastal Arabian Sea are unknown due to lack of data.

5. Possible mechanism that should be adopted to reduce the emissions of CO_2 from the Indian estuaries

The emissions from the Indian estuaries are relatively lower than elsewhere in the world (Laurelle et al., 2014) due to short residence time of waters in the estuary as a result of highly controlled flow from dams resulting in less modification of the organic matter within the estuary and formation of pCO_2. However, CO_2 emission during the discharge period contributes to ~80% of the annual emissions, and it was attributed to the bacterial decomposition of terrestrial organic carbon in the estuary. Added to this, controlled discharge through dams enhance water speed that leads to resuspension of surface sediment resulting in mixing of pCO_2 rich pore waters with estuarine waters that further enhances pCO_2. Instead of release of waters after complete filling of dam reservoir, periodic release of water may reduce this mixing that may decrease pCO_2 levels and therefore fluxes to the atmosphere. The release of agricultural wastes, such as fertilisers, enhances the bacterial decomposition of organic matter leading to increase in pCO_2. Though an increase in fertiliser release is expected to increase primary production, due to high suspended load, the photic depth is very shallow resulting in less primary production. The increased inputs of sewage to rivers/estuaries changes the pH of the water that modifies the inorganic carbon system towards formation of pCO_2, in case of decrease in pH. Hence, sewage must be treated and the pH brought to neutral before it is discharged to the rivers/ estuaries.

Reduced river discharge has significant impact on the ecosystem functioning and CO_2 fluxes in the Indian estuaries. Reduced river discharge enhances residence time and forms stratification with two-layer structure. This would enhance the stability of the water column that is conducive for phytoplankton to bloom as well as bacteria to decompose organic matter to CO_2. Acharyya et al. (2012) observed that reduced river discharge enhances phytoplankton blooms resulting in decrease in oxygen levels in the water column due to decomposition of organic matter. Such conditions will have significant impact on the formation of oxygen minimum zones and release of other trace gases such as nitrous oxide and methane. Therefore modification of river discharge will significantly enhance trace gas fluxes from the estuaries to the atmosphere. The ongoing interlinking rivers and new proposed dams may have a significant impact on trace gas fluxes.

6. Possible mechanism should be adopted to reduced the emissions of CO_2 from the Indian coastal waters

6.1 Unaltered river discharge

The coastal upwelling is one of the major sources of pCO_2 to the surface waters and flux to the atmosphere due to injection of pCO_2 rich waters from the subsurface. Upwelling is weaker along the east coast than the west coast of India due to strong salinity stratification that inhibits vertical mixing in the former region. Recently Sarma et al. (2015) observed that reduced river discharge during the positive Indian Ocean Dipole year of 2011 decreased stratification in the coastal waters leading to increase in intensity of upwelling and high pCO_2 levels in the surface waters. Therefore a decrease in river discharge, due to construction of dams or inter-linking of rivers, may weaken the stratification leading to occurrence of intense upwelling and high fluxes of CO_2 to the atmosphere from the coastal regions. In addition to upwelling, the east coastal region receives freshwater from Ganges during October to January due to equator ward flow of EICC resulting in low pCO_2 and low fluxes of CO_2 to the atmosphere. The decrease in Ganges River discharge is already reported due to construction of dams at the upstream end. Decrease in Ganges River discharge enhances pCO_2 levels due to increase in salinity leading to decrease in stratification and injection of subsurface pCO_2 to surface.

6.2 Decrease atmospheric pollution

Atmospheric dust deposition is found to be one of the major reasons for rapid acidification in the coastal waters along the east coast of India (Sarma et al., 2015); however, its impact on the west coast is unknown. The loading of acidic pollutants into the atmosphere has resulted from the increased industrialisation and fertiliser use in this part of the world (UNEP, 2008). The consumption rate of nitrogen and phosphorus fertilisers in India more than doubled, from 8000 and 3700 Mt (metric tons)/y, respectively, to 17000 and 8000 Mt/y, respectively, from 1991 to 2011, with the greatest increase in fertiliser use occurring during the most recent decade (Fertiliser Association of India; www.faidelhi.org). The increased fertiliser consumption on the Indian sub-continent may increase ammonia in the atmosphere through saltation of soil from agricultural fields and its deposition on the sea surface waters triggers nitrification that can lead to a decrease in pH (Doney et al., 2007). In addition to this, acidic ions can also be injected into the atmosphere through several industrial activities. Therefore, significant quality control must be done for the atmospheric emissions from the industries. The knowledge on the use of fertilisers to the requirement of the plant must be carried to the farmer to reduce excess use of fertilisers as the excess fertilisers may end up either in the atmosphere or routed to the rivers.

6.3 Natural nutrient Fertilization

Natural Fertilisation of nutrients from deep water would enhance primary production and remove atmospheric CO_2. Though it may remove atmospheric CO_2, the increased primary production may enhance organic matter production and its decomposition by bacteria may decrease dissolved oxygen levels. The care must be taken to balance oxygen inputs to the subsurface layers and its consumption through organic matter production/ decomposition.

7. Summary

Both Indian estuaries and coastal waters are strong sources of CO_2 to the atmosphere due to physical processes, such as upwelling, vertical mixing, submarine groundwater discharge, river discharge and microbial decomposition of organic matter. The contribution of CO_2 flux to the atmosphere from the Indian estuaries and coastal waters, including mangroves, amounted to 8.3 TgC y^{-1}. The fluxes of CO_2 from the Indian estuaries are an order of magnitude less than that of developed countries, where the fluxes from the coastal regions are high. Such high fluxes from the coastal regions have resulted from both natural and anthropogenic processes. The natural processes such as coastal upwelling, winter convective mixing, submarine groundwater discharge and high bacterial respiration rates of organic matter are due to the tropical climate. On the other hand, the anthropogenic processes such as atmospheric deposition of acidic pollutants, modifications in river discharge and release of sewage and excess fertiliser into the coastal oceans, lead to the increase in pCO_2 levels and their fluxes to the atmosphere. Modification of magnitude of river discharge, atmospheric aerosol loading, groundwater pollution and excess fertilisers inputs will have significant impact on pCO2 levels and fluxes to the atmosphere. Natural Fertilisation of coastal waters with deep water nutrients may be attempted to increase primary production, and therefore atmospheric CO_2 removal. However, a caution is warranted for the possible formation of oxygen minimum zones as subsurface waters along the Indian coast were already contained low oxygen levels.

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Greenhouse gas emissions from blue carbon ecosystems

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ABSTRACT

Blue carbon ecosystems are considered as one of the prominent sink of carbon; the conversion or loss of these habitats destabilizes the sedimentary carbon stores, releasing large amounts of greenhouse gases (GHG). An assessment of GHG emissions from mangrove and seagrass ecosystems along the mainland coast of India and the Islands was undertaken to delineate natural and human induced stress on these ecosystems. The net emission (in terms of CO_2 equivalents) was ~5,106 Gg CO_2e y^{-1} from mangrove surrounding waters and ~41 Gg CO_2e y^{-1} from seagrass ecosystems of India. Mangroves along the east coast contribute to 2,735 Gg Co_2e y^{-1} than mangroves along the west coast (~1,631 Gg Co_2e y^{-1}).It was observed that anthropogenic influences and seasonality intensifies heterotrophic mineralization in coastal ecosystems, leading to enhanced GHG emissions. This emphasises the need for conservation and restoration of these blue carbon ecosystems to enhance the carbon sequestration potential and to contribute to the climate mitigation efforts.

1. Introduction

Blue carbon ecosystems are considered as one of the most productive ecosystems on earth, storing large amount of carbon and predominantly underground. Ecosystems like mangroves and seagrasses have been a major focus for research in the recent years as these are dynamically altered by human action and by natural catastrophes. Various studies have estimated the global and regional carbon sequestration of these coastal habitats (Twilley et al., 1992; Chmura et al., 2003; Murray et al., 2011; Donato et al., 2011; Alongi, 2012; Fourqurean et al., 2012; Greiner et al., 2013; Siikamäki et al., 2013; Macreadie et al., 2014; Liu et al., 2014). All these studies contribute towards our understanding of the amount of carbon that is being stored in these ecosystems and points out that this same amount stands to be reintroduced into the atmosphere in case of deforestation, sediment oxidation, land conversion, occurrence of storms, and other processes that negatively affects the stored carbon. What is less understood is the source-sink dynamics of Greenhouse Gases (GHGs) to the atmosphere from these fragile ecosystems.

Conversion or loss of blue carbon habitats to other land uses such as aquaculture, saltpans, agriculture, coastal development/ industrialization and additional factors like natural hazards, destabilizes the sedimentary carbon stores and exposes them to increased microbial activity. As a consequence, large amounts of GHG are released directly to the atmosphere or into the water column (Sjöling et al., 2005; Granek and Ruttenberg, 2008; Strangmann et al., 2008; Sweetman et al., 2010; Pendleton et al., 2012; Garcias-Bonet and Duarte, 2017). These land conversions become major sources of CO_2 to the atmosphere, adding to the already super saturated atmospheric CO_2.

Another factor that governs emissions from the blue carbon ecosystems is the nature and the origin of the carbon. Reactive (labile) organic matter usually derived from autochthonous production or introduction from the land-based sources will be prone to transformation, remineralization processes resulting in its possible return to the atmosphere. Eventually, this implies that the blue carbon once disturbed/perturbed, can be released to the atmosphere (in the form of potent greenhouse gases such as CO_2, CH_4) and their emission can be highly variable in space and time, depending on land use and nature of the sedimentary carbon (Pendleton et al., 2012).

In general, anthropogenic contributions to the atmospheric GHG by combustion of fossil fuels largely out-compete the emissions from blue carbon ecosystems. Annual average growth in global mean CO_2 during 2000-2017 was 2.1±0.08 ppm (NOAA). At the present growth rate, greenhouse gas emissions would reach almost 685-ppm CO_2equivalent by 2050 (Marchal et al., 2011). However, given the current scenario of land conversion and natural disturbances in the coastal vegetated habitats, it is estimated that approximately 0.15–1.02 Pg (billion tons) of CO_2 is being released annually by their degradation, which contributes to as much as 3-19% of the emissions from the global deforestation (Pendleton et al., 2012).

Mangroves and seagrasses are the most threatened and rapidly disappearing ecosystems around the globe, thus, posing an imminent threat in terms of global GHG budget. Mangrove destruction globally is estimated to release approximately 0.12 billion tonnes of CO_2 annually, which contributes roughly 0.3% of the total anthropogenic CO_2 emissions (Siikamäki et al., 2012). Seemingly small, the emissions may become a greater risk in the future, knowing the current rates of mangrove loss (at 0.7% per year), projection estimates 16% of the global mangrove area will be lost in the next two decades (Siikamäki et al., 2012). Similarly, it is estimated that seagrasses have been disappearing at a rate of 110 km^2 per year since 1980 and as much as 29% of their total areal extent has disappeared since their first record (Waycott et al., 2009). Furthermore, the rate of decline has accelerated tremendously (from a median of 0.9% to 7% per year) between 1940 to 1990 (Waycott et al., 2009). These estimates will only become higher if the land use changes go unrestricted and unchecked. Although, mangrove and seagrass loss is a global occurrence, the rate of loss is more pronounced in the developing countries, where majority of the world's blue carbon ecosystems are located. Coastal ecosystems, are seen as potential areas for coastal development due to huge pressure on land areas. Further, increasing dependency and use of these habitats for coastal livelihood along with the indirect impacts of the upstream activities are leading to shrinkage in their overall extent. This combined with the natural threats such as climate change, coastal hazards etc. brings forth the serious need to conserve and restore these environmentally sensitive ecosystems. With this background, the assessment of GHG emissions from mangrove and seagrass ecosystems along the mainland coast of India and the Islands is studied and the results are presented.

Table 1: Different types of Mangroves of India

No.	Mangrove Type	Mangroves systems	State
1	Deltaic	Sundarbans	West Bengal
		Bhitarkanika, Mahanadi	Odisha
		Coringa	Andhra Pradesh
		Pichavaram, Muthupet	Tamil Nadu
2	Riverine/Estuarine	Dharmadom, Valapatnam (Kannur)	Kerala
		Aghanashini, Kali	Karnataka
		Mandovi, Zuari	Goa
		Thane, Ratnagiri	Maharashtra
3	Insular	Wright Myo, Bakultala, Diglipur	Andaman & Nicobar Islands
4	*Tidal (Dwarf)*	*Gulf of Kachchh*	Gujarat

2. Mangrove Ecosystems of India

Mangroves are found in the islands, major deltas, estuaries and backwaters of the east and west coasts of India. Indian mangroves are distributed in about 5,403 km^2 (NCSCM; unpublished data), constituting nearly about 4% of the world's mangroves (137,760 km^2) (Giri et al. 2011). East coast mangroves cover 56%, west coast mangroves 32% and Island mangroves cover 12% of the country's total mangrove forests (Figure 1). The east coast mangroves are more widespread compared to the west coast because of its distinctive geo-morphological setting.In India, there are mainly three types of mangrove forests (Table 1): i) Deltaic; ii) Riverine/Estuarine; iii) Insular (Ragavan et al., 2016 and references there in). Whereas, another type of mangroves completely dominant by tidal activities with minimal freshwater input from precipitations, typically characterized as majorly dwarf variety (*Avicennia marina*), as iv) Tidal (Dwarf mangroves).

2.1 Deltaic mangroves

Mangroves across the east coast are mainly deltaic type and distributed among the five major deltas of Ganges, Mahanadi, Godavari, Krishna and Cauvery. These mangroves receive a perennial supply of freshwater along with nutrient rich alluvial sediment through the major rivers. The east coast has gentle slopes with extensive flat substratum, aide mangrove colonization (Kathiresan, 2010). The *Sundarbans* is the largest mangrove forest in the world (Figure 2a), located in India and Bangladesh, situated on the lower deltaic plains of the Ganges–Brahmaputra Rivers. Deposition of river-borne sediments are dominant in these mangroves (Rogers and Goodbred, 2014); and the tidal processes plays a vital role in the eco-geography of this system (Banerjee et al., 2012; Kumar and Ramanathan, 2015). Along the Odisha coast Brahmani, Baitarani and Mahanadi delta with alluvial deposits are enriched with lush mangrove diversity in *Bhitarkanika* and *Mahanadi* (Panda et al., 2017). The *Coringa* mangrove ecosystem occupying the Godavari delta, receives freshwater and sediment loads through Gaderu and Coringa tributaries and seawater from Kakinada bay. The influence of both the tidal and freshwater hydrodynamic plays a vital role in the health and productivity of mangrove flora in *Coringa* (Subramanian and Sampath, 2001). *Pichavaram* and *Muthupet* mangroves are located on the northern and southern part of the Cauvery delta. Compared to other deltaic mangroves in India, these mangroves have a very low tidal amplitude (60 cm) and low freshwater flow period. Overall, deltaic mangroves undergo processes related to monsoonal flooding, tidal effect, and delta formation, which provide an ecological niche for the mangrove growth and the productivity. Mangrove area coverage, tidal amplitude and freshwater flow periodicity decreases along the east coast from *Sundarbans* to *Muthupet* (Kathiresan and Bingham, 2001).

2.2 Riverine/estuarine mangroves

Mangroves of the west coast are funnel shaped estuarine mangroves, with small size and less diversity. No major rivers and steep slope of Western Ghats geographical formations result into the fringing mangroves along the estuaries and creeks (Kathiresan, 2010). *Kannur* mangroves are scattered and distributed across the district, which cover about 80% of the total mangrove forest of Kerala. The *Kali* and the *Aghanashini* estuarine mangroves of Karnataka, are found in the polyhaline and mesohaline zones of the estuary, where the salinity usually ranges from 5 – 30. The two main rivers of Goa state, *Mandovi* and the *Zuari* with their inter-connecting Cumbarjua Canal form a major mangrove estuarine complex. *Thane* creek on the central-west coast of Maharashtra, is one such mangrove ecosystem, which suffers the consequences of heavy industrialization and urbanization that has occurred along its banks (Figure 2b). The creek is tidally influenced by the dominance of seawaters and negligible fresh water flow except during the monsoon. *Ratnagiri* mangroves are pristine and dominated by laterite soil.

2.3 Insular mangroves

Mangroves of Andaman and Nicobar Islands are probably the most pristine and the best developed in India in terms of their density and growth (Raghavan et al., 2016). There are no major rivers in the islands and precipitation is the main source of freshwater. The irregular and concaved coastline results in innumerable creeks, bays and backwaters, which facilitate the development of rich biodiversity, extensive and gregarious growth of mangroves compared to the mainland mangroves

2.4 Tidal mangroves

Gulf of Kachchh mangroves is tide dominated, which lack fresh water supply from any perennial river. High salinity in this region revealed by the presence of dominant species *Avicennia marina* about 97% of the total mangrove cover of Gujarat. Present mangrove areas of Gujarat were inundated due to rise in sea level (Selvam, 2003) with mangroves of thin canopy and less productivity.

3. Seagrass Ecosystems of India

Seagrass ecosystems are restricted from the lower intertidal zone to the open shores and in the lagoons mainly mudflats and sandy environment (Singh et al., 2015). Total areal cover of seagrass ecosystems is estimated to be 517 km^2, which is 0.15% of global seagrass cover (3.45 x 10^5 km^2) (UNEP-WCMC and Short, 2016). In India, six major seagrass sites are (i) Palk Bay (ii) Gulf of Mannar (Tamil Nadu) (iii) Gulf of Kachchh (Gujarat) (iv) Chilika Lake (Odisha) (v) Islands of Andaman & Nicobar and (vi) lagoons of the Lakshadweep Islands. Palk Bay and Gulf of Mannar of Tamil Nadu together contribute to 399 km^2, largest meadows in India, where the Palk Bay alone contribute to 330 km^2(Geevarghese et al., 2018) (Figure 3). Palk Bay and Gulf of Mannar seagrass meadows are more luxuriant and rich in biodiversity in the country,due to ideal topography and sediment texture (sandy, silty) (Ganguly et al., 2017; Geevarghese et al., 2018). The southern part of Chilika lagoon supports






dense interconnected monospecific and mixed seagrass patches (Banerjee et al., 2018), are very opportunistic due to seasonal variations and ranged between 65 – 85 km^2 (Geevarghese et al., 2018).

Several studies reported that the distribution of seagrass beds along the west coast of India is very scattered, and seasonal with the exception of Gulf of Kachchh, owing to the adverse benthic conditions (Geevarghese et al., 2018 and the references there in). The Gulf of Kachchh Marine National Park has 17 km^2 of seagrass beds distributed mainly in Bhural, Mundika, Sikka reefs and Pirotan Island. This area is the forage ground of *Dugong dugon*, which could be the reason of declining seagrass patches (Kamboj, 2013;Geevarghese et al., 2018). Apart from the mainland coast, the atolls of Lakshadweep have healthy seagrass patches, though it's under the natural pressure of overgrazing by turtles (Aparna et al., 2010). Islands of the Andaman & Nicobar archipelago sustain 5.8 km^2 of seagrass meadows. Rich seagrass patches are present around the islands of Little Andaman, Henry Lawrence, Havelock and Neil. Scattered patches are also located in North Wandur, Kalipur, Chatham, Chitiyatapu, Aves Island, Ross Island and Smith Island (Geevarghese et al., 2018). A wide heterogeneous species diversity in major seagrass beds in India follows the order Gulf of Mannar> Palk Bay > Andaman & Nicobar Islands > Lakshadweep > Gulf of Kachchh = Chilika Lagoon (Ramesh et al., 2018 and references there in).

Natural and Anthropogenic threats to mangroves of India

Indian mangroves are facing several specific issues, like 1) prawn farming practices, 2) cattle grazing, 3) tree felling, 4) reduced freshwater supply, 5) hyper-salinity, 6) heavy sedimentation, 7) natural calamities, 8) pest problems, 9) unsustainable fishing practices, and 10) lack of people's participation (Kathiresan, 1999; Sahu et al., 2015) (Table 2). Owing to these threats, India has lost about 40% of its mangrove cover in last century (Kathiresan, 2000; Sahu et al., 2015); of this, east coast has lost about 28%; west coast about 44%; and Andaman & Nicobar Islands about 32% (Naskar, 2004). Donato et al., (2011) estimated that, mangrove deforestation generates emissions of 0.02 - 0.12 Pg C y^{-1}, as much as around 10% of emissions from deforestation globally. As mangrove degradation is a serious environmental and economic concern; only effective governance, improvised planning for restoration of degraded mangroves, and awareness building in local communities can protect and restore this valuable critical ecosystem.

Table 2: System specific major threats of Indian mangroves

Mangrove Systems	State	Threats
Sundarbans	West Bengal	Change in land use pattern, Reduction in freshwater, Runoff from agricultural fields, Effluent discharges from aquaculture ponds, Invasive species.
Bhitarkanika and Mahanadi	Odisha	Aquaculture activities, Natural calamities, Encroachment and rehabilitation, Cutting for timber, fuel and charcoal.
Coringa	Andhra Pradesh	Aquaculture expansion, road and port construction, Woods for fire and boat making, grazing, Invasive species.
Pichavaram and Muthupet	Tamil Nadu	Dam construction, Reduction in fresh water flow, Tourist activities, agricultural runoff and sewage, Invasive species
Dharmadom and Valapatnam	Kerala	Land reclamation for agriculture, aquaculture and housing, barrages for irrigation, industrialization and urbanization, Ecotourism.
Aghanashini and Kali	Karnataka	Aquaculture and Agriculture activities, Sand mining, Pollution.
Mandovi and Zuari	Goa	Coastal development activities, Tourism activities, Logging and agriculture.
Thane and Ratnagiri	Maharashtra	Urbanization and pollution, Sewage and industrial wastes, Dumping of solid waste garbage, Conversion to saltpans, aquaculture plots, agricultural plots, residential.
Gulf of Kachchh	Gujarat	Transformation to Industrial development zones, Saltpans, Shrimp farming, Overexploitation for fuel and fodder, Domestic sewage,
North, Middle, and South Andaman Islands	Andaman & Nicobar	Natural calamities, Tourism development-encroachment, Agriculture, Exploitations for wood and wood products.

Table 3: System specific major threats of Indian seagrass ecosystems (Source: Ramesh et al., 2018 and references therein)

Natural and Anthropogenic threats to seagrasses of India

Location	Major Threats	Impacts	Reference
Palk Bay	High precipitation during north-east monsoon, Cyclones	Physical damage to seagrass and reduced light penetration due to high turbidity	Thangaradjou and Nobi, 2009
	Anchoring of boats, Propellers damage	Uprooting of seagrass	Thangaradjou and Nobi, 2009; Mathews et al., 2010
	Use of push nets, trawl nets, bottom set gill nets	Physical damage to seagrasses by uprooting of plants and damage to healthy leaves	Thangaradjou and Nobi, 2009; Sridhar et al., 2010; Mathews et al., 2010; D'Souza et al., 2013
	Nutrient enrichment from aquaculture wastes and proliferation of macroalgae	Eutrophication, growth of algae/seaweed, which competes with seagrass. Diminished light availability and sediment quality.	Sridhar et al., 2010; Thangaradjou et al., 2013
	Exotic Seaweed Cultivation	Affects light penetration leadingg to death of seagrass	Mathews et al., 2010
Gulf of Mannar	Southwest monsoonal winds, Northeast monsoon, Cyclones	Physical damage to seagrass and reduced light penetration due to high turbidity	Thangaradjou and Nobi, 2009
	Shell harvesting of Tellina angulata	Physical destruction of seagrass rhizomes and roots	Thangaradjou et al., 2007; Thangaradjou and Nobi, 2009,
	Anchoring of boats, Propellers damage	Uprooting of seagrass	Thangaradjou and Nobi, 2009, Mathews et al., 2010
	Use of push nets, trawl nets, bottom set gill nets	Physical damage to the seagrasses by uprooting the plants and removing the healthy leaves	Thangaradjou and Nobi, 2009, Mathews et al., 2010, D'Souza et al., 2013

Table 3 (Continued): System specific major threats of Indian seagrass ecosystems (Source: Ramesh et al., 2018 and references therein)

Location	Major Threats	Impacts	Reference
Chilika Lagoon	Natural hazards like storms, floods	Physical damage to seagrass and reduced light penetration due to high turbidity	Priyadarsini et al., 2014
	Dredging, inappropriate fishing, anchoring, coastal constructions	Uprooting of seagrass	Priyadarsini et al., 2014
	Coastal aquaculture wastes	Eutrophication, growth of algae that competes with seagrass. Diminished light availability and sediment quality.	Priyadarsini et al., 2014
Gulf of Kachchh	Industrial and domestic pollution	Eutrophication and formation of algal blooms	Kamboj, 2014
	Development of ports and harbours	Increase in sedimentation, solid waste and marine pollution	Kamboj, 2014
	Fishing and Boat activities	Physical damage to the seagrass leaves and rhizomes	Kamboj, 2014
Andaman & Nicobar Islands	Intense Boating and Tourism activities	Physical damage to the seagrasses roots/ rhizomes and leaves	Thangaradjou and Nobi, 2009
	Diseases – Leaf Redding	Decolouring of leaves leading to seagrass mortality	Ragavan et al., 2013
	Tsunami, Cyclones, Storms	Physical damage, sediment dumping on seagrass and increase turbidity	Thangaradjou and Nobi, 2009, Danielsen et al., 2005
Lakshadweep	Grazing by green turtles (protected species)	Grazing pressure can modify species composition	Lal et al., 2010; Kaladharan et al., 2013
	Boating and Tourism activities	Physical damage to the seagrasses roots/ rhizomes and leaves	Thangaradjou and Nobi, 2009; Nobi et al., 2013
	Sea erosion and siltation	Affects light penetration and seagrass die off	Nobi et al., 2013
	Disposal of fish waste and untreated solid waste	Localized eutrophication and seagrass damage	Thangaradjou and Nobi, 2009






4. Previous studies on GHG emissions from Indian Blue Carbon Ecosystems

Assessment of GHG emissions from mangroves is vital in resolving the carbon balance of coastal blue carbon ecosystems. Banerjee et al. (2014), pointed out a large inconsistency exists in the GHG flux estimations from Indian mangrove ecosystems; with respect to the uniform methodologies and time scale studies. There have been some studies from Indian coastal systems, which explains that the spatial and temporal CH_4 concentration/ fluxes are majorly governed by factors like sediment ebullition, anthropogenic perturbation, methanogenesis, CH_4 oxidation and lateral diffusion from catchments (Purvaja and Ramesh, 2001; Shalini et al., 2006; Barnes et al., 2006; Rajkumar et al., 2008; Rao and Sarma, 2016). Similarly, for CO_2 emissions high heterotrophic activity, residence time of water, soil-water interaction, and effect of rapid urbanization and industrialization are the major controlling factors (Sarma et al., 2001; Mukhopadhyay et al., 2002; Gupta et al., 2009; Sarma et al., 2012). GHG fluxes from 27 Indian estuaries were studied by Sarma et al. (2012) and Rao and Sarma (2016) and reported that the estuarine waters are always super-saturated with respect to CO_2 and CH_4. CH_4 fluxes were always lower by two orders of magnitude compared to CO_2 from Indian estuaries/ mangrove waters.

Earlier reported studies from Island mangrove waters showed emissions between 23 and 173 mmol m^{-2} d^{-1} for CO_2 and 0.11–0.47 mmol m^{-2} d^{-1} for CH_4 (Neetha et al., 2013); which accounts to be total emissions from mangrove waters (667 km^2) as 259 – 1,905 Gg CO_2e y^{-1}. Similarly, Sarma et al. (2012) found the annual CO_2 emissions from Indian estuaries as 7,040 Gg CO_2e y^{-1}, which is negligible compared to the anthropogenic emissions from the Indian subcontinent. Whereas Rao and Sarma (2016), reported higher methane emissions from west coast compared to east coast estuaries; with annual emissions amounted to 109 Gg CO_2e y^{-1}.

Exogenous nature of CH_4 in Sundarbans mangroves were reported by Dutta et al. (2015), and its emission accounts for 5% (2.60 Gg CO_2e y^{-1}) of total CH_4 supplied to the system. Changes in land use pattern of mangrove ecosystems to paddy fields and aquaculture trigger the methane flux to the atmosphere (4 folds) and thereby even reduces the sequestration potential (Chauhan et al., 2017). Seagrass ecosystems could play a potential role in the GHG budgets of coastal ecosystems. Whereas, there is a major lack of studies on GHG fluxes from seagrass meadows compared to other blue carbon ecosystems (Banerjee et al., 2018).

Simultaneous estimated data for both CO_2 and CH_4 from the same sites of different blue carbon ecosystems are sparse. Thus, the more detailed systematic approach is needed to reduce the uncertainties in the current knowledge of carbon fluxes from Indian blue carbon ecosystems. NCSCM has estimated emissions from Indian mangroves and seagrass ecosystems, which is first of its kind. Following the uniform methodology and considering areal extent of mangroves and seagrasses, pan India estimation have been made.

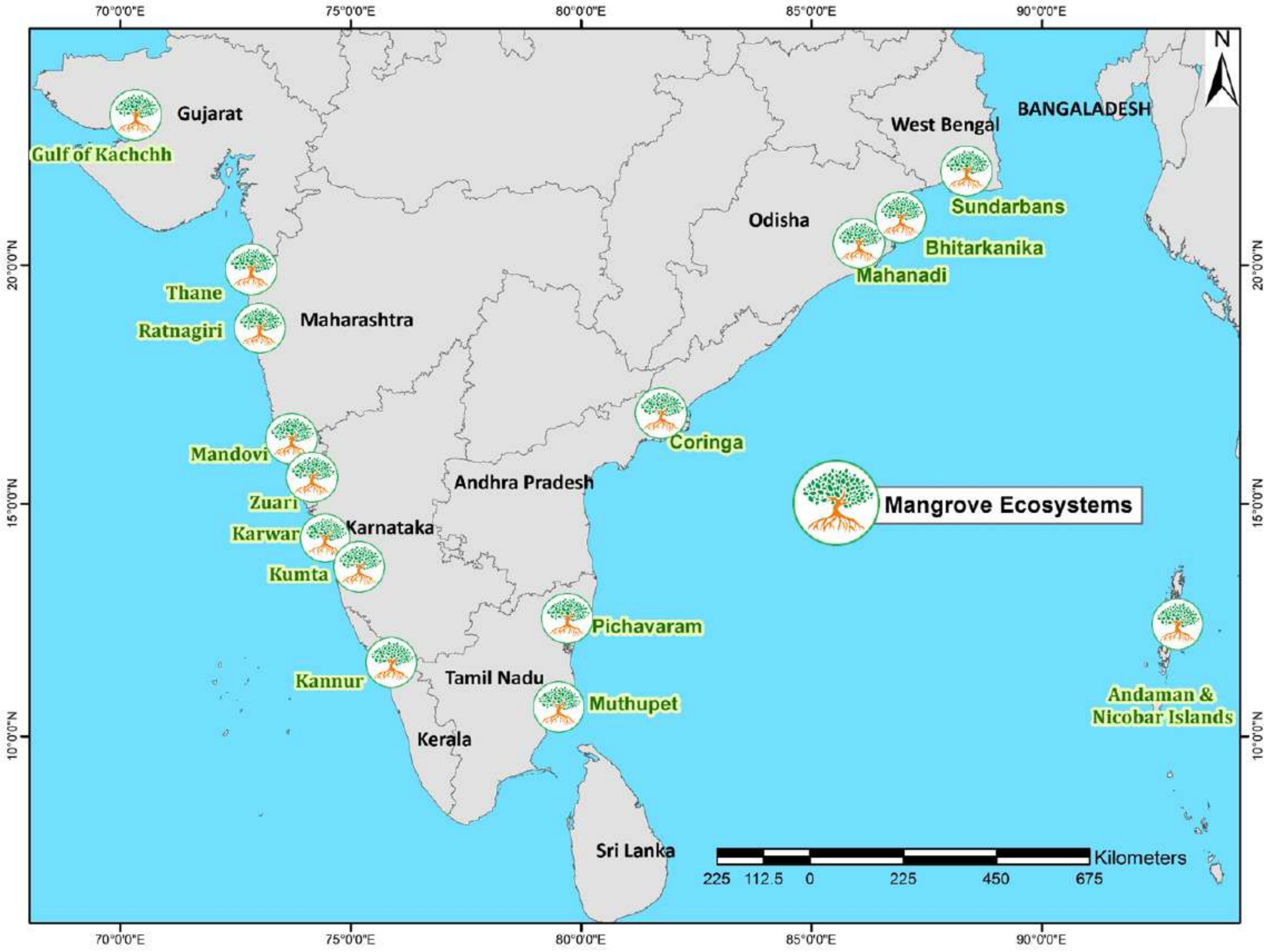

Figure 1: Distribution of mangroves along the Indian coast

Figure 2a: Pristine mangroves of Sundarbans

Figure 2b: Impacted mangroves of Thane

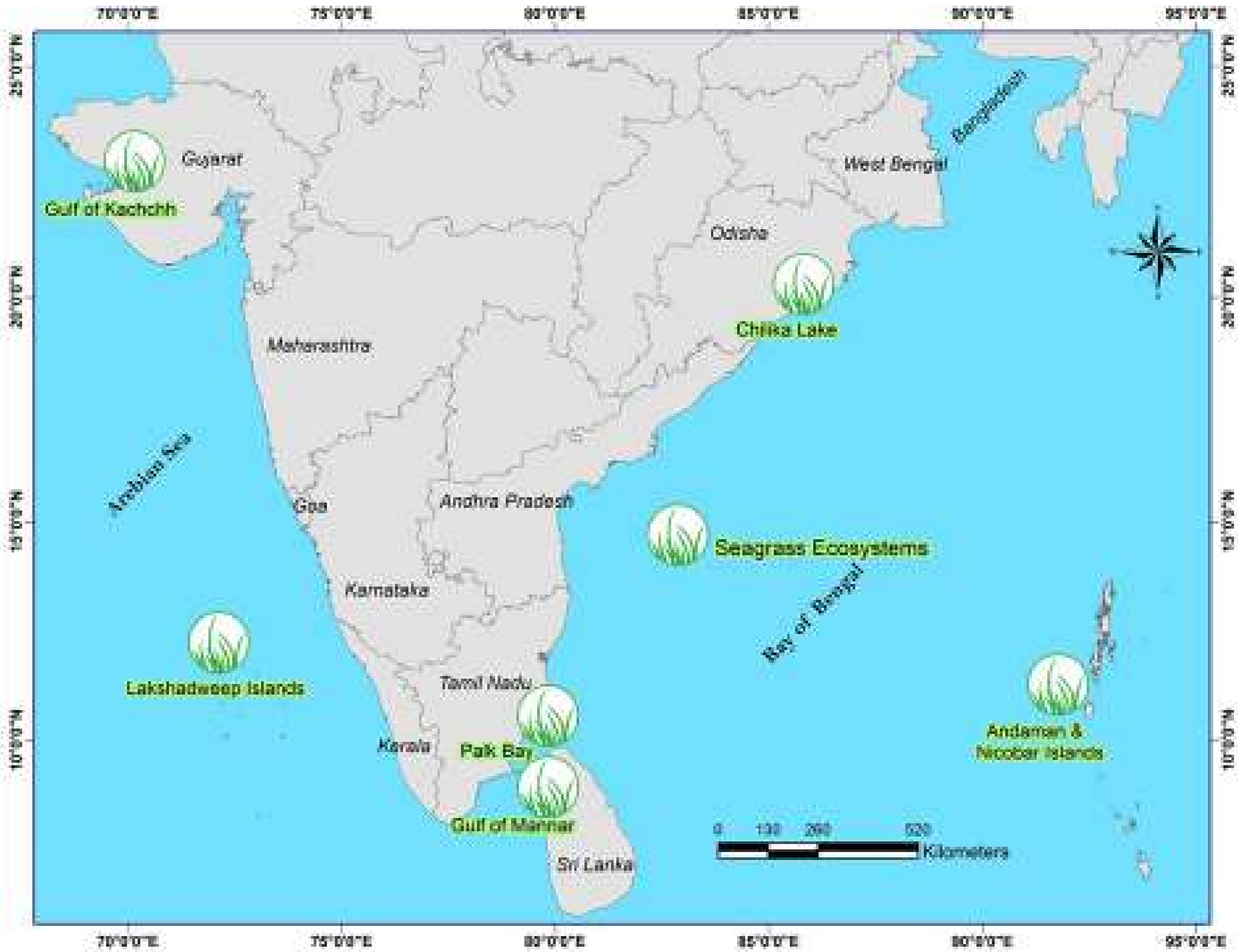

Figure3: Distribution of seagrass along the Indian coast

5. GHG emission scenarios from Indian blue carbon ecosystems

The Indian mangroves exhibited a wide range of variations in terms of biodiversity and biomass, which could be due to varying geographical and hydrological conditions resulting from variable freshwater discharge, flushing rates, and tidal amplitude. A complex interaction of dissolved and particulate materials drawn by rivers, including carbon and nutrients (Lovelock et al., 2004), sedimentation and re-suspension processes, which enhance soil and water microbial processes (Wang et al., 2009), ultimately releases greenhouse gases (CO_2, CH_4) from mangroves systems. Indian mangroves are generally tropical systems, because of the prevalent higher temperatures; higher rates of metabolism in mangrove surrounding waters would naturally be expected here. Pan India extensive surveys have been made to better understand a part of C cycling in terms of the seasonal and spatial variations of pCO_2 and dissolved CH_4 and their air-sea fluxes from mangrove surrounding waters. Assuming the mangrove systems inundated with water for some part of time; the fluxes were upscaled to the recent mangrove area estimation (5,403 km^2) (NCSCM unpublished data). The present work combined the emission measurements of both the GHG (CO_2 and CH_4) from the mangrove waters. The flux rates estimated here are based on the Borges (2004) parameterization (k); which were always on the higher side compared to Wanninkhof (1992).

The annual mean pCO_2 concentrations in the Indian mangrove waters ranged between ~650 to 6,300 µatm, with the lowest in Sundarbans and highest in mangroves of Thane. pCO_2 concentrations in Indian mangroves were 1.5 to 5 times higher during the wet season than that of the dry season. Annual mean CO_2 fluxes showed wide variations in the Indian mangroves, and ranged from 11 to 101 mol m^{-2} y^{-1} in the mangroves located along the west coast and 5 to 84 mol m^{-2} y^{-1} in the east coast mangroves. Relatively higher annual mean flux was found in the east coast mangroves (53 mol m^{-2} y^{-1}) than west coast mangroves (34 mol m^{-2} y^{-1}), except in mangroves of Thane which stands alone with highest emission 101 mol m^{-2} y^{-1}. Total CO_2 emission (in terms of CO_2 equivalents, considering the global warming potential of CO_2 as 1) from Indian mangroves was 5106 Gg CO_2e y^{-1}, considering the total mangrove area as 5,403 km^2.

The annual mean dissolved CH_4 concentrations in the east and west coast, mangrove waters ranged between ~18 to 108 nmol $L^{-1}$and ~14 to 104 nmol L^{-1}, respectively. Distinct seasonal variations were observed, with wet season ~1.5 to 3 times of higher CH_4 concentrations than the dry season. Indian mangrove waters were always super-saturated with dissolved CH_4 with respect to atmospheric equilibrium. The annual CH_4 fluxes from Indian mangrove waters ranged between ~0.01 to 0.12 mol m^{-2} y^{-1}, with an average of 0.05 mol m^{-2} y^{-1}. Total CH_4 emission (in terms of CO_2 equivalents, considering the global warming potential of CH_4 as 28) from Indian mangroves was ~88 Gg CO_2e y^{-1}, considering the total mangrove area as 5,403 km^2. State-wise % contribution of CO_2 and CH_4 emissions (in terms of Gg CO_2e y^{-1}) is given in (Figures 4a and 4b), respectively. Percentage contribution is not only dependent on the magnitude of emission, but also the areal coverage of mangroves of a particular state.

Table 4. Greenhouse gas fluxes from Indian mangroves ecosystems (Flux values are represented as Gg $CO_2e\ y^{-1}$)

No.	State	Area (km2)	Mangroves Studied	CO2 Flux	CH4 Flux	Net GHG Flux (CO2 + CH4)
EAST COAST						
1	West Bengal	2207	Sundarbans	445	12.6	457
2	Odisha	276	Bhitarkanika, Mahanadi	867	6.4	874
3	Andhra Pradesh	408	Coringa	1098	21.2	1119
4	Tamil Nadu	119	Pichavaram, Muthupet	283	1.9	285
WEST COAST						
5	Kerala	21	Dharmadom, Valapatnam	46	0.4	47
6	Karnataka	17	Aghanashini, Kali	26	0.4	27
7	Goa	33	Mandovi, Zuari	61	0.5	61
8	Maharashtra	307	Thane, Ratnagiri	803	6.8	810
9	Gujarat	1339	Gulf of Kachchh	666	20.9	687
ISLANDS						
10	Andaman & Nicobar	667	Wright Myo, Bakultala, Diglipur	725	16.4	741

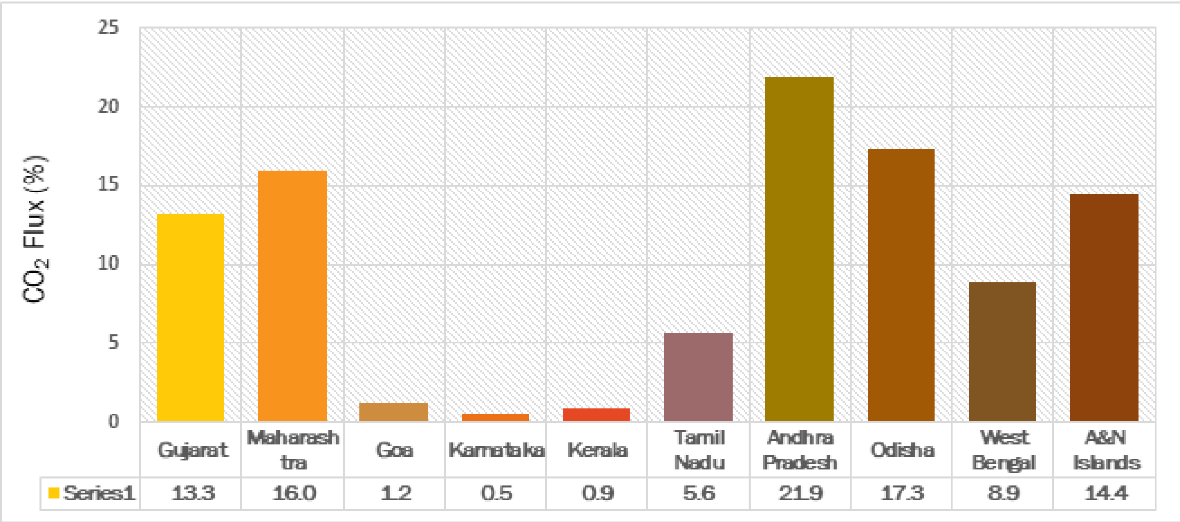

Figure 4a: State-wise % contribution of CO_2 fluxes from mangrove ecosystems (Flux values are represented as Gg CO_2e y^{-1})

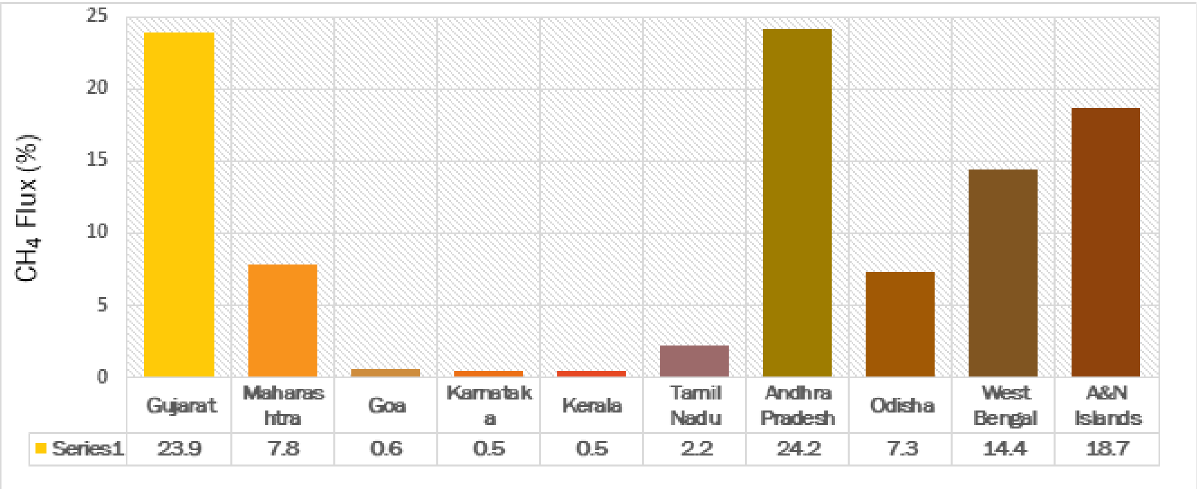

Figure 4b: State-wise % contribution of CH_4 fluxes from mangrove ecosystems (Flux values are represented as Gg CO_2e y^{-1})

Contribution of CO_2 flux of total emission is ~98%. The net emission (in terms of CO_2 equivalents) from Indian mangrove waters was found to be 5,106 Gg CO_2e y^{-1}. Mangrove surrounding waters act as a weak source of GHG, though the entire system is considered a net sink of carbon. East coast mangroves contribute to the highest emission, ~2,735 Gg CO_2e y^{-1}, followed by west coast mangroves, ~1,631 Gg CO_2ey^{-1} and islandic mangroves, ~741 Gg CO_2e y^{-1} (Table 4, Figure 5). Emissions from east coast mangroves are related to high riverine discharge along with organic matter load, which aids heterotrophic respiration, leading to higher emissions. In the west coast mangroves, due to low residence time of the waters, the microbes get less time for the decomposition of organic matter, leading to comparatively less emissions. The study supports the substrate availability to the mangrove waters and its residence time is the major factor controlling the GHG emissions from Indian mangroves. Apart from that, salinity and wind speed plays major role in controlling GHG emissions from mangroves.

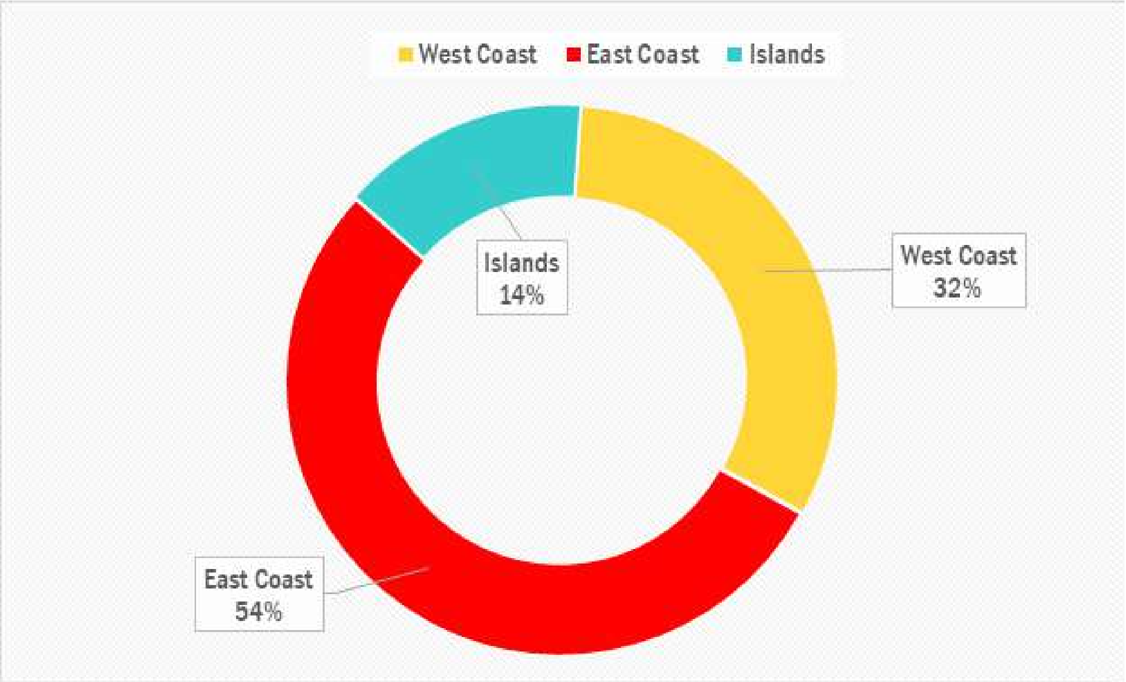

Figure 5: Net Emission (Gg CO2 equivalent) scenarios from Indian mangrove waters

The classic example is the presence of megacity like Mumbai, with not so effective wastewater treatment systems, making the mangrove ecosystems in Thane more vulnerable and major sources of GHG. Elevated levels of labile organic matter from the watershed area enhances oxygen consuming decomposition processes, resulting in increased CO2 and further anoxic water column produces CH4, causing emissions at the water–air interface of the system. Whereas mangroves of Gulf of Kachchh, in spite of high organic load, emits less GHG, because of the constant high salinity, which acts as a natural buffer for GHG emissions.

Seagrass ecosystems of India, are perennial net sink of CO2, however when disturbed they act as a minor source. Prominent seasonality of GHG fluxes in seagrass meadows alters the net magnitude of the sink. Whereas, seagrass meadows acts as a weak source of CH4, although the contribution of CH4 flux to the net emission is around ~2%. It was observed that CO2 emissions from seagrass are several times lesser than nearby non-seagrass zones. Species level study from different systems revealed that Cymodocea sp. bed captures dissolved CO2 most effectively among other species. Study from Palk Bay showed diurnal variation in pCO2; with distinct seasonal pattern (Ganguly et al., 2017). pCO2 in Palk Bay seagrass meadows are always under-saturated during dry season (<429 µatm) with atmospheric equilibrium and plays a dominant role in biological carbon fixation. However, Banerjee et al., 2018, found Chilika seagrass meadows as a minor source of CH4 (0.03 – 0.39 mmol m-2 d-1) throughout the year, but a minor sink of CO2 (-33.9 mmol m-2 d-1) during dry season. Net emission of GHG from major seagrass ecosystems shows ~32 Gg CO2e y-1 (Figure 6). It is evident that factor like anthropogenic influences and seasonality, intensifies the heterotrophic mineralization and thereby enhances the GHG emissions from seagrass ecosystem (Banerjee et al., 2018). The GHG emission comparison between seagrass and mangroves ecosystems of India clearly shows that the later contributes substantially (Figure 7)

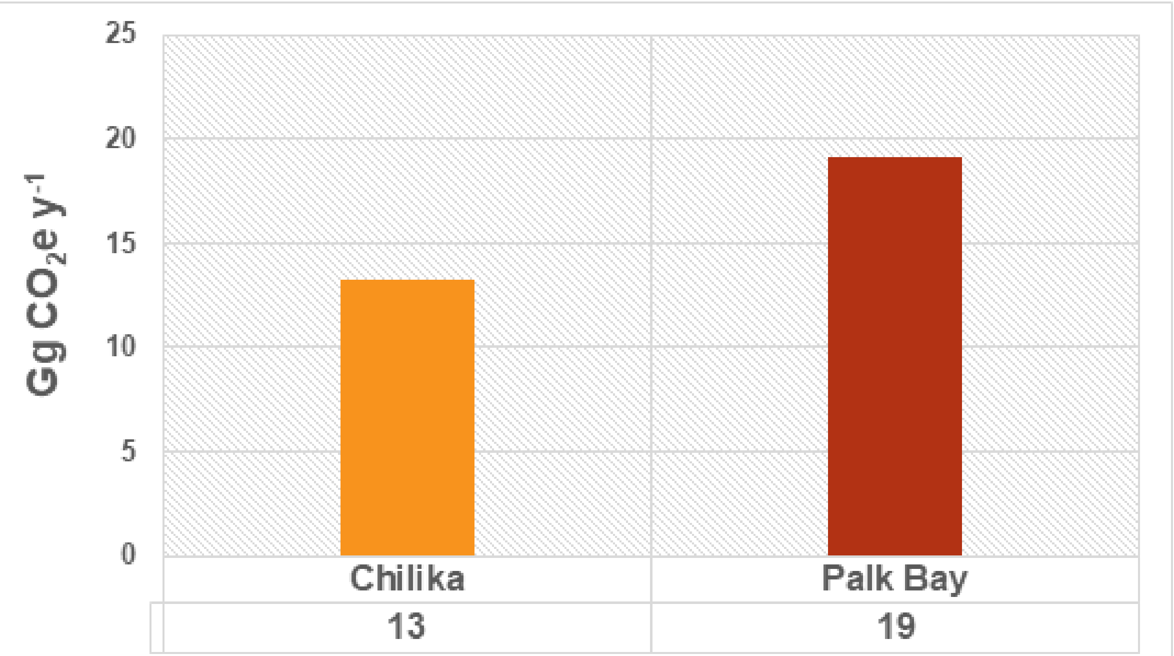

Figure 6: Net Emission (Gg CO_2 equivalent) scenarios from major Indian seagrass ecosystems (Areal extent Palk Bay 330 km^2 and Chilika 75 km^2, ~80% of the total cover 517 km^2)

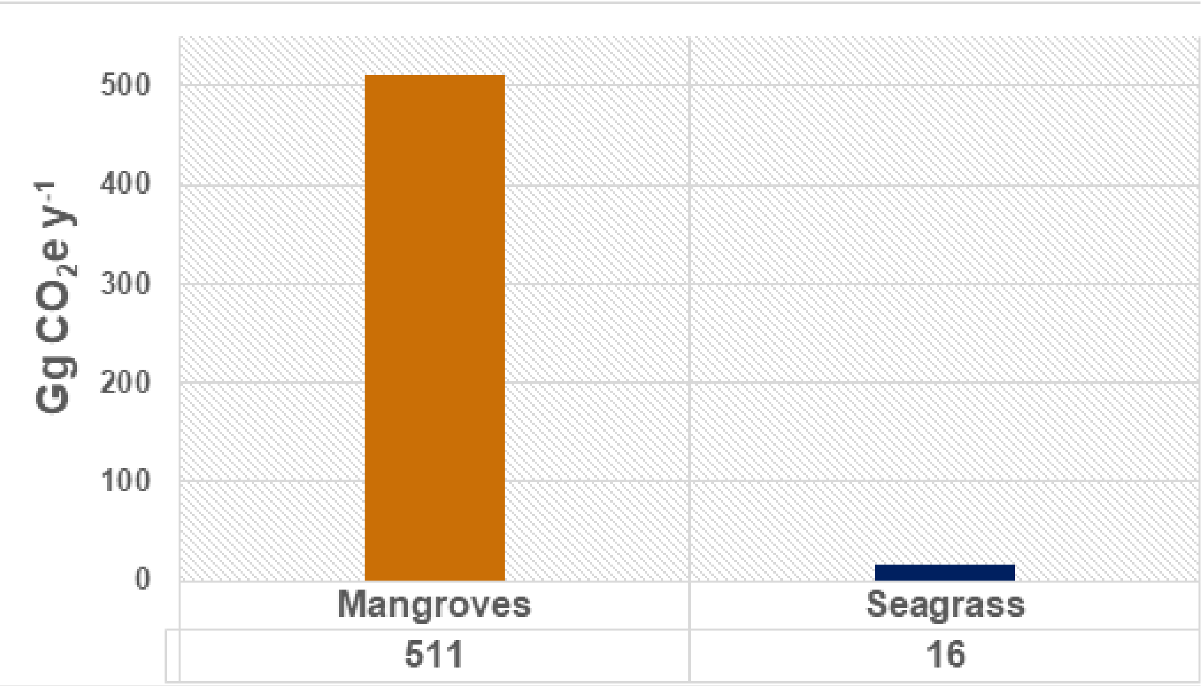

Figure 7: Comparison of Net Emission (Gg CO_2 equivalent) scenarios from major studied Indian Blue carbon ecosystems (Total mangrove and seagrass cover 5,403 km^2 and 517 km^2, respectively)

6. Factors affecting CO_2 and CH_4 emissions in Blue Carbon Ecosystems

Mangroves as a whole ecosystem scale are considered as net sink of CO_2, although mangrove sediments and surrounding waters are generally sources of CO_2 (and CH_4) to the atmosphere. It is observed from most of the studied systems that, mangrove surrounding waters are heterotrophic, and the heterotrophic nature were varying among the systems and particularly dominant during the wet season. CO_2 loading from the watershed area of rivers and difference in the production and respiration rates in water and benthic column ultimately regulates the source/sink characteristics of CO_2.Hence, comparatively higher emissions are observed from deltaic mangroves (east coast mangroves) due to large altered watershed area, high water discharge rate and higher organic load. GHG flux dynamics in mangrove ecosystems are triggered by nature and rate of OC loading through various sources like agriculture/aquaculture activities, domestic and industrial sewages. Apart from this, the residence time of the water in the systems also governs the magnitude of CO_2 emission from the waters to the atmosphere. Mangroves of the west coast are on comparatively steep topography than the east coast, which facilitates the water to drain out of the system faster and less time for the organic load to metabolized into gaseous CO_2. The influence of damming and deforestation alters the riverine/organic load to the mangrove waters and thereby the CO_2 fluxes.

Similarly, CH_4 fluxes in mangroves are driven by a multitude of factors of which the anaerobic microbial decomposition of the sedimentary organic matter takes place with the help of available oxygen/electron acceptors. Primarily, CH_4 is produced in the pore waters, which drains to the adjacent creek waters during tidal cycle, ultimately escaped in gaseous form to the atmosphere from both mangrove sediment and water column. Comparatively, lush mangroves of the east coast, support surplus supply of labile organic matter from the litters; which triggers the CH_4 flux from its anoxic sediments. Apart from these, the variation in hydrodynamic conditions like temperature, salinity and depth influences the microbial actions in the system, in turn affects CH_4 fluxes from mangrove surrounding waters.

Seagrass ecosystems represent one of the most ecologically rich and productive blue carbon ecosystems.Maximum seagrass spread, abundance, and species richness are usually associated with high and stable salinity regions. As an example, the average and maximum seasonal seagrass patch size for the entire shallow Chilika lagoon ranged between 85 km^2 (dry) and 65 km^2 (wet). Lagoon and bays viz. Chilika, with a fluctuating range of salinity are usually associated with a limited number of species with a maximum spread only during dry season. The growth of seagrass depends upon sediment texture, sandy to silty-mud supports dense meadows. Whereas, sea grass meadows quite often become silted and degraded during monsoon with freshwater flooding in, leading to shrinking of seagrass patch due to degradation, ultimately influences seagrass mediated GHG dynamics. This leads to the release of excess CO_2 due to the higher decomposition of decayed seagrass and enhanced decomposition of decayed seagrass and intrusion of land derived organic detritus in the system. Another determining factor for *in situ* CO_2 production is dissolved organic carbon (DOC) and it's quality. As DOC, with higher non-labile fractions, are more resistant to microbial activities (degradation), resulting controlled GHG emission through heterotrophic respiration. Seagrass sediments are enriched in organic carbon derived from the litter fall, creating anoxic environment and aiding CH_4 emission. Hence, seagrass meadows are generally considered as a minor source of CH_4, whereas healthy and dense seagrass beds can effectively capture dissolved CO_2. Hence, both temporal and spatial changes in environmental and physical parameters influence the growth, diversity and biological processes in seagrass, which in turn significantly modify the trace gas dynamics of the system. As an example, the spatial variations of CO_2 and CH_4 fluxes and possible influencing factors between different parts of seagrass and the role of vegetative ecosystem has been summarized and represented as a conceptual diagram in Figure 8.

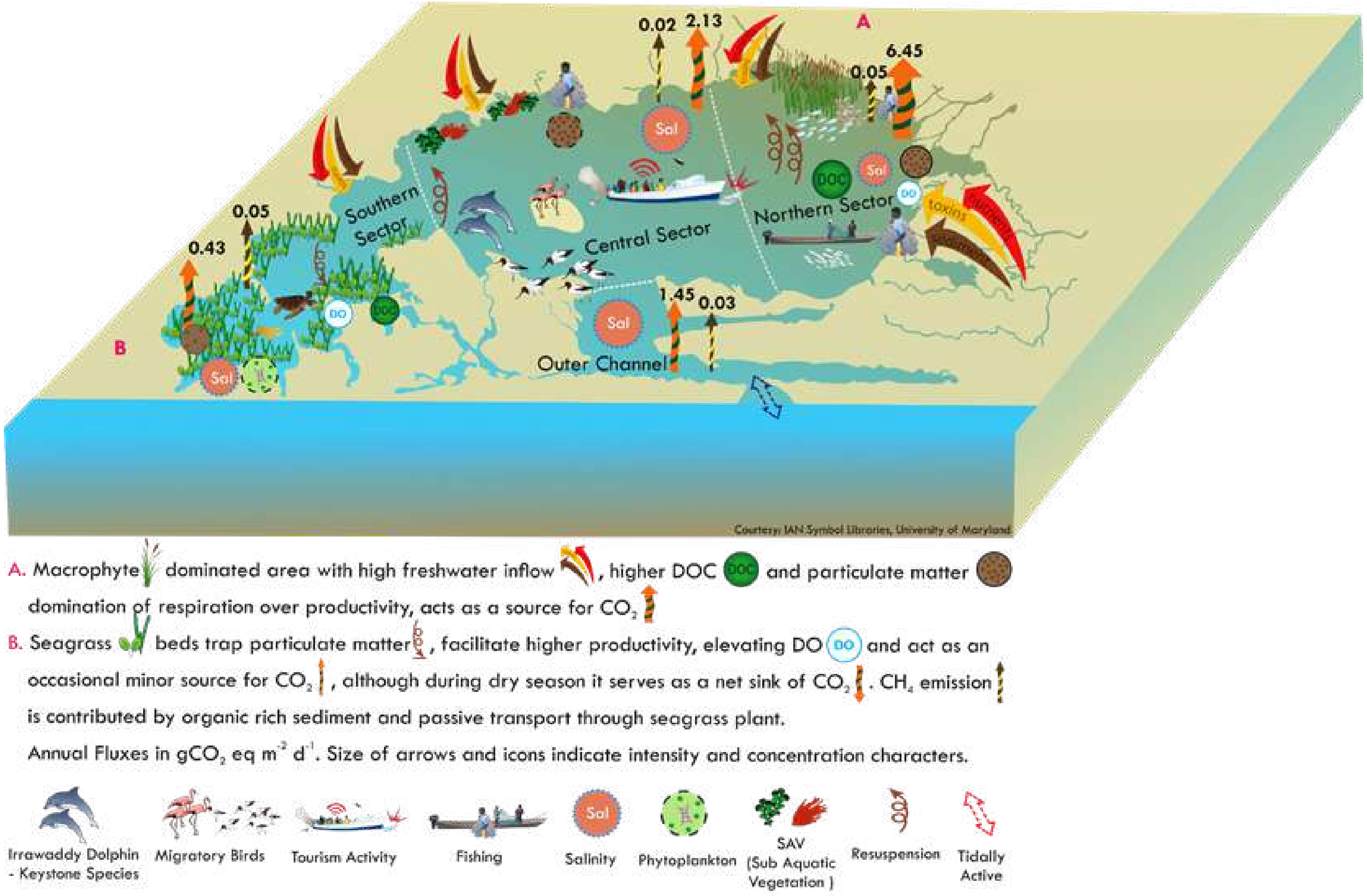

Figure 8: Conceptual diagram summarizing spatial variations of CO_2 and CH_4 fluxes and possible influencing factors in Chilika Lagoon

Conclusion

Coastal wetlands such as mangroves, seagrasses and salt marshes are having natural carbon dioxide removal techniques from the atmosphere by sequestering carbon for long-term, as a "Blue Carbon". However, some of the sequestered carbon naturally get metabolized and returns to the atmosphere as CH_4, offsetting C burial potential of any coastal ecosystem.Apart from the natural offsetting mechanism, excessive human induced pressures, largely reduces the climate mitigation potential of mangrove ecosystems, sometimes making them sources of greenhouse gases instead of sink.

To maintain the sustainability of coastal wetlands with respect to carbon storage in the future, there is a dire need of research related to understanding of carbon capacity and fluxes from the blue carbon ecosystems. This would give a state of knowledge to the policy makers on the potential incentives of coastal blue carbon.Increased atmospheric CO_2 concentration is considered as one of the most significant root cause of global climate change, which has gathered much attention in the scientific communities. To combat climate change, there are two conventional mitigation strategies - reduction of emission and preservation and enhancement of natural carbon stores.

Even though the surrounding waters of both blue carbon ecosystems emit GHGs, seagrass meadows aids in reducing the GHG emission by effectively capturing the dissolved CO_2 compared to the other aquatic vegetation like –macrophytes. Seagrass meadows also benefits the adjacent coral ecosystems in Palk Bay by modifying the water chemistry. Similarly, the CO_2 sinking potential of mangrove canopy over ride the emission found from its surrounding waters, and act as an important regulator of GHG. Our GHG emission results strengthen the quantification and reduces the uncertainties in the carbon budget of Blue carbon ecosystems; and thus emphasize the importance of conserving it.

This pan India greenhouse gas estimation from blue carbon ecosystems, indicate the overall potential environmental impacts on them, which will be useful to assess the net carbon storage potential of each ecosystem. Based on the status of each blue carbon ecosystem, existing policy and governance framework should be implemented focusing on restoration and conservation strategies towards the climate mitigation efforts. It is estimated that conservation and restoration of 100 ha of the degraded mangrove and seagrass forest may reduce 144×10^3 tonnes and 52.2×10^3 tonnes of CO_2 emissions per year, respectively. Apart from that, 20% increase in mangrove cover along the Indian coast may create an additional sink of $\sim 669 \times 10^3$ tonnes CO_2 per year. Similarly, a 20% increase in seagrass area cover in India may create an additional sink of $\sim 82.4 \times 10^3$ tonnes CO_2 per year.

7. Acknowledgements

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Carbon sequestration by coastal ecosystems

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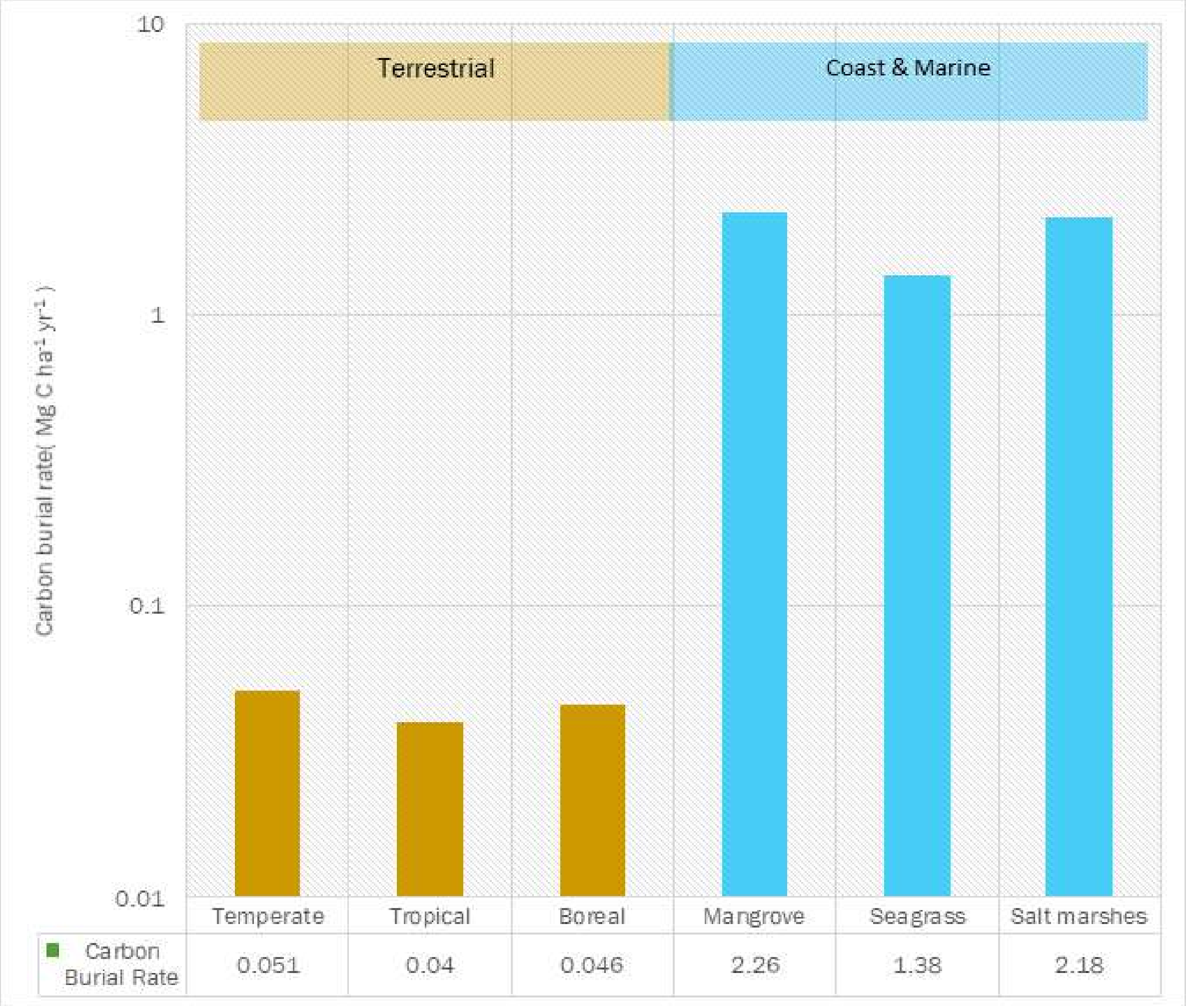
ABSTRACT

Contribution through carbon sequestration by blue carbon ecosystems is considered to be significant in climate change mitigation. The sequestration capacity by blue carbon ecosystems (mangrove and seagrass) of India has been reviewed and synthesised to understand their regulatory role in regional climate change mitigation. The study showed significant variations in the net C flux and storage in the sediment with space and time, depending on various environmental and anthropogenic factors. The mean C stock in top one-metre mangrove soil ranged between 62 and 207 Mg C ha^{-1}, whereas, C-sequestration seagrass sediment ranged between 107 and 143 Mg C ha^{-1}. It is estimated that these coastal ecosystems of India can be three times more efficient in terms of capturing atmospheric CO$_2$, than the terrestrial forest ecosystems.

1. Introduction

The global average atmospheric carbon dioxide concentration increased to 408 parts per million (ppm) in August 2018 (http://co2now.org/), the highest level in the past 8 million years. The Intergovernmental Panel on Climate Change (IPCC 2007) estimates that by the year 2050, global CO_2 emissions must be reduced by 85% from levels seen in 2000 to prevent a global mean temperature increase of 2°C. In order to reduce atmospheric CO_2 concentrations, a more recent approach has been suggested that include combined reduction of anthropogenic CO_2 sources (mitigation) with supporting CO_2 uptake and storage through the conservation of natural coastal ecosystems with high C sequestration rates and capacity. Mangroves, seagrass and salt marshes are popularly termed as "Blue Carbon Ecosystem" as these coastal vegetated ecosystems are associated with high rates of carbon sequestration with carbon storage on longer time scales (Figure 1).

These ecosystems sequester C within their underlying sediments; living biomass as above-ground (e.g. leaves, stems, branches) and below-ground (e.g. roots), and in non-living biomass. Blue carbon is sequestered over short term (decennial) in biomass and over longer (millennial) timescales in sediments (Duarte and Jensen, 2017). This new recognition of "blue carbon" is primarily based on research demonstrating that seagrass meadows, mangrove forests, and tidal salt marshes are highly efficient C sinks (Chmura et al., 2003; Duarte et al., 2005, 2010; Bouillon et al., 2008).



	Temperate	Tropical	Boreal	Mangrove	Seagrass	Salt marshes
🟩 Carbon Burial Rate	0.051	0.04	0.046	2.26	1.38	2.18

Figure 1: Carbon burial rates (Mg C ha^{-1} y^{-1}) of different (terrestrial and Coastal & marine) vegetative ecosystems (redrawn from Mcleod et al., 2011)

a. Mangrove ecosystems

Mangrove forests efficiently capture atmospheric carbon, trap sediment material, undertake autochthonous production (e.g. algae and benthos) and receive allochthonous organic matter (riverine or marine) through their intricate root systems (Kristensen et al., 2008). Furthermore, approximately one-third of the primary production is lost as litter-fall. However, the breakdown of organic litter by decomposers such as crabs, act as a source of organic carbon to the sediment (Alongi and Robertson, 1992). Hence, mangrove environments are sites of intense carbon processing with a potentially high impact on the global carbon budget (Kristensen et al., 2008).

Duarte and Cebrian, (1996) estimated that approximately 10% of the mangrove production is buried in sediments, and the rest is either exported (~30%), consumed (~9%), decomposed (~40%), or unaccounted (~10%). However, these percentages are strongly dependent on site-specific environmental conditions (Duarte and Cebrian, 1996). These rates (litter production, export and carbon burial) vary from one system to another and are dependent on several factors including community structure, hydrodynamics and other coastal processes (Alongi and Robertson, 1992). Estimates by Mcleod et al. (2011), indicate mangroves covering an area of 1.38 - 1.52 x 10^3 km^2 bury upto 31.1 - 34.4 Tg C per year globally, with the burial rate reaching as high as 949 g C $m^{-2}yr^{-1}$ (mean C burial rate 226 ± 39 g C $m^{-2}yr^{-1}$).

b. Seagrass ecosystems

Globally the area covered by seagrass meadows has not been comprehensively mapped yet, although estimates suggest that these ecosystems cover an area between 1,50,000 and 43,20,000km^2 (Duarte, 2017). One of the key reasons for the inconsistencies in mapping of the extent of seagrass ecosystems is its seasonality in distribution. The health and cover of the seagrass ecosystem, largely depends on the salinity of the ambient water column and high influx of fresh water during monsoon, causing considerable stress to these systems. Globally, seagrass ecosystem is estimated to account for ~10% of the yearly estimated organic carbon (C_{org}) burial in the oceans with rates as high as 190 g C m^{-2} yr^{-1} and,48 - 112 Tg C yr^{-1}; despite the low percentage of area cover compared to world's ocean area (<0.2%). (Fourqurean et al., 2012).

The high carbon burial rates of seagrass have been attributed to high primary productivity of these ecosystems and their capacity to filter particles from the water column and store them in soils. This is combined with low decomposition rates OC in the oxygen-poor seagrass soils. Furthermore, this is complemented with the stability of seagrass bed sediments, which allows C_{org} to accumulate over millennia into sediment deposits much deeper than 1 m.

1.1 Blue Carbon Ecosystems: Need for Conservation

It is estimated that the near-surface susceptible carbon content (i.e. in the top one meter) in sediments layer averages to 326 Mg CO_2/ha (tonnes of carbon dioxide per hectare) for seagrass, 593 Mg CO_2 / ha for salt marshes and 933 Mg CO_2/ha for mangroves (Pendleton et al., 2012). Despite the high carbon sequestration rates, these systems are lost rapidly. During past decades, the cumulative losses of coastal vegetation have been estimated as 25–50% of total global area of each type with estimated annual loss varying from 0.5% to 3% (Pendleton et al., 2012). Causes of habitat conversion vary around the world ranging from transformation of mangrove areas to aquaculture and agriculture, exploitation of forest resources, to conversion of mangrove ecosystems for industrial and urban development. Action is urgently required to prevent further degradation and loss of such key ecosystems. Recognising the C sequestration value these ecosystems provide, there is a strong need for their protection and restoration.






2. Blue carbon ecosystems (seagrass and mangroves) of India

2.1 Distribution and diversity of Indian mangrove ecosystems

India has a mangrove cover of 5403 km^2 (NCSCM Data, unpublished), the fourth largest mangrove area in the world. Around 57% of the mangrove cover of India is located in the east coast, 30% in the west coast and the remaining 13% in the islands.

Propagation and growth of mangrove is dependent on environmental setting such as geomorphology, climate, tidal amplitude and freshwater inflow. Furthermore, the influence of fresh water inflow and nutrients are the major decisive factors of mangrove community zonation and plant succession. Regions with low salinity are often associated with species like *Heritiera fomes* and *Excoecaria agallocha*; whereas the more resilient *Avicennia sp.* dominate in high saline regions (Satyanarayana et al., 2002, Mishra et al., 2005, Singh et al., 2016). Distinct variations in primary production, litter decomposition and carbon content are observed, with the mangrove species zonation (Komiyama et al., 2008).

Species diversity and distribution

India has the third highest mangrove biodiversity after Indonesia and Australia, comprising of 46 true mangrove species belonging to 14 families and 22 genera (Raghavan et al., 2016). The east coast of India with over 40 species has higher mangrove biodiversity than the west coast with 27 species (Table 1).

2.2 Distribution, diversity, types and zonation of Indian seagrass ecosystems

Seagrasses are considered as a biological group with about 72 species that belong to four independent evolutionary lineages (Les et al.,1997). However, their species diversity is limited as extreme adaptations are required to survive in the marine environment. The actual number of seagrass species is a matter of debate, depending in part on their proximity to the marine environment and on the level of discrimination in physical taxonomy and genetics. Seagrass habitats in India are restricted from the lower intertidal zone to the open shores and in the lagoons (Table 2).

Dense meadows of seagrass are observed along Palk Bay and Gulf of Mannar, Chilika lagoon, Gulf of Mannar, Gulf of Kachchh and in a few islands of Lakshadweep (Arabian Sea) and Andaman and Nicobar Islands (Bay of Bengal). The maximum seagrass cover, abundance, and species richness are usually associated with regions with high salinity and less variation throughout the year (Table 2)

Table 1: Mangrove species diversity and distribution in India[1]

State/UT	Mangrove Diversity	Dominant species
East Coast of India		
West Bengal (Sundarban)	33 true mangrove species; 21 genera and 14 families	**Eastern Sector:** Heritiera fomes mixed with Excoecaria agallocha, Sonneratia sp, and Xylocarpus sp. **Central Sector:** Ceriops decandra with patches of Phoenix paludosa (mangrove associate), Rhizophora mucronata, Excoecaria agallocha, Aegialitis rotundifolia, Avicennia marina. **Western Sector:** Avicennia marina, A. alba, A. officinalis, Excoecaria agallocha, Bruguiera gymnorrhiza, Ceriops decandra, Xylocarpus granatum, Sonneratia apetala
Odisha (Bhitarkanika)	35 true mangrove species; 20 genera and 14 families	Heritiera fomes occupies the major portion of Bhitarkanika while in other parts it is mixed communities of Excoecaria agallocha Other dominant species include Sonneratia apetala, Avicennia marina, A. alba, Excoecaria agallocha, Lumnitzera racemosa
Andhra Pradesh (Coringa)	22 true mangrove species; 15 genera and 11 families	Avicennia officinalis, Excoecaria agallocha, Avicennia marina, Avicennia alba, Rhizophora mucronata
Tamil Nadu (Kaveri delta)	17 true mangrove species; 12 genera and 8 families	**Pichavaram:** Avicennia marina occupies 94.67% of the area followed by Rhizophora sp. along the fringes **Muthupet and Villunivayal:** Avicennia marina
Puducherry	15 true mangrove species; 10 genera and 7 families	Avicennia sp., Rhizophora sp. with mangrove associates such as Suaeda sp. Clerodendrum inerme, Pandanus tectorius
West Coast of India		
Gujarat	15 species; 10 genera and 6 families	**Gulf of Kachchh & Gulf of Khambat:** Avicennia marina, Ceriops decandra, Rhizophora mucronata
Daman and Diu	4 species; 4 genera and 4 families	Avicennia marina, Acanthus ilicifolius, Aegicera scorniculatum, Sonneratia apetala
Maharashtra	22 species; 15 genera and 11 families	**Thane:** Avicennia alba, A. officinalis, Rhizophora mucronata, Sonneratia alba, S. apetala **Ratnagiri and Sindhudurg:** Avicennia marina, Sonneratia alba, S. apetala, Rhizophora mucronata, Acanthus ilicifolius, Ceriop sdecandra, C. tagal
Goa	16 true mangrove species; 11 genera and 7 families	Sonneratia alba, S. caseolaris, Rhizophora mucronata, Avicennia marina, A. officinalis, Bruguiera gymnorrhiza, Kandelia candel, Acanthus ilicifolius, Excoecaria agallocha

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[1] Sources: i) NCSCM Data, ii) SAC Report 2012: Coastal Zones of India; and ii) Raghavan et al., (2016)

State/UT	Mangrove Diversity	Dominant species
Karnataka	16 species; 11 genera and 7 families	Rhizophora mucronata, R. apiculate Sonneratia alba, S. caseolaris, S. alba, Kandelia candel, Avicennia officinalis and Bruguiera gymnorrhiza,,
Kerala	19 mangrove species; 12 genera and 8 families	Avicennia marina, A. officinalis, Rhizophora mucronata, R. apiculata, Bruguiera cylindrica, Sonneratia caseolaris, Excoecaria agallocha, Kandelia candel
Islands of India		
Andaman and Nicobar	38 mangrove species belonging to 13 families and 19 genera	Rhizophora mucronata, R. apiculata, Sonneratia alba, S. apetala, Avicennia marina,A. officinalis Bruguiera sp., Ceriops tagal Kandelia candel, Xylocarpus sp.,Excoecaria agallocha, Aegiceras corniculatum, Heritiera fomes, Nypa fruticans and Phoenix paludosa
Lakshadweep	8 species belonging to 5 genera and 3 families	Bruguiera cylindrica, Ceriops tagal and Pemphis acidula

Table 2: Seagrass species diversity and distribution in India[2]

S.No.	Location	State	Area (km^2) *	Unique features	Reference
1.	Chilika	Odisha	87.08	largest brackish water lagoon in Asia significant temporal changes in hydrological regimes Common species; Halophyla ovalis and Halodule uninervis	Ganguly et al., 2017b
2.	Palk Bay (incl. Gulf of Mannar)	Tamil Nadu	398.80	most extensive cover of seagrass in the Indian subcontinent 14 seagrass species present; most common: Cymodocea serrulata, Syringodium sp., Thalassia sp., Halophila sp., Enhalaus sp	Purvaja et al., 2018
3.	Gulf of Kachchh	Gujarat	17.02	High tidal amplitude (>8m) Highly stressed Common species: Halophila beccarii Other species recorded are Thalassia hemprichii, Halodule uninervis, Halophila ovalis and H. ovata	

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[2] Sources: i) NCSCM Data, ii) SAC Report 2012: Coastal Zones of India; and ii) Raghavan et al., (2016)

S.No.	Location	State	Area (km^2) *	Unique features	Reference
4.	Andaman & Nicobar Islands	A & N Islands	14.6	▸ Dense patches at Mahatma Gandhi National Park, Wandoor& Rani Jhansi National Park ▸ 8 species are recorded ▸ Enhalus acoroides, Halophila ovalis, H. ovata, Thalassia hemprichii, Cymodocea rotundata, Halodule uninervis, H. pinifolia and Syringodium isoetifolium	Thangaradjou et al., 2010
5.	Kalpeni & Kadmat Islands.	Lakshadweep Islands	0.57 0.15	▸ 7 seagrass species reported from Lakshadweep ▸ Cymodocea serrulata as the most dominant one. Other species include Halophila decipiens, Thalassia hemprichii, Cymodocea rotundata, Halodule uninervis, H. pinifolia and Syringodium isoetifolium.	Nobi et al. (2011)

All area (km^2) of seagrass is sourced from Geevarghese et al., 2018 unless specified.

3. Carbon Uptake in Blue Carbon Ecosystems

3.1 Carbon uptake in Mangrove ecosystems

Net primary production (NPP) is the first visible step in carbon accumulation that is quantified as the conversion of atmospheric CO_2 into plant biomass (Running et al., 2004). The difference between photosynthesis and autotrophic respiration is termed as net primary productivity and is a major index of carbon assimilation capacity (Chen et al., 2001, 2009). Mangroves play a significant role in atmospheric carbon capture with high carbon sequestration rates per unit area compared to the terrestrial forests (Figure 2).The estimates of net primary production by different mangrove species in various parts of the world show considerable variations ranging from 0.5 – 112.1 Mg DW ha^{-1} yr^{-1}. Other than the inconsistency in methodology used in estimation, distance from equator, temperature, rainfall, evapotranspiration, day-length etc. are also factors that affects net primary production (Alongi, 2008).

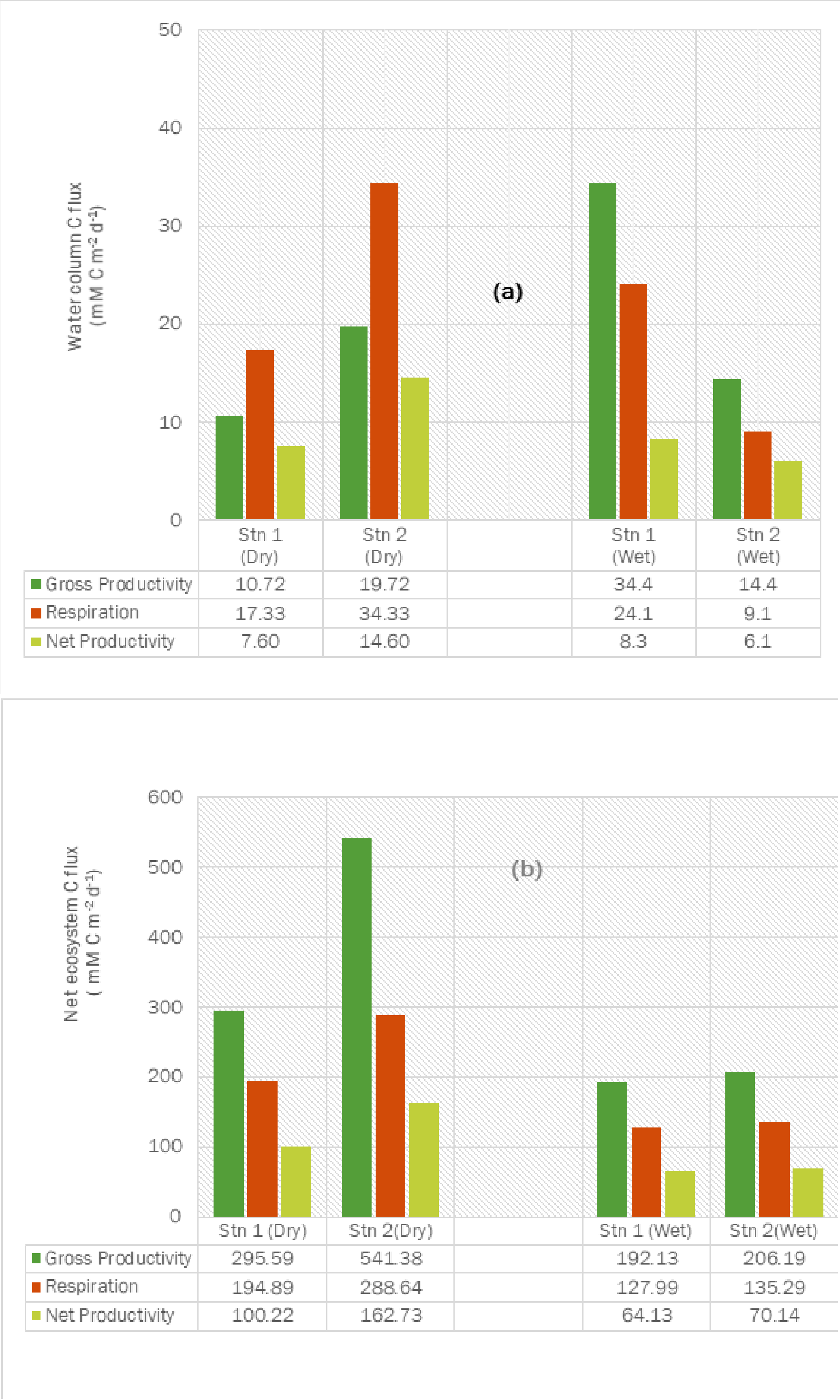
Studies are underway to estimate the distribution of photosynthetic production rate using remote sensing based vegetation indices along with process based models. The leaf Area Index (LAI) which is a measure of the canopy structure of vegetation, has been used in the study to assess the various ecological processes including rates of photosynthesis, transpiration (Pierce and Running, 1988); net primary production (Monteith, 1972; Gholz, 1982; Meyers and Paw, 1987); rates of energy exchange (Gholz et al., 1991). Using linear regression models, the relationship between Normalized Difference Vegetation Index (NDVI) and LAI has been established to develop LAI maps which were then utilized for estimating the spatial Net Canopy Photosynthetic Productivity rate (P_N) of various mangrove community zones (English et al., 1997; Green et al., 1997).

Results indicate the presence of highly productive and diverse mangrove species with dense crown cover in Sundarban, Bhitarkanika, Coringa and Pichavaram along the east coast (P_N ranged between 3.26 Mg C ha^{-1} yr^{-1} to 35.44 Mg C ha^{-1} yr^{-1}, NCSCM, unpublished data). Highest P_N is observed in *Heritiera fomes, Excoecaria agallocha, Avicennia marina* community in the eastern part of Sundarbans. Higher value of P_N in the eastern side is commensurate to the net productivity rate of *Heritiera fomes* (6.93 µmol m^{-2} s^{-1}) and a leaf area index reaching 6.24. Maximum net canopy productivity of A*vicennia marina* zone in Pichavaram is estimated to be 28.8 Mg C ha^{-1} yr^{-1}. Fringe mangrove zone of *Rhizophora apiculata – Rhizphora mucronata* along the creeks of Pichavaram has high a crown cover density of 60-70%, although the net photosynthetic productivity amounts to only 18.33Mg C ha^{-1} yr^{-1}. This is comparable to the Net productivity of *Rhizophora apiculata* (11.35 Mg C ha^{-1} yr^{-1}) estimated through LAI and gas exchange method of Matang Mangrove forest reserve, Malaysia (Ong et al., 1995).Compared to east coast, mangroves of west coast are patchy and less diverse and composed mainly of single species zonation. The maximum P_N estimated from the west coast is 26.98 Mg C ha^{-1} yr^{-1} and the minimum is 2.33 Mg C ha^{-1} yr^{-1}.

3.2 Carbon uptake in Seagrass ecosystems

Net Community Productivity (NCP), which corresponds to the difference between gross primary productivity (GPP) and community respiration (R) was estimated for major seagrass ecosystems of India (Palk Bay and Chilika). Combined metabolic activities (photosynthesis and respiration) of both the benthic (seagrass), as well as water column producers (phytoplankton) mostly contributed to the net community productivity (NCP) in these shallow ecosystems. The study revealed that in mixed seagrass meadows, NCP, GPP and R were higher than monospecies meadows (Ganguly et al., 2017). Further it was recorded that the net community metabolism was several folds higher than the water column metabolism (mostly regulated by plankton community) and both were inversely related (Figure 2).

Seasonal variation plays an important role in governing productivity (P) and health of the water column as the system changes from net heterotrophic in dry season to net autotrophic in wet season (P:R ranges 0.57 to 1.36). In both the ecosystems (Chilika and Palk Bay), higher water column productivity was observed in the wet compared to the dry season. This increase is a result of ecosystem response to nutrient enrichment during wet season. However, the net productivity rates, attributed to seagrass ecosystems, were high during the dry season, coinciding with high photosynthetically active radiation (PAR), water temperature and lower dissolved nutrients (Ganguly et al., 2017). This indicated greater dependence of seagrass dominated net ecosystem productivity on pCO_2 and PAR than the other physicochemical parameters such as temperature, pH and dissolved nutrients. Further, seagrass productivity was high during early morning hours, which coincided with peak CO_2 concentrations in the ambient water column. Increased seagrass productivity, biomass growth and long-term burial have been predicted under elevated concentrations of CO_2 conditions by Russell et al., (2013).



	Stn 1 (Dry)	Stn 2 (Dry)		Stn 1 (Wet)	Stn 2 (Wet)
🟩 Gross Productivity	10.72	19.72		34.4	14.4
🟥 Respiration	17.33	34.33		24.1	9.1
🟨 Net Productivity	7.60	14.60		8.3	6.1

	Stn 1 (Dry)	Stn 2(Dry)		Stn 1 (Wet)	Stn 2(Wet)
🟩 Gross Productivity	295.59	541.38		192.13	206.19
🟥 Respiration	194.89	288.64		127.99	135.29
🟨 Net Productivity	100.22	162.73		64.13	70.14

Figure 2: (a) Net ecosystem carbon fluxes and (b) Water column (biological) carbon fluxes for carbon at Palk Bay (mM C m^{-2} d^{-1}) (Ganguly et al., 2017).

4. Carbon Burial in Blue Carbon Ecosystems

4.1 Carbon burial in mangrove ecosystems

The efficiency of mangrove forests to trap atmospheric carbon as biomass production has been studied by several researchers across the globe (Figure 3, Sappal et al., 2016). Globally the annual above ground biomass production by mangrove is estimated to be 66.4 ± 37.3 Tg C, whereas the average ratio for mangrove wood production to litter fall is estimated to be 1.03 ± 0.54 (Bouillon et, 2008, and references therein). Primary data for mangrove below ground production is scare. However, Raich and Nadelhoffer, (1989), estimated the average root production of 82.8 ± 57.7 Tg C (below ground biomass) per annum by using the ratio of mangrove root production by litter fall rates (in C equivalent) of 1.20 ± 0.76.

Net carbon captured by mangrove biomass has not been studied in detail for all Indian mangrove systems, although a few studies exist from the east coast of India. In Sundarbans, West Bengal, among several mangrove species, the total biomass was found to be higher for *Sonneratia apetala* in the western part whereas *Avicennia alba* and *Excoecaria agallocha* were associated with high biomass in central area (Banerjee et al., 2013).Ray et al., (2011) reported that the overall annual accumulation rate of carbon as live biomass (4.71–6.54 Mg C ha^{-1} y^{-1}) was higher than that of losses as litter fall (4.85 Mg C ha^{-1} y^{-1}) in the Indian Sundarbans.

In the core area of Bhitarkanika mangroves, Odisha, mangrove trees are large in size and characterized with high biomass. The distribution and density varied with site, *Avicennia officinalis* and *Sonneratia apetala* were dominant in Bhitarkanika and Dangamal forest blocks, whereas *Sonneratia caseolaris* and *Rhizophora mucronata* formed top canopy at Thakurdia and Kakranasi blocks. However, it was *Exoecaria agallocha* (tree density 3585/ha) and *Hertiera fomes* (tree density 2011/ha) with high basal area that dominated the overall canopy (Mishra et al., 2005, Upadhyay and Mishra, 2014).

In Coringa mangroves, Andhra Pradesh, *Avicennia* sp. dominated in the lower intertidal region, *Bruguiera, Rhizophora, Ceriops, Aegiceras* and *Lumnitzera* in the middle and *Xylocarpus* at elevated grounds. Satyanarayna et al., (2002) observed that the basal cover of mangroves varied from10 m^2ha^{-1} to 109 m^2 ha^{-1}. It has been estimated that, a total of 29.76 Tg Carbon has been sequestered by mangrove plants and soil (depth 30 cm) of Gujarat, the second largest mangrove cover in India. The highest carbon sequestration rates have been observed from mangroves of south Gujarat (180.24 $Mgha^{-1}$) followed by Saurashtra (83.42 $Mgha^{-1}$) and Gulf of Kachchh (82.90 $Mgha^{-1}$) (Pandey and Pandey, 2013). Highest carbon stock per unit area however, is observed in the mangrove sediments of Andaman and Nicobar Islands at 118.3 Mg C ha^{-1} (Mall et al., 1991). Similar observation has been made by various researchers for mangroves of Tamil Nadu (62.81 Mg C/ha, Kathiresan et al., 2013) Karnataka (50.41 Mg C/ha, Suresh et al., 2013), Gujarat (24.57 Mg C/ha, Pandey and Pandey, 2013) and West Bengal (25 Mg C/ha, Ray et al., 2011). In an intimal estimate by NCSCM, mean sediment organic carbon content per unit area was highest in mangrove forest in Andaman island (207 Mg C ha^{-1}) followed by west coast (104 Mg C ha^{-1}) and west coast (62 Mg C ha^{-1}) of India. For Indian mangroves, the total sediment carbon stock is estimated as ~ 41.5 Tg C. Andaman mangroves were estimated to contain13.8Tg C whereas in mainland coast, Sundarban (8.7 Tg C) in the east coast and Gujarat Mangroves (7.7 Tg C) in the west coast has the highest sediment carbon stock.

The potential C capture in island mangrove sediments is often higher than the estuarine mangroves since the former contains a distinct organic-rich layer overlying hard, peat/muck (Figures. 5-6). Further, higher mean carbon content of west coast as compared to East coast of India can be attributed to heavily impacted mangroves, receiving high quantity of sewage (Alongi, 2014). In particular, Thane mangroves along the west coast were associated with high sediment organic load (Figures 3-4) which may be attributed to sewage influx from the surrounding area (Nikam et al., 2008).

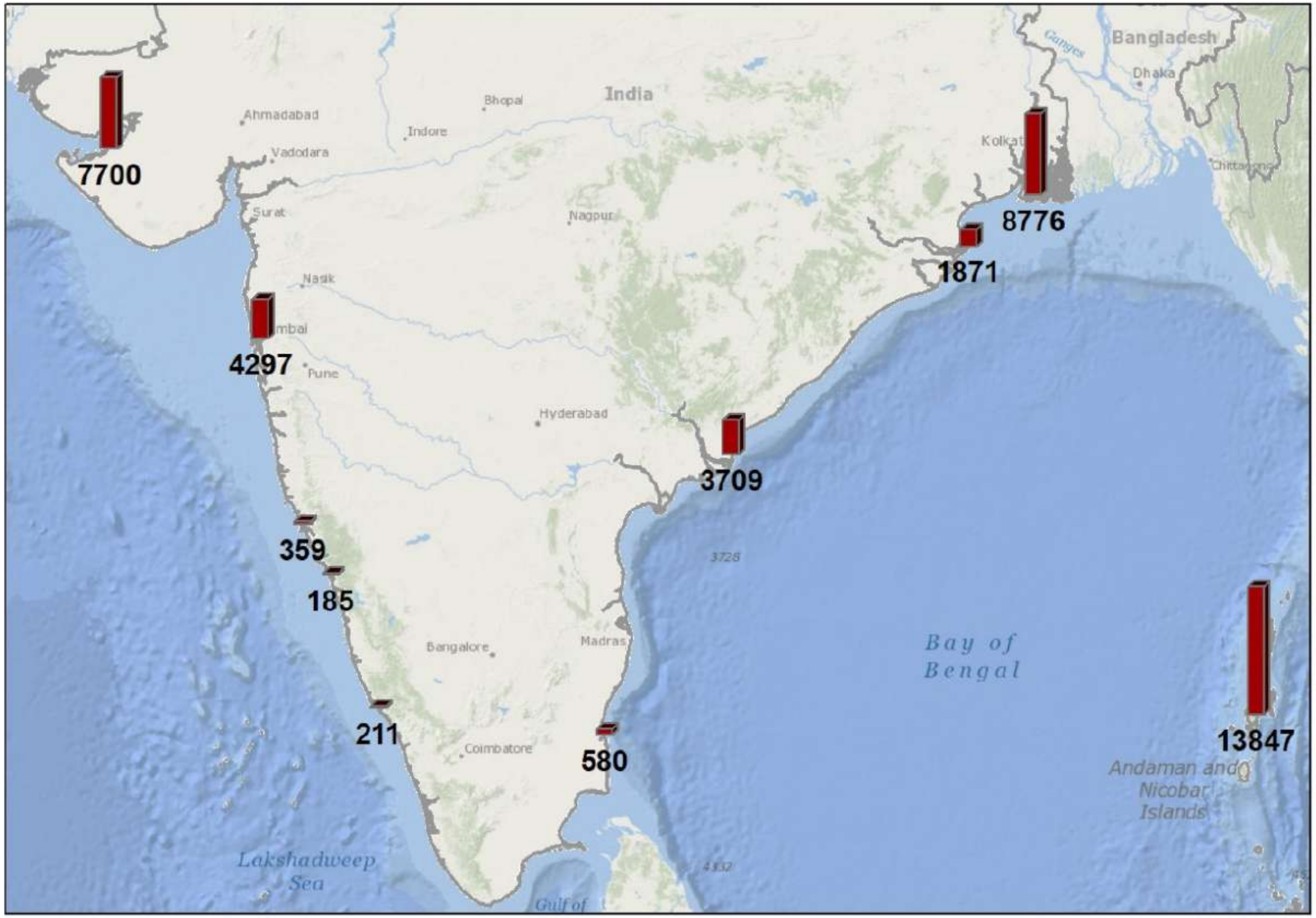


Figure 3: Total Sediment Carbon Stocks (Gg) in Indian Mangrove Ecosystems

In India, studies on the actual carbon burial rates are still in the nascent stage and rates are available from only a few mangrove ecosystems. Further, much of the carbon sequestration studies have been carried out considering total sediment organic carbon which often includes the anthropogenic organic load. This external organic load is prone to rapid mineralisation rather than sequestration.

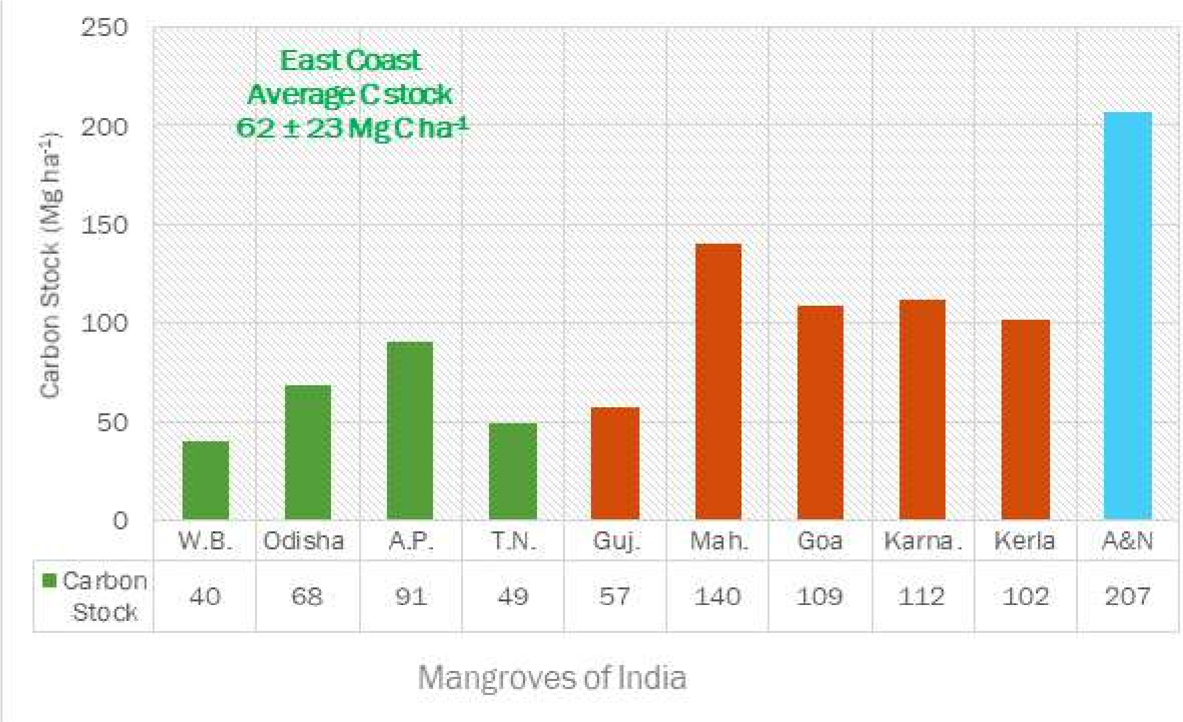


Figure 4: Variability in sediment carbon stock per hectare in mangrove forests of India

4.2 Carbon burial in seagrass ecosystems

Biomass of seagrass as standing carbon stock at a single point was calculated for Chilika Lagoon and Palk Bay. The biomass was divided into above-ground biomass (AGB; leaves/sheaths) and below-ground biomass (BGB; roots/rhizomes). The dry root biomass for all the seagrass species was higher than the biomass of the shoot and leaves. The biomass of three major seagrass species in Palk Bay varied from 220 to 300 g fresh wt. m^{-2} (*Cymodocea serrulata*), 85–110 g fresh wt. m^{-2} (*Halodule pinifolia*) and 185–225 g fresh wt m^{-2} (*Syringodium isoetifolium*. The difference in the shoot/root ratio indicates the efficient transfer of photosynthetically fixed carbon in the below ground biomass (Figure 5).

Similar observations were made from Lakshadweep atolls with mean seagrass biomass of 112±37 g dwt m^{-2}; 116±29 g dwt m^{-2} and 420± 64 g dwt $m^{-2}$for Kavaratti, Agatti and Kiltan respectively (Kaladharan et al., 2013). This below-ground biomass of these primary producers with root systems can be buried for centuries to millennia. This makes the seagrass ecosystem a potential CO_2 sink and can be effective in mitigating the negative impacts on the ocean ecosystems during ocean acidification events.

The total carbon stored as seagrass biomass in Palk Bay was estimated as 0.94 Mg C_{org} ha^{-1} (94 g m^{-2}) assuming mean carbon content as 35% of total seagrass biomass (Duarte, 1990; Fourqurean et al., 2012). Extrapolating the values for entire Palk Bay (i.e. 330 km^2), the carbon stored as biomass was estimated as ~ 31 Gg C. Similarly, considering the total area (85.5 km^2) covered with thick seagrass vegetation (>70%) live biomass was calculated to be ~ 2.4 Gg C in Chilika lagoon (NCSCM study).

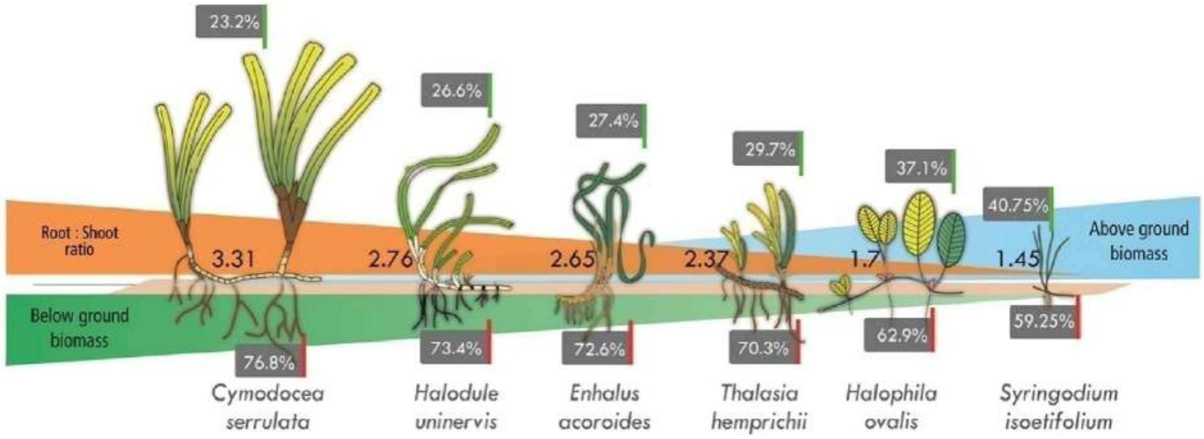


Figure 5: Biomass distribution in major seagrass species of India (Purvaja et al., 2017)

It is obvious from the previous studies (Russell et al. 2013; Duarte and Jensen, 2017) that seagrass sediments can store sequestered carbon for millennia and act as an ultimate sink. Seagrass meadows contribute about 50–64% of organic carbon sequestered annually by coastal vegetated ecosystems (Duarte et al. 2013) and they act as sink for 20% of the carbon buried in the global ocean (Duarte et al. 2005; Kennedy et al. 2010). Inter-species and inter-seasonal variations in sediment organic carbon between various seagrass meadows along the Indian coast are significant. Strong linear relationships between soil organic (Mg C/ha) carbon and seagrass AGB from different seagrass species were recorded from earlier studies (Ganguly et al, 2017). In general, the C stored in the top 1 m sediment is known as 'near-surface' carbon, and considered as susceptible to any degradation or disturbance. These soil organic carbon values were extrapolated for Palk Bay (up to 143 Mg C ha^{-1}) and Chilika (up to 107 Mg C ha^{-1}) and the mean organic carbon stocks for the top 1 m were estimated as 2.44 Tg and 0.76 Tg, respectively. Sediment organic carbon in seagrass meadows of Palk Bay (1.03%) and Chilika (0.60%) was lower than the global mean (2.5%; Fourqurean et al. 2012). Apportionment of carbon stores in the seagrass ecosystems indicates sediment act as a major storehouse for carbon compared to live biomass.

5. Blue Carbon Ecosystems:
Relevance to Climate Change

Healthy blue carbon ecosystems are known for their efficient biological removal of atmospheric greenhouse gases (GHGs) and the process is considered as one of the important mechanisms to mitigate global climate change. India has 69.20 million ha (21.05% of its total geographical area) under forest cover. It ranks 10th in the world in terms of forest area as per the Global Forest Resource Assessment (GFRA), 2010. Despite the fact that total area cover of blue carbon ecosystem is less than 5 % of total forest cover, the carbon stock per unit area is comparable with other terrestrial ecosystems of India (Figure 6). Conservation of coastal/ marine ecosystems, restoration of degraded mangrove forest ecosystems and creation of new blue carbon ecosystems could simultaneously result in enhanced CO_2 sequestration, reduction in GHG emissions and effective storage of sequestered carbon. The United Nations Framework Convention on Climate Change (UNFCCC) introduced "REDD^{+}"in 2010, as a mechanism to discourage deforestation and degradation of forests to reduce carbon emissions. In this context, reduction in deforestation and forest degradation (REDD^{+}) may have both national as well as global significance. The inclusion of blue carbon ecosystems through the available mechanisms like REDD+, considering their global and regional contribution in C sequestration and storage, could ensure better conservation and corresponding regulation of climate change.

Contrary to the creation of new blue carbon sinks, habitat destruction/degradation may cause permanent damage of carbon sequestration/storage capacity of salt marshes, mangroves, and seagrass. Residing mostly in sediments, this 'blue carbon' can be released back as CO_2 and other greenhouse gases to the atmosphere when these ecosystems are converted or degraded. It is estimated that 26% of mangrove forests worldwide is degraded due to over-exploitation for firewood and timber production. At the same time, the current rate of global annual loss (land-use conversion) was estimated to be 1–2% for tidal marshes; 0.7–3% of mangroves; and 0.4–2.6% of seagrass (Pendleton et al, 2012). Degradation of mangrove and seagrass ecosystems may release the stored CO_2 (933 and 326 Mg CO_2 ha^{-1}, respectively) to the atmosphere. However, at present, carbon emissions from the conversion of vegetated coastal ecosystems are not included in the emissions accounting or carbon market protocols. Further, there is none or very limited data on other degraded blue carbon ecosystems and the corresponding loss of C along the Indian coast.

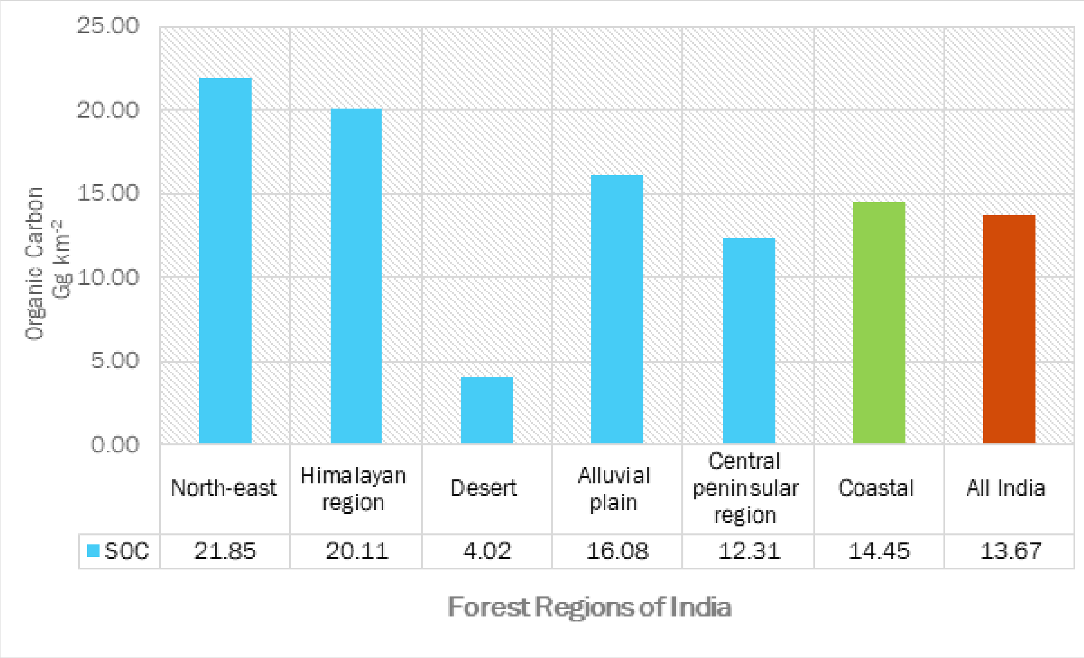


Figure 6: Comparison of sediment organic carbon stocks in major forest ecosystem of India (Khurana, 2012 and NCSCM study, unpublished data).

The Government of India has taken several initiatives to mitigate GHG emissions and to reduce the emissions intensity of its GDP by 33 to 35 % by 2030 from 2005 levels as indicated in its INDC. One of the key mandates is to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030. In this context, the coastal ecosystem plays a vital role with respect to their high carbon sequestration rates. Based on our studies four scenarios are projected:

i. A 20% increase in the mangrove cover (present total area 5400 km^2) along the Indian coast may create an additional C sink of 160 Gg C y^{-1} (removal of ~587 Gg CO_2 y^{-1}). Of this, 1.14 Gg C (removal of ~4.17 Gg CO_2 y^{-1}) may be transferred to the sediment pool for long-term storage.

ii. A 20% increase in the seagrass cover (total area 516 km^2) along the Indian coast may create an additional C sink of 7.1 to 22.4 Gg C y^{-1} (removal of ~26.1-82.4 Gg CO_2 y^{-1}). It is expected that 2.13-11.2 Gg C (removal of ~7.8-41.1 Gg CO_2 y^{-1}) may be transferred to the sediment pool for long- term storage.

iii. At an annual global rate of 112–392 Mg C released per hectare of degraded mangroves, conservation and restoration of 100 ha of the degraded mangrove forest may reduce CO_2 emissions of 41-144 Gg CO_2 y^{-1}

iv. At a global mean C emission rate of 142 Mg C ha^{-1} from the degraded seagrass meadows, conservation and restoration of 100 ha of these meadows may cause a significant reduction in CO_2 emission of 52.2 Gg CO_2 to the atmosphere.

Conclusion

In order to offset CO_2 emissions, creation of new blue carbon pools (afforestation and reforestation) is necessary. Additionally, restoration of degraded ecosystems, to prevent CO_2 seepage from the sediment to the atmosphere and in providing new C-sinks is also equally important. On an average, creation of new C sink through blue carbon ecosystems along the Indian Coast could be 3 times more efficient than the terrestrial forest ecosystems. Conservation and restoration of degraded blue carbon ecosystems on an urgent basis could be one of the most efficient ways to significantly, reduce atmospheric CO_2 emission in short timescales.

5. Acknowledgement

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Ocean thermal desalination

A climate change perspective

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ABSTRACT

Population increase, high industrial growth, and climate change have resulted in severe water stress today. It has become imperative to find means to augment water through innovative methods. One such effort is seawater desalination which is seen as a viable option in India due to the long coastline. This chapter highlights the various methods of desalination along with impacts on climate change. This chapter also elaborates on an ecologically safe thermal desalination method suitable for implementation in islands, offshore and in power plants near the coast called Low Temperature Thermal Desalination (LTTD), pioneered by the National Institute of Ocean Technology (NIOT). The energy requirement of desalination systems and the socio-economic angle are also discussed as the environmental and ecological cost as well as the economic cost has to be considered for a meaningful comparison of desalination technologies. NIOT's low temperature thermal desalination method appears to be equal or lower in cost than an RO plant of similar capacity. Whether installed in power plants or islands, LTTD appears to have a positive impact from the climate change perspective.

1. Introduction

Climate change and its deleterious impact are seen across several aspects and has become a cause of grave concern. Though its impact is felt indirectly or directly in many areas, the most noticeable one is on the hydrological cycle, as changes in this process are the reason for increased floods, sea level rise and storm surges. The Intergovernmental Panel on Climate Change (IPCC), 2014) document has clearly shown through climate change prediction models that floods and droughts will affect more and more regions around the world. Renewable surface and groundwater resources are predicted to reduce further, creating water stress and droughts in various sectors.

The water stress arising out of climate change is worsened by other factors like increasing population, spurt in industrial growth and general lifestyle changes due to economic growth and technological advances.

In India, water scarcity is felt in agriculture, industrial requirements, as also in rural and urban domestic water supply. Thus, there is an urgent real need to find ways and means to augment available water. Around the globe, desalination of seawater / brackish water is becoming a technologically and economically viable solution to tackle challenges associated with water scarcity. Desalination refers to the process by which potable water is recovered from seawater / brackish water by removing dissolved solids using different forms of energy. While desalination first became popular in the Gulf countries, any coastal and water-starved areas can today consider it for water augmentation. India with its long coastline of nearly 7500 km has great potential to look at desalination as a possible solution for the 30% of the population living in the coastal areas. Technologies used for desalination can be broadly classified as thermal or membrane processes, which are discussed in detail.

2. Desalination methods

2.1 Thermal Technologies

2.1.1 Multi Stage Flash (MSF)

In MSF, saline water is heated by steam and then fed into a series of vessels (effects) where reduced pressure leads to immediate boiling (flash) and the steam generated is condensed in a sequence of stages, producing high- quality fresh water.

Multi-Stage Flash (MSF) desalination process plays a vital role in the provision of fresh water in many areas of the world, particularly in the Middle-East countries and they account for approximately 34% of the world's desalination capacity (El-Ghonemy, 2017). It is the most reliable and mature desalting process with more than 40 years of experience in its design, operation, material selection and maintenance (Darwish and Alsairafi, 2004). It needs high temperature and pressure steam and several stages. It is very capital intensive.

2.1.2 Multi-Effect desalination (MED)

In the multi-effect distillation (MED) process, saline water is desalinated by means of evaporation and subsequent, though here the vapour passes inside the tubes, which is the reverse of the MSF process. MED is getting more attention among thermal desalination technologies due to its major advantages such as low energy consumption compared to MSF, higher overall heat transfer coefficients, less specific area as compared to MSF, low operating steam temperature and that other low grade heat sources can be used to power it. The multiple-effect distillation process can be found in various industries, like sugar, paper and pulp, dairy, textiles, acids and desalination units.

2.2 Membrane Methods

2.2.1 Reverse Osmosis (RO)

Reverse osmosis membrane technology has developed over the past 40 years and has a 44% share in world desalting production capacity, and an 80% share in the total number of desalination plants installed worldwide (Greenlee et al., 2009). Among the different available techniques, Reverse Osmosis (RO) has proved to be the most reliable, cost-effective, and energy efficient in producing fresh water. Pressure is used to drive water molecules across the membrane and the energy needed to drive water molecules across the membrane is directly related to the salt concentration. RO has been most often used to drive brackish waters that are lower in salt concentrations (Buros, 2000).

The operating pressure for brackish water systems ranges from 15 – 25 bar and for seawater systems from 54 to 80 bar (the osmotic pressure of seawater is about 25 bar). Since the pressure required to recover additional water increases as the brine stream is concentrated, the water recovery rate of RO systems tends to be low. A typical recovery value for a seawater RO system is only 40% (Spiegler et al., 1994).

Due to the high- pressure requirement, RO is usually not applicable for concentrated solutions. Because all RO membranes and devices are susceptible to fouling, the RO process usually cannot be applied without pre-treatment. RO feed streams must be compatible with the membrane and other materials of construction used in the devices. If the feed stream contains incompatible compounds, these must be removed in pre-treatment, or another compatible device and/or membrane must be considered (Younos and Tulou, 2005).

2.2.2 Forward Osmosis (FO)

Osmosis or forward osmosis has new applications in separation processes for various uses like wastewater treatment, food processing, and seawater/brackish water desalination. Forward Osmosis (FO) is an emerging low energy desalination technology with several merits over the other conventional pressure-based reverse osmosis (RO) desalination technologies. Unlike the pressure driven RO desalination process, the driving force in the FO process is the osmotic pressure produced naturally by the concentrated draw solution (DS) (Cath et al., 2006)

2.3 Electrodialysis (ED)

The ED process is effective with salt removal from feed water in which the water cost is relatively high but lower than that of conventional distillation processes of the same capacity. Electrodialysis (ED) has been used for many years; this is an electrochemical process for the separation of ions across charged membranes from one solution to another under the influence of an electrical potential difference used as a driving force. This process has been widely used for the production of drinking and process water from brackish water and seawater, treatment of industrial effluents, recovery of useful materials from effluents and salt production (Oztekin and Altin, 2016).

2.4 Membrane Distillation (MD)

Membrane distillation (MD) is a thermal, membrane-based separation process (Lawson and Lloyd, 1997; Lei et al., 2005). The driving force for the MD process is different from other membrane processes, being the vapour pressure difference across the membrane rather than an applied absolute pressure difference, a concentration gradient or an electrical potential gradient, which drives mass transfer through a membrane (Lawson and Lloyd, 1997; Schneider, K. and van Gassel, 1984). High energy consumption and brine disposal problem is faced in the RO process due to the limited recovery of water. These problems may be overcome by other membrane thermal processes such as a membrane distillation (MD). MD is an emerging technology for brackish water desalination and is not yet fully implemented in industry. MD appears to be a better alternative to RO for desalination as found in the literature (Pangarkar, 2011).

3. Demerits & Impacts of desalination systems and climate change

As can be seen from the earlier section, there are several different technologies, each of which have different processes and components involved.

It is important to understand the impacts of these desalination technologies. It is understood that when the natural state of seawater, which has 35000-40000 ppm levels of dissolved solids, undergoes a process of salt removal, the portion left over after fresh water is obtained may have properties significantly different from the sea water that was used in the process. Membrane methods like Reverse Osmosis remove salts, and fresh water is the output. However, concentrated salt solution or brine gets left behind. In thermal systems, there is no brine formation, since only vapour is condensed; on the other hand, the main reason that makes desalination expensive is the high energy requirement. The following flowchart depicts any desalination system (Figure 1).

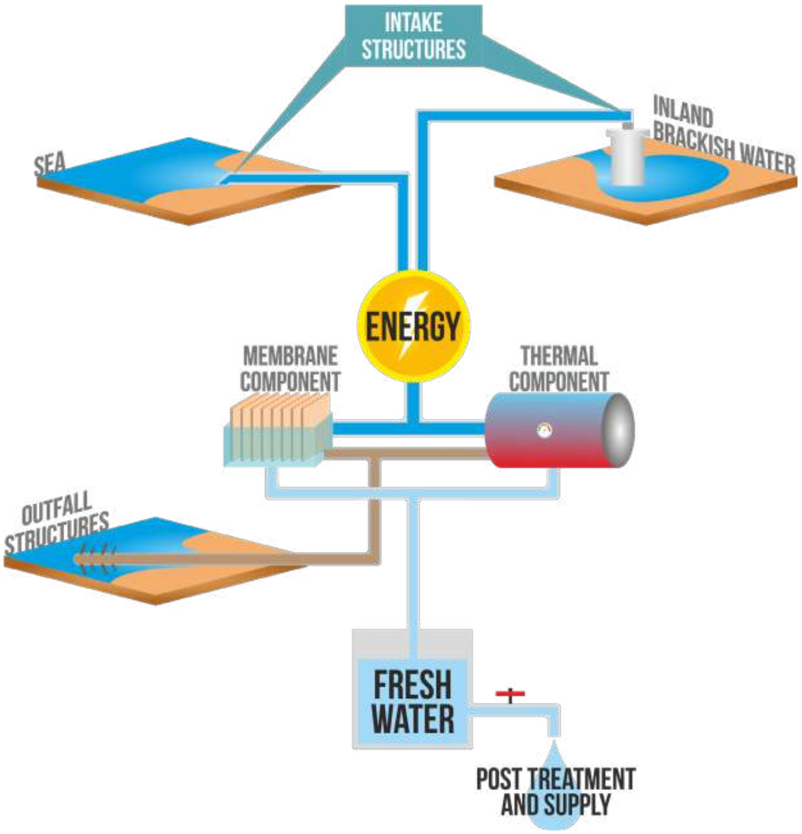

Figure 1: Components of any desalination system

The common units of any desalination system are the intake and outfall systems. The intake systems essentially are engineering structures and need only careful design and proper installation techniques. However, they can also cause harm by impingement and entrainment, if poorly designed. If designs are inadequate, plants and animals, including eggs and juveniles of endangered species, can get trapped and killed. The outfalls, on the other hand are important structures because

i. the effluent after desalination is let out through them.

ii. the quantity & quality of effluent is extremely important from the environmental perspective in terms of polluting capacity.

iii. the location and design have potential to affect shipping routes, fishing vessels, marine animals by affecting salinity, temperature and localized flow velocities.

Each process has its own limitations which can have an adverse impact from the climate change perspective and the main issues are enumerated below:-

3.1 Membrane Systems

1. **Chemicals used for pre-processing of the intake water or the desalination system itself.**

   Popular processes like RO require chemicals for pre-processing of the intake water itself. These chemicals are chlorine, carbon-di-oxide, hydrochloric acid, etc. and eventually are let out in the discharge system and can lead to polluting the coastal sea. This can lead to serious environmental impact on biological systems.

2. **Effluents from the systems other than fresh water**

   Membrane processes leave behind brine which is very heavily concentrated solution. If this is let out to sea, the salinity levels and in turn, overall sea water quality can deteriorate leading to various issues. Today many computational studies are being taken up to understand the speed, direction and quantity of the spread or dispersal when the effluent is let out. Computational models can be run for short time frames with idealistic equations and assumptions regarding boundary conditions. The actual effect after a few years cannot really be predicted. The negative impacts can have cascading effects in terms of destruction not only of flora and fauna but also increase in salt water intrusion. Soil quality can be impacted on land and groundwater can get affected and this, in combination with other climatic changes, can have serious consequences. The super-saturated salt water also decreases oxygen levels in the water causing animals and plants to suffocate.

   The organisms most commonly affected by brine and chemical discharge are the plankton, especially phytoplankton, which being the base of the food chain, form the basis of marine life.

3. **Disposal of components of the system**

   Membranes used in RO systems today are mainly imported especially for seawater desalination. The pressures in these systems are high since osmosis is being used to force salt particles out of the seawater or brackish water. Hence the membranes need to be extremely strong structurally to be able to withstand the large pressures. Thus, once the membranes have outlived their utility, their destruction or disposal is a challenge. In the near future, it is likely that huge piles of membranes from large scale desalination plants may become an environmental hazard.

   On the other hand desalination systems using MSF, MED and other thermal methods face none of the above challenges and hence are eminently suitable to be used in the context of climate change. However, all these processes need steam at high pressure and high temperature. Use of steam is expensive as it needs components designed to be robust and fail-proof. Thermal desalination is also energy intensive. As is known, the main source of excess carbon-di-oxide emissions is the burning of fossil fuels. Thus indirectly, desalination systems in some way contribute to the climate change scenario.

   The National Institute of Ocean Technology has pioneered a thermal desalination process for regions near the coast and islands wherein no steam is required and has been found to be ecologically safe and the next section discusses this.

4. Ocean based Low Temperature Thermal Desalination (LTTD)

The Low Temperature Thermal Desalination (LTTD) process utilises the temperature gradient between two water bodies to evaporate the warmer water at low pressures and condense the resultant vapour using the colder water to obtain high quality fresh water. Thermal gradient between different layers of the ocean water column provides huge reservoirs of warm and cold water that can effectively be utilised for power generation and desalination (Rognoni et al., 2008, Kathiroli and Jalihal, 2008, Sistla et al., 2009). Figure 2 shows a schematic diagram of the LTTD unit.

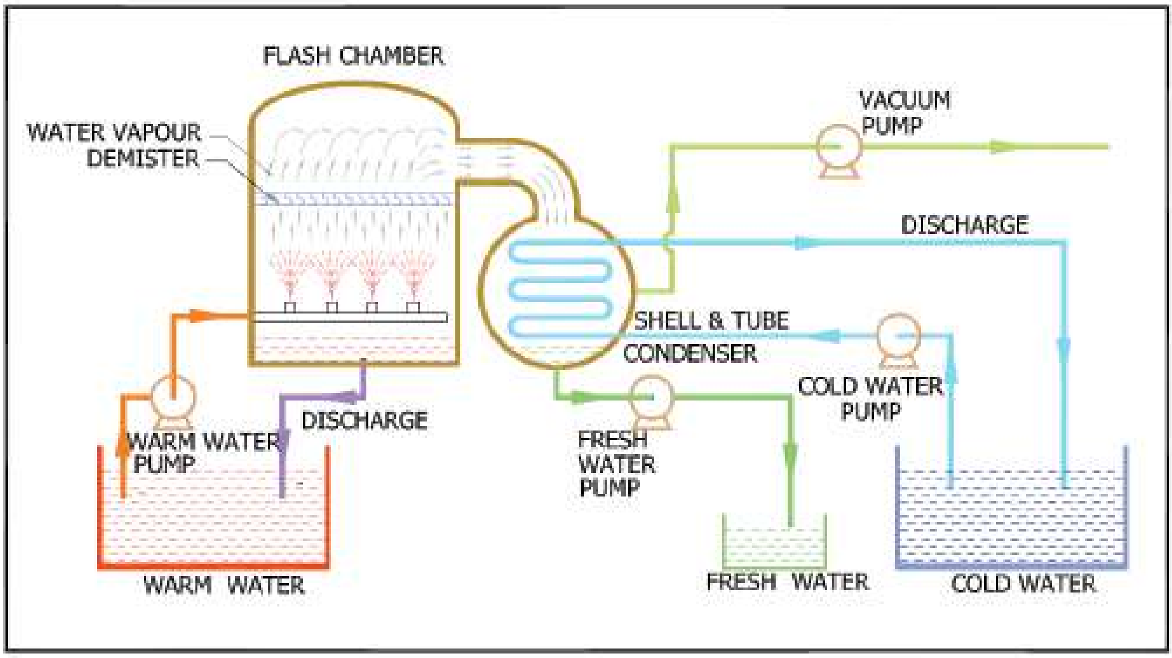

Figure 2: Schematic of LTTD unit

The main components required for a LTTD plant are evaporation chamber, condenser, pumps, pipelines to draw warm and cold water and a vacuum pump to maintain the sub atmospheric pressures. One of the advantages of the process is that it can be implemented even with a low -temperature gradient of about 8-10 °C between the two water bodies.

Thus, it can be used in the ocean scenario with surface water, and deep sea cold water or in a power plant using surface sea water as the cold water and the condenser reject hot water as the warm water.

The successes and projects developed using this technology is discussed in detail.

NIOT has been working on LTTD process to develop technology at laboratory as well as field levels. Starting from 0.5 m^3/, an experimental laboratory was set up in 2003 and was increased later to a 5 m^3/day; A floating desalination plant of 500 m^3/day using ocean temperature difference was successfully demonstrated in 2005 off Tuticorin, South India.

A 100 m^3/day land-based plant was commissioned at Kavaratti island in Lakshadweep in 2005 (Figure 3) for the first time in the world. This plant has been continuously generating fresh water for the past thirteen years to meet the drinking water needs of the island community. The water is of excellent quality as well as meeting the design quantity. The plant is housed in a structure on the shore. The bathymetry at the island is such that water at 10-12°C is available at a depth of 350 m at a distance of around 300-400 m from the shore which is the source for cold water.

The cold water is brought to the surface through a 600 m long High Density Poly Ethylene pipe (HDPE). The temperature of seawater at the surface is 28-30°C, which is the source for warm water. This first-ever plant has become the main source of drinking water for the islanders and health of the people has improved considerably. Water related diseases like diarrhea, hypertension, etc. have reduced and the societal impact has been tremendous.

Figure 3: Desalination Plant at Kavaratti

Subsequently, an offshore barge-mounted plant was taken up in 2007 with requirements of the mainland as the target. The plant was of 1000 m^3/day capacity, mounted on a barge and moored in over 500 m water depth at 40 km off Chennai. The plant was successfully commissioned and produced water of potable quality. Even though all the plant components had the same configuration as those of the land-based island plant, the configuration of the cold water pipe was completely different because the pipe had to be connected vertically below the floating barge that houses the plant. A long 1 m diameter High Density Poly Ethylene (HDPE) pipe was assembled near shore on the mainland and towed to deep waters. The barge was moored using a single point mooring, and then the HDPE pipe was connected to the barge. The plant was operated for a few weeks during its sea trial in 2007 (Figure.4).

Subsequently, two more island plants in Agatti & Minicoy were commissioned successfully in 2011 (Figure.5).

Figure 4: Barge mounted desalination Plant

Figure 5: Desalination Plant at Minicoy & Agatti Islands

It is interesting to note that the same technology can be applied to any scenario where two bodies of water at different temperatures are available. Coastal thermal power plants discharge huge amounts of condenser reject water into the nearby ocean. The temperature of condenser reject water is 8°-10°C above ambient temperature which causes environmental and thermal pollution. This available thermal gradient between the condenser reject water and nearby surface seawater can be utilised in the LTTD process to evaporate the warmer condenser reject water at low pressure and to condense the resultant vapour with the colder surface sea water to obtain fresh water.

With this concept, a land-based 150 m^3/day capacity desalination plant was established in 2009 in the North Chennai Thermal Power Station (NCTPS) to demonstrate the utility of the process for any coastal thermal power plant that discharges huge amount of condenser reject water into the nearby sea (Figure 6). The 600 MW NCTPS plant discharges about 100,000 m3/hr of condenser reject water at about 38-43°C. In order to reduce the thermal pollution issues arising out of mixing this water with the nearby seawater at 26-30°C, NCTPS lets the water run through a long open channel where the water is brought to about 33-37°C. NIOT plant just tapped the intake to the condenser and outlet from the condenser to demonstrate the technology.

Figure 6: NCTPS desalination Plant

Large quantities discharged at less warm temperature can be beneficial to the environment. Thus if this system is adopted when power plants are in the early stages of planning, the LTTD plant can play the role of cooling towers, where energy is being pumped today to cool the outlet water. Thus, LTTD using condenser reject heat can help in the context of climate change.

Thus, NIOT through various demonstration plants of different capacities, experience in terms of design, and selection of materials, installation, operation and maintenance has perfected the LTTD technology.

Industry participation has been sought for more plants in islands, power plant and offshore plant. The long coastline of India and several islands in the Arabian Sea as also coastal power plants warrant a serious venture into the utilisation of the LTTD technology to meet the growing drinking water requirements of coastal communities in India.

Concisely, LTTD plants can be made operational whenever a temperature difference across two strata of water is available, either in the ocean or using waste heat from power plant condensers. No expensive steam is required, and environmentally too the method is extremely safe since there are no membranes or components to replace or destroy. The efficiency of thermal system is low in term of conversion efficiency hence a tiny fraction of intake water gets converted to fresh water and hence the remaining water returns as is, to the sea, and thus no brine formation occurs. Thus, in general, LTTD desalination plants has these positive factors:

1. Utilisation of vast renewable energy in the sea for generating fresh water
2. Installation and operational simplicity
3. Fewer maintenance issues and thus sustainability
4. Almost nil environmental hazards due to non-discharge of chemicals or waste or brine as opposed to the membrane-based desalination plants.
5. Reduction in power plant cooling water discharge temperature to prevent thermal pollution.

5. Desalination Plants and Energy

Desalination is considered to be an energy-intensive process. The electrical energy used in the process is usually derived from fossil fuels, burning of which emits carbon dioxide resulting in pollution of the environment. Thus, a measure of the viability of a desalination process is the amount of energy consumed. Electrical energy for desalination is utilised from coal, thermal or nuclear grids. In islands, diesel generators are needed to supply power. To make the desalination processes green, it is prudent to consider the use of renewable energies. To this end, Solar-PV systems combined with RO are tried. While this can certainly reduce the pollution arising from the energy consumed, the inherent issues with RO remain.

A few years ago, the Department of Science & Technology funded a project to an industry with technical support from NIOT for a Solar Multi-effect Distillation plant at Ramanathapuram in Tamil Nadu. This plant is considered green due to the usage of solar energy and is also safe environmentally since it is a thermal desalination system. However, the fluctuating and short availability of insolation makes its viability at this point questionable. The footprint for solar systems on land is also high, which is not desirable in this age of high land costs.

In the year 2003, NIOT also demonstrated a wave energy powered RO plant. This was the first plant, wherein energy from the sea was used to desalinate seawater. This plant, however a demonstration unit was and hence was decommissioned after the local fishing community used the water for three years.

NIOT is now, therefore embarking on a first of its kind system at Kavaratti Island, where the LTTD plant will be powered by Ocean Thermal Energy Conversion. This means the plant will be self-powered and not dependent on diesel generators. The design caters to generating power just sufficient to power the desalination process. No extra power will be pumped to grid. This hybrid system has the merits of clean and green energy, environmentally safe desalination and low cost since energy is produced from existing ocean thermal gradient.

The success of this plant can pave way to make fossil fuel free desalination plants in islands thus creating fresh water for pristine locations with no contribution to climate change.

6. The Socio-Economic Angle

The detrimental effects of certain types of desalination have been discussed earlier. In addition to environmental and ecological effects, desalination plants can cause noise pollution, gaseous emissions and chemical spills. In case of discharged concentrate, total dissolved salts (TDS), temperature and specific weight of the discharge are of critical importance as they result in damage to aquatic environment (Venkatesan, 2014). Increased density causes sinking of the discharge to the seabed, smothering the benthic ecosystem resulting in an effect referred to as desertification of seas causing harm to certain parts of the ecosystem.

Having mentioned the environmental impacts which can directly be linked to climate change, it is also essential to talk about costs. Today due to energy recovery systems, RO plants consume less energy than thermal systems thus making RO the preferred technology across the globe.

However, it is important to take the environmental factors into account for understanding the actual cost. Apart from the capital cost and operating cost models using the internal rate of return and amortisation, it is necessary to consider the environmental and ecological cost per litre of desalinated water.

i. Environmental cost per litre of desalinated water is arrived at on the basis of additional energy consumed per litre of desalinated water over the technology option with the least specific energy consumption. In the Indian context, one megawatt hour (MWh) energy consumption is assumed to imply a tonne of carbon dioxide emission. If a process involves reduction of specific energy consumption by one MWh, it is assumed to have earned one certified emission reduction (CER).

ii. Ecological cost per litre of desalinated water is arrived at as the change in GDP per litre of desalinated water in the 'project catchment area' due to the introduction of a particular technology.

Concepts like the Leontief inverse can be used in mathematical terms to factor in the above costs so that the true cost of a desalination system can be arrived at.

Comparison of RO & LTTD (Venkatesan, 2014) showed that while the power used for RO is less, resulting in lower environmental cost, the ecological cost for RO is significant as it disturbs the ecological system. Overall it can be concluded that LTTD will be equal or lower in cost per litre than RO of a similar capacity.

Conclusions

Comparing the merits and demerits of various desalination technologies specifically the popular method RO and new technology LTTD from the ecological, economic and social angle both have its pros and cons.

In case of LTTD, sea desertification is negligible, while the same from an RO plant is quite high. RO also has high levels of chemical discharge causing ecosystem disturbance, while the same is negligible in the case of LTTD, MSF and MED. As a result, the adverse impact on fishers involved in activities such as ornamental fishing is minimal from the LTTD, MSF or MED plant vis-à-vis the RO alternative.

From the climate change perspective LTTD has a positive impact, whether installed in islands or power plants. Environmental analysis show that the higher specific energy consumption in a technology process vis-a-vis the best technology option in the project area (in terms of specific energy consumption) is measured in terms of certified emission reduction. Towards an ecosystem analysis, the emphasis is to find out whether the introduction of technology disrupts the surrounding ecosystem and such disturbance costs associated per unit output (per unit output of desalinated water) is quantified as the ecological cost. These assessments need to be made in terms of a common *numeraire* or yardstick and the composite cost per unit output needs to be worked out for the choice of best technology option for the project area (Venkatesan, 2014).

Finally, if ecological cost is carefully brought in, climate change issues will be taken care of in the method adopted. Use of renewable energy can further reduce the carbon dioxide emissions. A holistic approach can make desalination a safe option for the future.

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Renewable energy technologies for mitigating climate change

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ABSTRACT

Advancements in renewable energy technologies are crucial for combating climate change by reducing fossil-fuel based energy and increasing energy harvest from renewable sources such as solar, wave, tide, geothermal, wind etc. India has made significant advancement by using innovative technologies to identify and harvest the energy potentials along the coast. National Institute of Ocean Technology (NIOT) is involved in designing and fabrication of state-of-art-technologies for renewable resources such as solar driven Multi-effect Thermal Desalination system (MED), Oscillating Water Column (OWC) device, wave powered navigational buoy, cross flow hydrokinetic turbine etc. NIOT has the distinction of setting up the first ever low temperature thermal desalination plant using Ocean Thermal Energy Conversion (OTEC). Large potentials of tidal energy have been identified at Gulf of Khambat and Gulf of Kachchh in Gujarat and Durga Duani Creek in Sundarbans, West Bengal. Wind is one of the potential resources over the Indian sub-continent and constitutes around 55% of the total renewable energy of the country. National Centre for Sustainable Coastal Management (NCSCM) has computed offshore wind energy potential along the Indian coast for 2012 and estimated the available grass electrical power between 0-200 m depths at about 5339 GW at turbine hub-height of 90 m. The state-of-art technologies for generation of energy from renewable sources by India could ensure significant reduction of fossil-fuel based energy and can contribute towards climate change mitigation effort.

1. Introduction

The present world energy supply is dominated by fossil fuels which is not a sustainable solution for the future. Air pollution is an immediate consequence of combustion of fossil fuels. Coal and conventional gas continue to be relatively easy to extract and they are also the most polluting. There is a lot of scientific evidence today that climate change and global warming are largely due to the rise of carbon dioxide in the atmosphere. Both of these effects are considered to be a result of anthropogenic greenhouse gases (GHGs) with CO_2 being the most important (Letcher, 2014). Replacing fossil fuels with renewables is a gigantic task. Currently, energy sources other than fossil fuels make up about 20% of the global energy consumption (Table 1, Letcher, 2014).

Table 1: Total global energy consumption percentages for 2010

Type of Energy	Energy Consumption %
Oil	35.3
Coal	27.0
Natural gas	20.5
Nuclear	5.0
Hydroelectric	5.8
Biomass	6.3
Other renewable	1.1

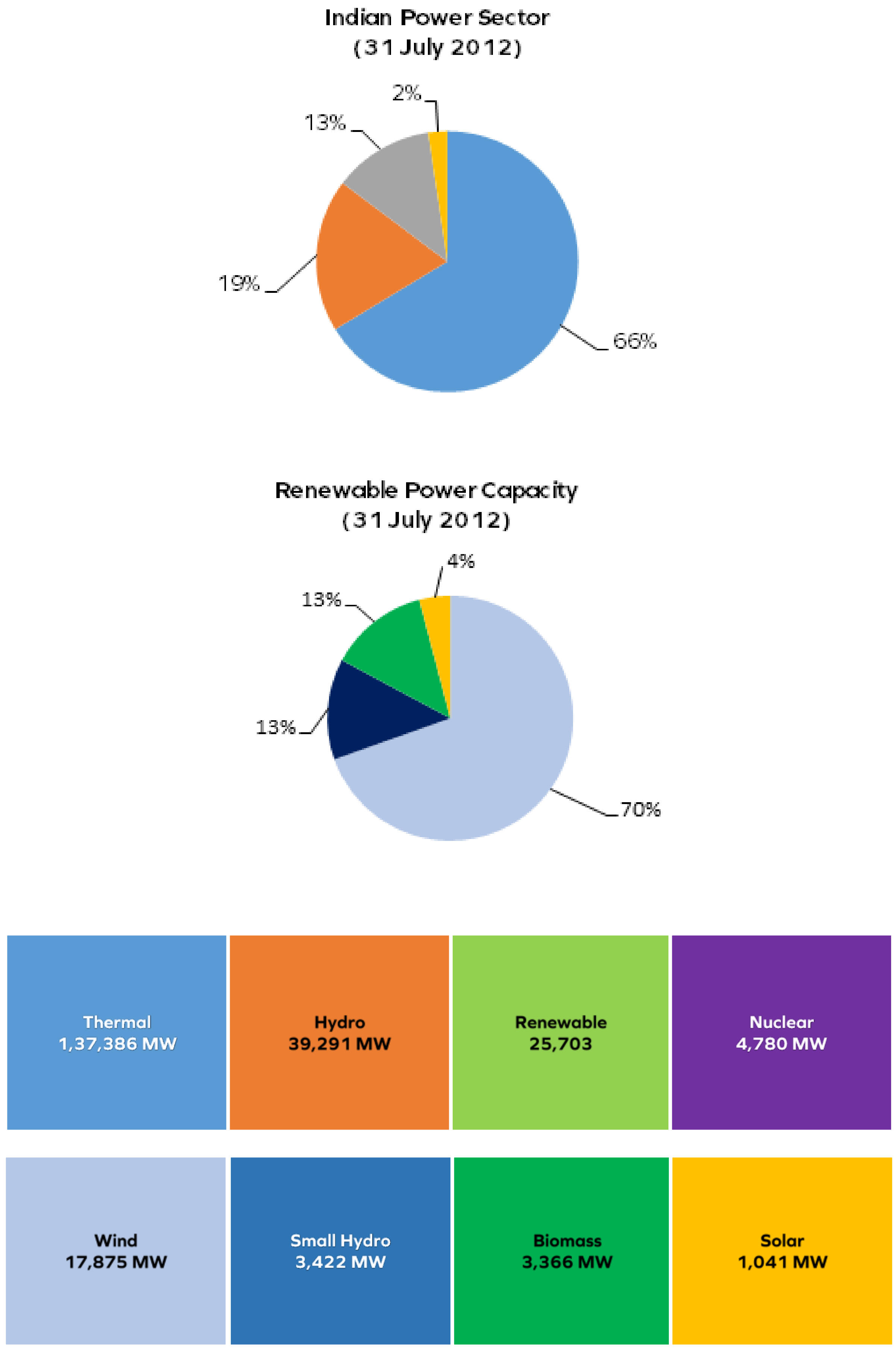
It is evident that increasing the renewable energy sources is essential but in reality is extremely difficult. In comparison to CO_2 sources from industries like forestry, cement, transport, commercial and residential, the highest emission of CO_2 is from electricity production. The renewable forms that are widely studied and utilised are solar energy, geothermal energy, marine renewable energy including wave, tidal, currents and thermal gradient and onshore and offshore wind. While solar, wind, biomass and other renewable forms are already being tapped across the globe on land; energies which can be harnessed from the vast ocean have yet to move from the research arena to the realm of commercialisation. The oceans offer vast spaces where new technologies can be developed without affecting human settlements or the environment. Hence the need of the hour is to develop technologies for harnessing marine renewable energies. This chapter discusses the renewable energy that can be tapped from the oceans.

2. Solar Energy

Solar energy offers a clean, eco-friendly, abundant and inexhaustible energy resource and is relatively well-spread over the globe. Its availability is greater in warm and sunny countries. Solar energy can be utilised in various forms like solar power, solar desalination etc. Thus, solar energy utlisation can make considerable contributions to solve some of the most urgent problems the world now faces in terms of climate change, energy security, and universal access to modern energy services.

In India, among the various renewable energy resources, solar energy potential is the highest in the country. The global solar radiation over India varies between 4-7 kWh/sq. /day. The states that have the maximum insolation are Rajasthan and Gujarat. In addition, the states of Tamil Nadu, Andhra Pradesh, Madhya Pradesh, and Chhattisgarh also have good insolation level. The total installed capacity is 1041 MW, which is 4% of the total renewable energy produced by India.

Photovoltaic (PV) or concentrated solar thermal power plants are used to convert sunlight into electricity. Through PV which is the direct process, sunlight is converted to electric current using photoelectric effect. In the concentrated solar thermal process which is indirect, lenses or mirrors and tracking systems are utilised to focus a large area of sunlight into a small beam. This small concentrated heat source is used in a conventional plant.



Thermal 1,37,386 MW	Hydro 39,291 MW	Renewable 25,703	Nuclear 4,780 MW
Wind 17,875 MW	Small Hydro 3,422 MW	Biomass 3,366 MW	Solar 1,041 MW

Figure 1: Renewable power capacity in India

2.1 Concentrated solar thermal power plant

Concentrating technologies use four common forms - parabolic trough, dish Stirlings, concentrating linear Fresnel reflector, and solar power tower. Through this concentrated solar power system (CSP), these mirrors or lenses are used to concentrate a large portion of sunlight/solar thermal energy on to small area. Concentrated light is converted to heat producing electrical power which is used to drive a heat engine, mostly steam turbine which is connected to an electrical power generator. Though simple these are far from the in theory maximum concentration and thus, CSPs technology which was started 1984 in the United States, stopped in 1990 and till 2006 no CSPs were built anywhere.

Table 1: Deployment of CSP plants around the world from 1984 to 2012 (except 1991-2005)

Concentrated Solar Power (MWp)

Year	1984	1985	1989	1990	...	2006	2007	2008	2009	2010	2011	2012
Installed	14	60	200	80	0	1	74	55	178.50	306.50	628.5	630
Cumulative	14	74	274	354	354	355	429	484	662.5	969	1597.5	2227.5

2.2 Photovoltaic solar power plant

In photovoltaic power plant, sun light is converted into electric current using the photoelectric effect, wherein solar photovoltaic cells are often electrically connected and encapsulated as a module. Connected solar modules termed “array." Solar cells are also usually connected in series in modules and create additive voltage. Connecting cells in parallel will yield a higher current; however, very significant problems exist with parallel connections. The modules can be interconnected to create an array for needed DC voltage and loading current capacity, it is advisable to utilise independent maximum power point trackers (MPPTs)

There are three major steps followed in the working of the solar cells-

1. Semi-conducting materials like silicon are used to absorb the photons from the sunlight when it hits the solar panel.
2. The electrons are knocked loose from the atoms resulting in an electric potential difference. In the process, current starts flowing through to cancel the potential and this electricity is captured. Solar cells are designed in a way that the electrons are only allowed to move in a single direction.
3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

Materials for photovoltaic cell

Various materials display varying efficiencies and have different costs. Materials for efficient solar cells must have characteristics matched to the spectrum of available light. Some cells are designed to efficiently convert wavelengths of solar light that reach the earth surface. However, some solar cells are optimised for light absorption beyond earth's atmosphere as well. Light absorbing materials can be configured in multiple ways to absorb different light and charge separation mechanism. Monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride and copper indium selenide/sulphide are some of the materials used on PV solar cells.

The available solar cells are made from bulk materials that are cut into wafers between 180 to 240 micrometers thick and are then processed like other semiconductors. Other materials are made as thin-films layers, organic dyes, and organic polymers that are deposited on supporting substrates. A third group are made from nanocrystals and used as quantum dots (electron-confined nano particles). Silicon remains the only material that is well-researched in both bulk and thinfilm forms. The over 200 MW Agua Caliente Solar Project in the United States, and the 214 MW Charanka Solar Park in India are the world’s largest photovoltaic power stations.

Charanka Solar Park

The largest site within the Gujarat Solar Park is built on 2,000-hectare near Charanka village in Patan district, northern Gujarat. This hosts about 17 different projects by various developers. The world's largest photovoltaic power station was commissioned on 19 April 2012 with a total of 214 megawatts (287,000 hp); today it hosts 500 MW of solar power systems using state-of-the-art thin film technology (Figure 2).

Figure 2: Charanka Solar Park in Gujarat state

2.3 Solar Desalination

By utilising solar energy, a desalination system can be integrated to produce freshwater from the abundantly available sea water. Most of the tropical coastal regions face scarcity of fresh water but have abundant solar energy. For such circumstances, the Multi Effect Distillation (MED) or Multi Effect Humidification (MEH) process can be used. The plant will be operational for 6-8 hours per day utilising the steam generated from solar field with Fresnel Reflector System (Figure 3). With other heat sources like bio-mass or waste steam available, the plant can be operated for longer periods.

As part of the technology demonstration and development, the National Institute of Ocean Technology (NIOT) in association with K G Design Services Pvt Ltd. and G.B. Engineering Enterprises Pvt. Ltd. under the sponsorship of Department of Science and Technology (DST) was involved in the design, fabrication and commissioning of a 6 m^3/hr solar driven multi-effect thermal desalination system (MED). The complete system was integrated and commissioned at Narippeyyur, Ramanathapuram in South Tamil Nadu with an intake of seawater at 40 m^3/h and fresh water production of 6 m^3/hr & 2 ppm quality. At present, the performance analysis is underway.

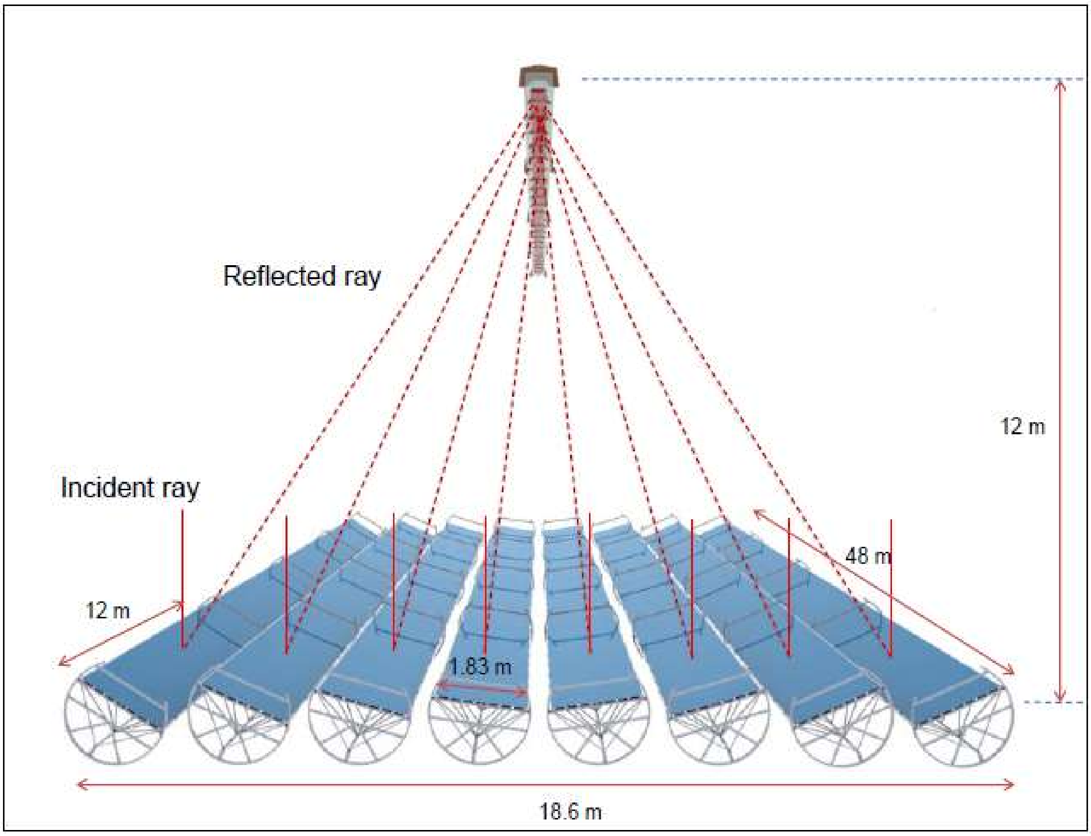


Figure 3: Schematic diagram of linear Fresnel reflector power plant

Figure 4: Overall solar steam generating system

3. Wave Energy

Winds blowing on its surface cause waves in the ocean. However, due to the irregular nature of the wind, waves are also an irregular phenomenon and their intensities vary with seasons as also the location on the globe. Waves can be as low as 0.5m in height to as high as10-11m during cyclones especially during the northeast monsoon season in India

Wave energy devices extract energy directly from the motion of waves at the surface or from the pressure fluctuations below the surface. Some of the wave energy devices that are tried around the world are point absorbers, tapered channel, Oscillating Water Column, and Pelamis. (Yemm, 1999).

While waves contain a fair amount of energy i.e. 5 to 20 kW/m (IREDA, 2014), any structure or equipment to be mounted in the open sea needs to resist the forces to which it is continuously subjected while generating power. Moreover, seawater is also very corrosive hence materials used should be suitable for long- term usage, maybe to last at least twenty years in the sea environment. Thus the design of wave energy devices is very challenging. In India, the average wave power annually is low though during the southwest monsoons (June to August) and northeast monsoons (November to January), the waves can be of very high intensities for few months during this period.

In India, for nearly two decades, research was carried out on an Oscillating Water Column (OWC) device at Vizhinjam in Kerala (Figure 5). This was a large OWC in a caisson near the breakwater in 10 m water depth (Ravindran et al., 1997). Much insight was derived as a part of the process in which several power module designs were tried out. While the peak power generated crossed 80 kW, an average of 13 kW was used to run a Reverse Osmosis (RO) based desalination plant of 10,000 litres per day capacity (Sharmila et al., 2004). This was the first ever self-sustaining system globally where power was generated from the sea to make fresh water out of seawater. However, from the view of improving efficiencies by understanding the complex behavior of the pneumatics of the OWC, mechanical motions and hydrodynamics together, work is now more focused on smaller floating wave-powered devices for remote locations.

Figure 5: Wave energy plant at Vizhinjam

NIOT is working on a floating wave powered device called the Backward Bent Ducted Buoy (BBDB) as shown in Figure 6. Extensive computer simulations and laboratory testing have been carried out for determining the hydrodynamic behaviour, mooring loads and performance of the power module.

Figure 6: Backward Bent Ducted Buoy (BBDB)

Several sea trials were conducted successfully. The exercise has led to gain a thorough understanding of matching of OWC inside a floating body and turbine which is a major outcome in itself, making way for scaling up. Simultaneously a wave powered navigational buoy has been developed as a product. Today navigational buoys are required at all ports and harbours. The NIOT wave powered navigational buoy runs on wave power and value-add by measuring few oceanographic parameters. Technology is transferred to industry and learning utilised for scaling up (Figure 7).

Figure 7: Navigational Buoy

4. Marine currents

Ocean currents are driven by wind and solar heating of the waters near the equator, although some currents result from variation in water density and salinity. Ocean currents are much slower in comparison to wind speeds. However, water is about 835 times denser than wind so a smaller water flow can be equivalent to wind with extremely high velocity. Energy can be extracted from such ocean currents using submerged turbines that capture energy from hydrodynamic lift and drag forces. Tidal ranges are high only in certain specific locations. For instance in India, mostly around the peninsular coast, the tidal range is low but in places like Gulf of Khambat and Sundarbans, it can be as high as 6-8 m. Not much work has been attempted for turbines working on tidal ranges. Marine hydrokinetic turbines run using water velocity. Water currents similar to waves, change direction and magnitude according to seasonal variations. Marine current turbines need to be designed for optimum speeds for maximum power output.

As a result of extensive laboratory studies, NIOT carried out successful sea trials in Andaman and Nicobar Islands on a small cross flow hydrokinetic turbine which was designed and developed in- house in 2016. This type of turbine can work in tidal streams as well as marine currents in the ocean. A 0.8 diameter turbine with 1 m long blades was designed to generate 100 W electrical power at seawater current speed of 1.2 m/s. The turbine was fabricated for study purpose and it successfully generated the design power output in a seawater channel. This unit also generated 300 W electricity whenever current speed reached 1.8 m/s. Following this success, the turbine underwent rigorous testing in Macpherson Strait in South Andaman. These tests pave way for scaling up for off grid units for remote coastal locations (Dudhgaonkar et al., 2016). Currently this success has led to scaled up designs for 1 kW turbine for remote locations in Andaman (Figure 8).

Figure 8: Marine Current Turbine tested at Andaman

5. Tidal Energy using Tidal range

Barrage based tidal energy harnessing becomes feasible for tidal ranges greater than five metres (approximately 16 feet). In India, the Gulf of Khambat and the Gulf of Kachchh in Gujarat on the west coast have the maximum tidal range of 11 m and 8 m with an average tidal range of 6.77 m and 5.23 m respectively. That apart, these locations and a few more in Andaman Islands have high tidal currents where tidal stream based hydrokinetic turbines can harness tidal energy. Deeper regions in Gulf of Khambat and Gulf of Kachchh are suitable for tidal stream based hydrokinetic turbines for harnessing tidal energy; whereas shallower regions of these gulfs are suitable for tidal barrage based energy conversion.

Other potential regions along Indian coastline for the development of small to medium capacity barrage based tidal power plants are the delta regions of Hooghly River and Mahanadi River, and creeks nearby Mumbai coast.. According to a study by Jalihal et al. (2005), through tidal barrage technology, the Gulf of Khambat and Gulf of Kachchh has an estimated potential of 9000 MW and 2000 MW respectively. Few places in Sundarbans in West Bengal like Durga Duani Creek also have a potential of 100 MW. The total estimated tidal energy potential in India is 11.5 GW according to this study. However, a reassessment of tidal energy potential in India needs to be carried out, and locations with high potential need to be identified in order to realize tidal energy harvesting at large scale systematically.

Generally, these turbines are large in size and weight which is also an important factor as its cost further adds on to the capital investment. One of the bulb turbine units in La Rance Tidal Energy Plant has a tip diameter of 5.35 metres and it weighs 470 tonnes. It has four blades and 24 guide vanes. Its operating head range is from 3 metre to 11 metre with peak output of 10 MW (Jalihal et al., 1999).

6. Ocean Thermal Energy Conversion (OTEC)

The sun warms the surface sea water to the extent that all the energy is captured in a region up to 100 m in thickness near the surface. This is called 'mixed layer' since wind and wave actions cause the temperature and salinity to be uniform in this layer. As we go deeper down into the ocean, the water becomes colder. A huge amount of cold water exists at depths of around 1000m, which is due to accumulation of ice-cold water that has melted from the polar regions. The two bodies of warm water from the surface at 28-30°C and cold water from the deep at 7-8°C can be used to run the Ocean Thermal Energy Conversion (OTEC) cycle for generating power. Essentially, an OTEC device converts a low-grade heat source into electricity by using a thermodynamic cycle. The ideal efficiency is determined by the Carnot cycle and is generally around 7-8%, which is for an ideal reversible heat engine. However, in reality components such as heat exchangers, turbine, pumps, and generator, contribute to large losses and hence the actual efficiency is much lower than the ideal one i.e. 3-3.5 % approximately. The major components of an OTEC system are:

- **Heat exchangers** - The working fluid like ammonia or R134a needs to be vaporised by warm surface seawater to drive the turbine and further needs to be condensed using deep sea cold water which is achieved by using heat exchangers.
- **Turbine** - Generally axial and radial turbines of single or multiple stages are used (Nitesh et al., 2012). The pressure ratio across the turbine is dictated by the working fluid and speed of the turbine is important from the generator's perspective. The efficiency of the turbine – generator system directly affects the overall efficiency of power generation. For achieving high overall efficiency for OTEC system, the combined efficiency of the turbine and generator needs to be above 75%.
- **Seawater pumps** - Large volumes of seawater of the order of several tonnes/ sec are required to be pumped up for the OTEC cycle. Generally, the losses, especially in the long cold water conduit, are mostly due to frictional losses. Thus the pumps required are high discharge and low heat pumps. The power requirement of the pumps governs the net power generated in the OTEC cycle and hence the overall efficiency.
- **Cold water conduit** - The most complex and challenging component of the OTEC system is the cold water conduit. An offshore floating plant will need to be positioned in deep waters with a long conduit hanging vertically down or supported in some configuration to draw cold water continuously from depths of around 1000 m (Jalihal et al., 1999). The conduit has to be designed for loads due to waves and currents and also for installation and deployment scenarios. As the rating becomes larger and larger, the size of the conduit becomes huge and is known to be the single most complex unit in the entire system. Internationally studies on the conduit are still under progress.
- **Platform** - When land- based or shelf mounted plants are not possible, a floating platform is required to support the process equipment as well as the conduit to draw cold water. Various platform configurations are being studied the world over including barges, semi-submersibles and spars. The platform design is critical because it has to be an all-weather one and if it is directly supporting the conduit, forces induced by it due to environmental conditions on the conduit can lead to high stresses in the conduit.
- **Station keeping and mooring** - A floating platform needs to be kept in position or at station else the cold water conduit connected to it may start drawing warm water due to vessel drift. Moorings have to be designed to be all weather for this purpose. The current offshore practice has codal requirements for moorings in the oil industry. However long- term moorings for OTEC are yet to be attempted. Additionally, proper data acquisition and control and systematic startup and shut down procedures are required.

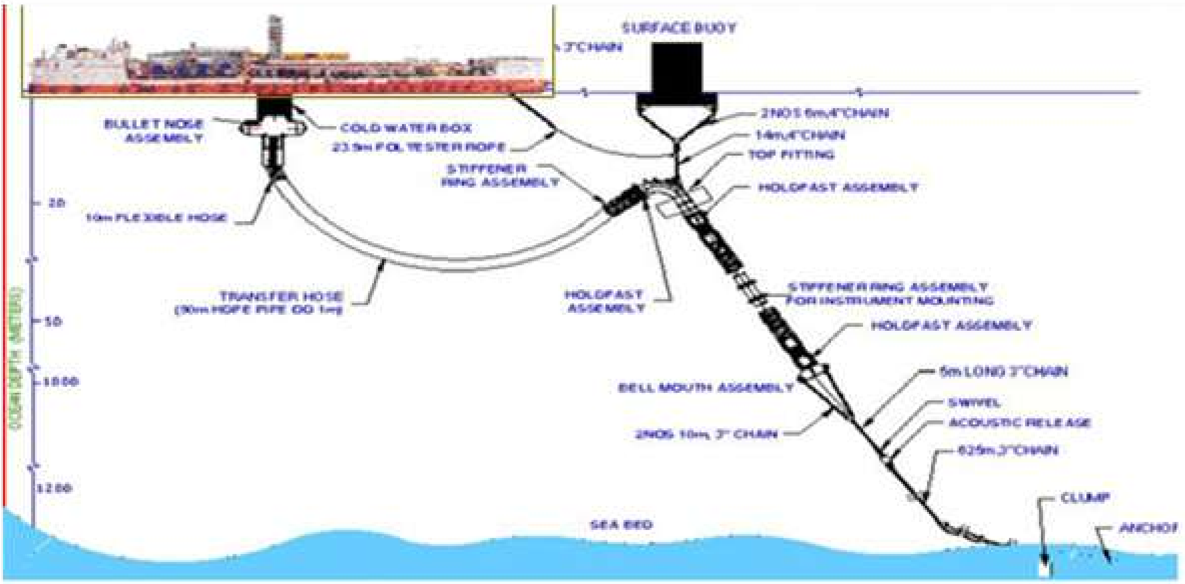


Figure 9: Platform and mooring arrangement of 1 MW OTEC Plant

Figure 10: View of the Barge Mounted Desalination Plant

Indian efforts towards OTEC

NIOT under the Ministry of Earth Sciences (MoES) embarked on efforts towards setting up a 1 MW floating OTEC plant at1000 m water depth about 40 km from the coastal city of Tuticorin in South India in 1998 (Figure 9).

As part of the commissioning activities, various subsystem qualification tests were carried out on shore as well as in shallow waters. The OTEC barge Sagar Shakthi was berthed near the port, and many subsystems trials were carried out. Several trials in shallow waters also were carried out and subsystems qualified successfully (Jalihal et al., 2005; Jalihal et al., 2012; Jayashankar et al., 1998). Finally, the 1000 m long pipe of 1 m diameter was towed 40 km to the desired site. Sufficient offshore handling facilities were not available on the eastern coast of India, hence the deployment had to be carried out with serous limitations and the project could not be completed. Later the same barge was used for mounting desalination equipment and fresh water was first generated in shallow water (Figure 10). The learning was used for setting up desalination plants using thermal gradient successfully. India has the distinction of setting up a low- temperature thermal desalination plant in Kavaratti, Lakshadweep for the first time ever in the world in 2005.

Thermal Desalination expertise has now been developed along with offshore experience for deploying pipes for drawing cold water. NIOT has now set up a laboratory to run the hybrid cycle of OTEC and desalination. Efforts are now on to power desalination using OTEC and such a system is being designed for an island in Lakshadweep. Self-powered desalination systems show promise for the future.

7. Geothermal

It is estimated from geological, geochemical, shallow geophysical and shallow drilling data that India has about 10,000 MWe of geothermal power potential that can be harnessed for various purposes. Rocks in the surface of India range in age from more than 4500 million years to the present day and is distributed in different geographical units. The rocks comprise of Archean, Proterozoic, the marine and continental Palaeozoic, Mesozoic, Tertiary, Quaternary era. More than 300 hot spring locations have been identified by the Geological Survey of India (Thussu, 2000). The surface temperature of the hot springs ranges from 35° C to 98° C. These hot springs are grouped together and termed as different geothermal provinces based on their occurrence in specific geotectonic regions, geological and structural regions such as occurrence in orogenic belt regions, structural grabens, deep fault zones, active volcanic regions etc. The different orogenic regions are – Himalayan geothermal province, Naga-Lushai geothermal province, Andaman-Nicobar Islands geothermal province and non-orogenic regions are – Cambay graben, Son-Narmada- Tapi graben, west coast, Damodar valley, Mahanadi valley, Godavari valley, Puga Valley (J&K), Tatapani (Chhattisgarh),Godavari Basin Manikaran (Himachal Pradesh),Bakreshwar (West Bengal), Tuwa (Gujarat), Unai (Maharashtra),Jalgaon (Maharashtra)., there are no geothermal plants in India till date.

8. Onshore & Offshore wind

In India, the installed capacity of onshore wind power is over 32.7 GW, and it constitutes around 55% of the total renewable energy of the country (Figure 11). Assessment of onshore wind potential by National Institute of Wind Energy (NIWE) in the country was estimated to be 302 GW at 100 m above ground level (Table 2). It was concluded that India's policy goals on energy security challenges and low carbon growth can be met by harnessing the vast untapped wind power potential, in a cost-effective manner.

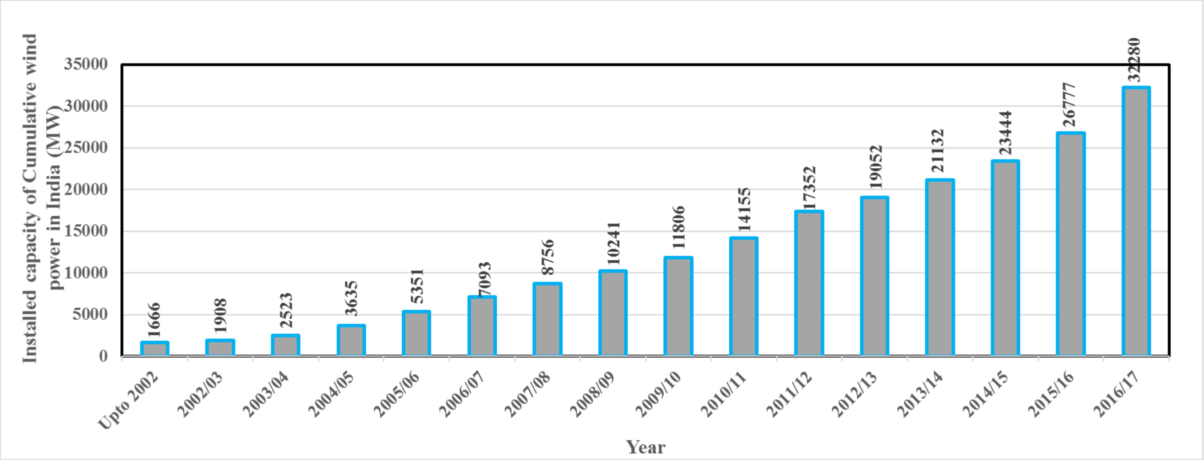


Figure 11: Installed capacity of cumulative onshore wind potential along the Indian coast (Akshay Urja, 2017)

Table 2: Re-assessment of onshore wind energy potential by NIWE (Akshay Urja, 2017)

S.No	State	Onshore wind power potential at 100 m in GW
1	Andhra Pradesh	44.23
2	Gujarat	84.43
3	Karnataka	55.86
4	Madhya Pradesh	10.48
5	Maharashtra	45.39
6	Rajasthan	18.77
7	Tamil Nadu	33.80
Total (7 windy States)		**292.97**
8	Other State	9.28
All India Total		**302.25**

Wind and particularly offshore wind is one of the significant resources of renewable energy available globally. Wind power generation along the coast has received importance due to demand for high energy requirements as a result of the rapid development of both inland and coastal areas. Based on the availability of land, extraction of terrestrial wind energy has already reached a level of saturation. Wind speed, in general, is higher in the offshore region compared to onshore, making it a more consistent source for production of electricity. It is expected that an important part of the future expansion of wind energy utilisation will come from offshore sites and hence a reliable prediction of the wind resources becomes crucial.

Mani Murali et al. (2014) reported the feasible sites for offshore wind energy potentials along the Indian coast. Site selection for offshore wind depends on climatological wind speed and its spatial distribution. Mesoscale meteorological models provide useful information on the climatological wind distribution over the potential areas as the models consist of a series of equations that contain conservation of mass, momentum, heat, and water among other variables. The Indian wind energy sector (on land) has an installed capacity of 20 GW as on December 2013. The National Institute of Wind Energy (NIWE), India and the Lawrence Berkeley National Laboratory, USA, have conducted 'Re-assessment studies on wind potential estimates for India: Economic and Policy Implications' and reported that the onshore wind power potential in India is 102.7 GW at 80 m hub height. It is estimated that this would provide only about 8% of the projected electricity demand in 2022 and 5% in 2032 (Phadke et al., 2011). Studies by Lawrence Berkeley National Laboratory (2011) estimated wind energy potential for India to range from 2,006 GW at 80 m hub height to 3,121 GW at 120 m hub height\, with a minimum capacity factor of 20%.

In India, land-based wind energy development is prevalent (approximately 95% of the onshore wind energy potential) in five states of southern India (Tamil Nadu and Andhra Pradesh) and of western India (Karnataka, Maharashtra, and Gujarat). In order to meet increasing demands, offshore wind energy development becomes very important to achieve an electricity generation of 15% of the total power capacity through renewable resources by 2020. Considering the long coastline of India of more than 7,500 km (including the islands of Andaman & Nicobar and Lakshadweep), the Government of India is preparing a time-bound action plan for the development of offshore wind energy along the coastal states of Gujarat, Maharashtra, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal (GWEC, 2012). As of now, detailed studies on the offshore wind energy development in India are scarce, although a few such as those of the Scottish Development International (SCI) and World Institute of Sustainable Energy (WISE) are available for India's offshore waters. The SCI reported that the state of Tamil Nadu is likely to lead in harnessing wind energy from its offshore wind resources. According to the other studies, Tamil Nadu has a potential of about 1GW north of Rameshwaram and south of Kanyakumari. Recently, WISE conducted a study in potential areas in the southern Indian Peninsula and the Kachchh region of Gujarat. It was reported that the availability of offshore wind energy along the coast of Tamil Nadu is 127 GW at 80 m hub height.

A feasibility assessment of potential offshore wind energy resources was conducted by the National Centre for Sustainable Coastal Management (NCSCM). In order to assess the potential, a Weather Research Forecasting (WRF) model was configured in the coastal regions of mainland and islands (Andaman & Nicobar and Lakshadweep), from the coast up to the Exclusive Economic Zone (EEZ) for simulation of offshore wind potentials. Model simulations conducted for all months during 2012 and offshore wind energy potentials at different water depths was assessed. The diurnal and monthly averaged wind speeds extracted for different potential locations from the model results and wind power density was estimated (Figure 12). Further, wind energy blocks were developed using eight wind speed classifications. The gross offshore electrical power and energy was estimated from the eight offshore wind energy blocks. The model results revealed that the states such as Tamil Nadu and Gujarat are high potential sites for offshore wind energy by considering a sustained wind speed of >7.5 m/sec. These two potential sites, i.e. Gujarat and, Tamil Nadu had wind speeds >7.5 m/sec for 9 and 10 months' period respectively in the year 2012. The gross offshore electrical power at different water depths such as 0–30 m, 30–50 m, 50–100 m, 100–200 m, and 30–200 m was estimated about 5339 GW.

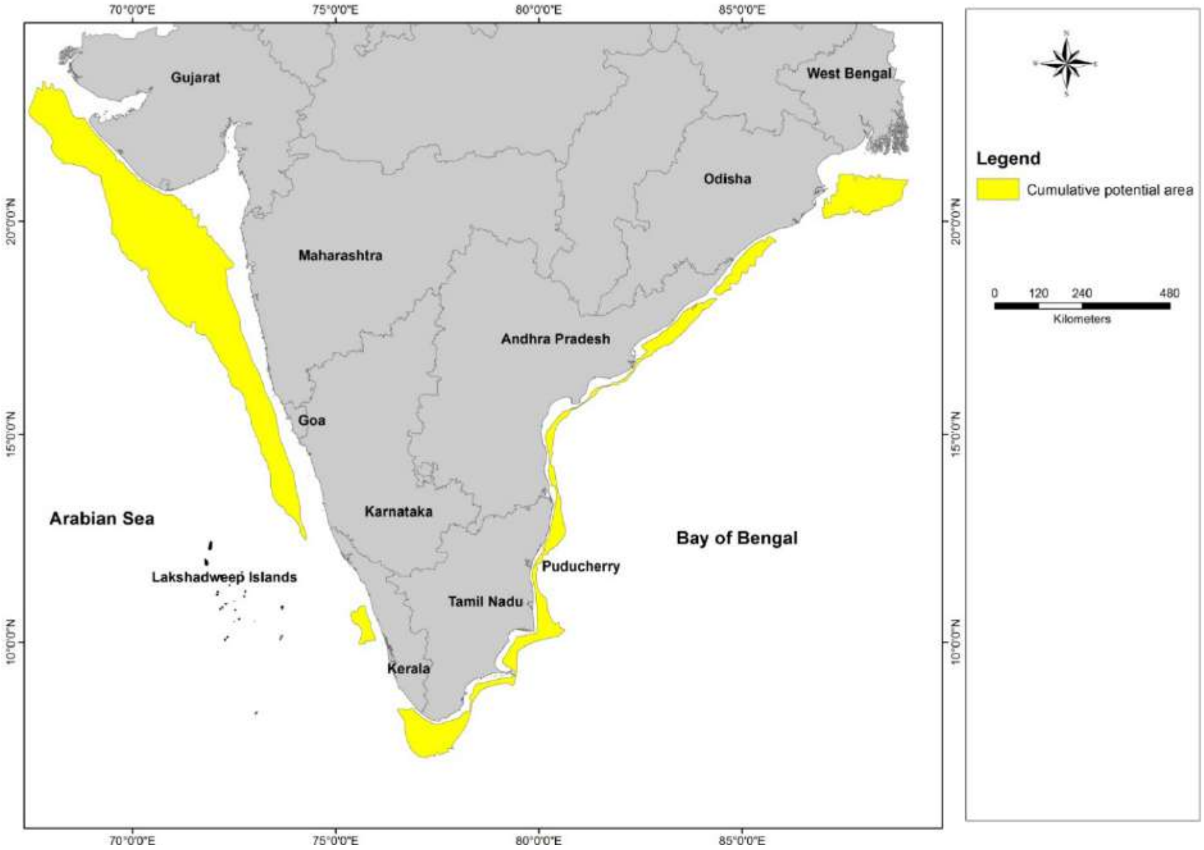


Figure 12: Map of potential area for offshore wind energy along the coast of India for 2012

Conclusion

The potential to harness natural sources for the growing energy demands in an environmentally sustainable manner is fine- tuned constantly through technical advancement. Thus, in order to reduce dependence on fossil-fuel for generating energy, various advanced measures have been facilitated in India in different sectors of renewable energy technology (solar, wind, wave, tide, geothermal etc.).

Solar energy is abundant in India, and it can offer a clean, eco-friendly, inexhaustible option and solves several critical problems of the world such as climate change, energy security, and universal access services. Further, technologies like desalination of seawater by solar energy and low temperature thermal desalination plant using Ocean Thermal Energy Conversion (OTEC) technology has also been successful.

Further, India has also been able to harvest wave energy efficiently, using an Oscillating Water Column (OWC) device. Similarly, successful sea trials for harvesting renewable energy from marine currents have been initiated. High offshore wind energy potential using numerical weather models has been identified on the Indian coasts.

Such endeavours have indicated the vast potential of tapping renewable energy from the coasts and thereby adding on to India's climate change mitigation policy by replacing fossil fuels and filling the wide gap between the demand and generation of energy. The contribution of clean and eco-friendly energy from different renewable sources using advanced renewable technologies can gradually reduce the use of fossil-fuel and significantly contribute to climate change mitigation in future.

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Governance

22

Coastal governance in times of climate change

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ABSTRACT

Transformation of India's coastline has been rapid due to increase in coastal development and intensity of natural hazards. The positive aspect though has also been the consistent conservation efforts, providing stability to the coast. Coastal governance in India has primarily been regulatory in nature through the various laws that govern coastal activities such as the Coastal Regulation Zone (CRZ) Notification, 2011. Most coastal issues have upstream origin and hence a comprehensive management of the entire coastal system is essential. The evolution of coastal governance and links to climate change is critical to better understand the need for an integrated regulatory and management framework. This is currently being undertaken by the Ministry of Environment, Forest and Climate Change by effective implementation of the CRZ Notification, 2011 and India's Integrated Coastal Zone Management (ICZM) Programme.

1. India's Coast

India's mainland coast is distributed among nine maritime states and two union territories. There are 75 coastal districts with a population of 0.193 billion of the total Indian population of 1.21 billion (Census of India, 2011). A number of large towns, cities (including the two megacities of Kolkata and Mumbai) and urban agglomerations such as Chennai are located along the coast. Currently, there are 12 major ports and 187 non-major ports along the mainland coast of India. Several industries of varying sizes and nature, are strategically located adjacent to ports, harbours and power plants, with increased urban agglomerations.

The coast has been referred to as the 'final frontier' (MoEF, 2009) because it serves as a barrier from hazards originating from the sea such as cyclones and tsunami, and the limit of land-based development. The coast has a variety of geomorphological features (e.g. sandy beaches and dunes) and ecosystems (e.g. mangroves and coral reefs) that serve as effective natural barriers to hazards from the sea. Increased development in coastal areas amplifies the risk from coastal hazards in two ways. First, development often results in the conversion of natural habitat into other land use such as agriculture, aquaculture, industries and settlements with associated loss of the buffering capacity. Secondly, development close to the coast or in low-lying areas results in increased population, infrastructure, and the associated economic investments at risk. All these very clearly indicate the importance of governance of the coastal areas.

2. Climate Change

The most important impacts of climate change in coastal areas are rising sea levels and increasing sea surface temperatures. An increase in global mean sea level at a mean rate of 1.7 mm yr^{-1} has been observed between 1900 and 2010 whereas the rate has increased to 3.2 mm yr^{-1} from 1993 to 2010 (Han et al., 2010). Recent research has shown that uneven rise in sea level in the Indian Ocean threatens coastal areas along the Bay of Bengal and the Arabian Sea (Han et al., 2010). The authors note that, if future anthropogenic warming effects in the Indo-Pacific warm pool dominate natural variability, the northern Indian Ocean may experience significantly more sea-level rise than the global average.

Variations in sea-level between seasons appear to be higher in the Bay of Bengal coast than any other coasts of South Asia. The sea-level along the Indian coast in and around Visakhapatnam (south-west coast of Bay of Bengal), has been rising by 0.93 mm per year between 1937 and 2000 and near Diamond Harbour (West Bengal) by 4.96 mm per year between 1948 and 2010 (Unnikrishnan et al., 2015). In the Arabian Sea, the sea level in and around Mumbai has been rising by 1.08 mm per year between 1878 -1993 and around Kochi by 1.81 mm per year during 1939-2007 (Unnikrishnan et al., 2015).

Impacts of rising sea levels include increased beach erosion, saltwater intrusion into groundwater and flooding of coastal lands. Generally, beach loss from erosion exceeds that due to direct inundation. The area eroded will depend on the average slope of the beach out to a water depth where waves cease to impact the sub-surface (generally about 10 m deep). Located close to the equator, the sub-continent is expected to experience much higher rises in sea levels than higher latitudes.

Kolkata and Mumbai, both densely populated cities located in low lying areas are particularly vulnerable to the impacts of sea-level rise, tropical cyclones, and riverine flooding as well as heavy inundation during the monsoons. Most recently, in the 2018 south-west monsoon season, heavy downpours along the west coast have caused intense flooding of large areas of coastal Karnataka (especially Mangaluru) during May, Maharashtra (Mumbai) during July and Kerala during August resulting in widespread damage. Kochi airport, the largest airport in Kerala, was closed for over two weeks due to rain and flooding (Anon, 2018). The 2010 Indian Network for Climate Change Assessment (INCCA) report states that for a one metre rise in sea level, about 169 km^2 of the coastal region surrounding Kochi would be inundated, as the area covers backwaters. Vast inland areas are far from the coast, but are adjacent to tidal creeks, backwaters and lakes which will cause considerable increase in the total area of inundation. The INCCA report also indicated that Paradip on the east coast is most vulnerable with about 478 km^2 likely to be inundated with the extent of the probable inundation zone extending 40 km inland. In case of Nagapattinam, also located on the east coast, 4.2 km^2 is expected to be inundated (INCCA, 2010).

Figure 1: Aerial view of Floods in Kerala during August 2018[1]

Studies carried out by Mandke and Bhide (2003) indicated that the frequency of storms forming over Indian seas has decreased significantly. Studies of the long period data from 1901-1998 have revealed that the storm frequency has decreased on a decadal scale since 1980s despite increasing sea surface temperatures that are conducive to the formation of storm surges. However, analysis indicates that systems are moving towards southern latitudes and might be more intense in future as compared to the present under the global warming scenario (INCCA, 2010). Simulations showed increase in frequencies of tropical cyclones in the Bay of Bengal, with particularly intense events during the post-monsoon period for the increased Greenhouse Gas (GHG) emissions (Unnikrishnan et al., 2006). Overall, the impacts of climate change can be discerned at two classes – one on the ecosystems and the other on the socio-economic conditions (Figure 2).

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[1] https://www.firstpost.com/tech/news-analysis/what-caused-the-kerala-floods-4993041.html

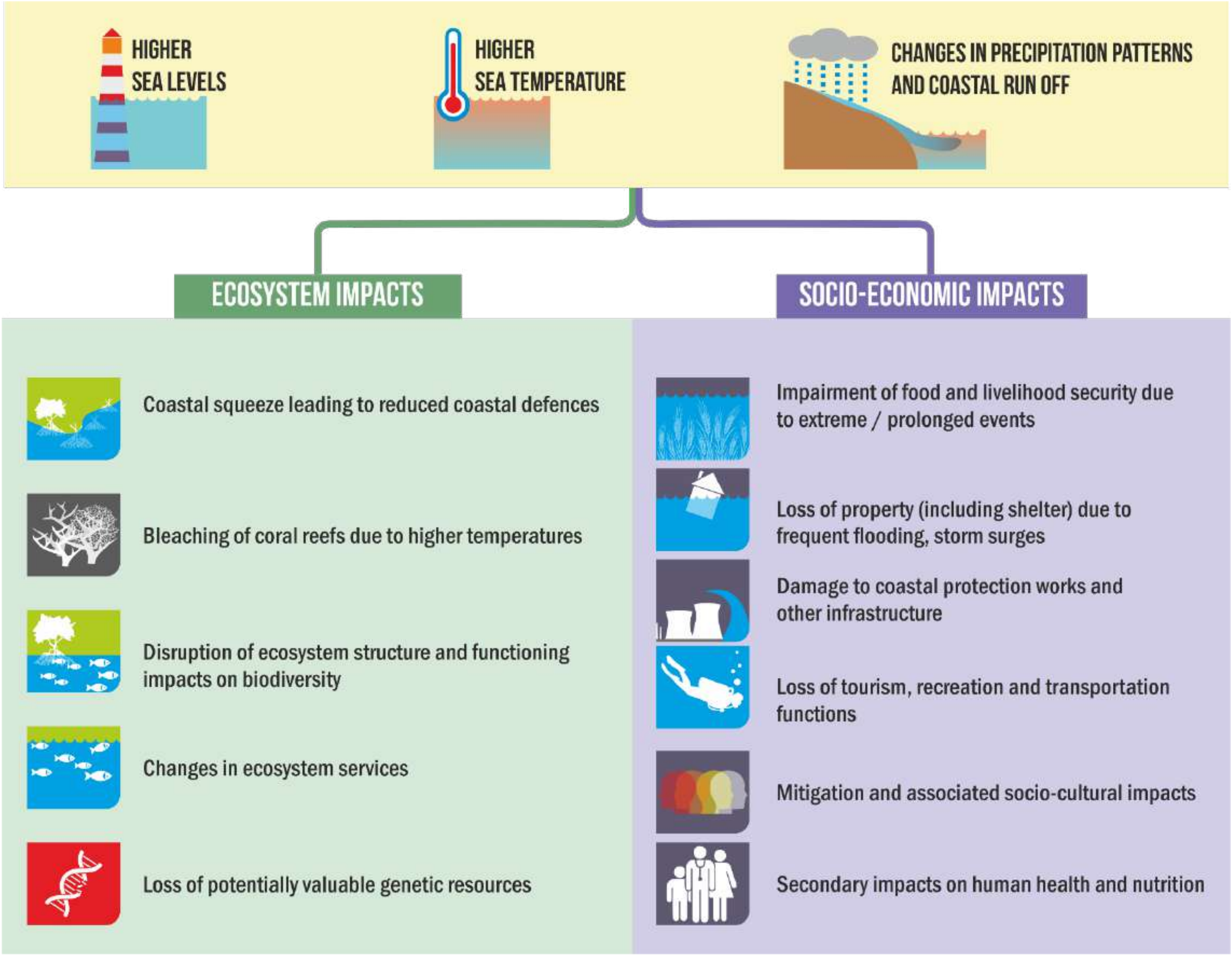

Figure 2: Climate change impacts on the coast

3. Governance of Coastal Areas

3.1 Early approaches

Prior to 1980s, activities that had major adverse impacts on coastal areas were few and consequently, the approach to management was sectoral. India was largely still using legislations of pre-Independence times such as the Indian Fisheries Act, 1897 and the Indian Forest Act, 1927, to name two that were also relevant to coastal areas. While the Fisheries Act 1897 prohibited destructive fishing and regulated use of certain gears, the Indian Forest Act, 1927 and its predecessor (1878) sought to consolidate and reserve areas having forest cover, or significant wildlife, to regulate movement and transit of forest produce. It was also to levy duty on timber and other forest produce, apart from defining the procedure to be followed for declaring an area to be a Reserved Forest, a Protected Forest or a Village Forest.

Shipping, a major activity was dealt with by the Ministry of Commerce till 1949. In 1951, it was moved to the Ministry of Transport and Shipping. The Shore Nuisance (Bombay and Kolaba) Act of 1853 and the Oriental Gas Company Act of 1857 imposed restrictions on the fouling of water. It was only in 1974 that an exclusive Water (Prevention and control of pollution) Act, 1974 was enacted. Other relevant Acts in this context include the Indian Coast Guards Act, 1974 and the Maritime Zones of India (Regulation of fishing by foreign vessels) Act, 1981.

3.2 United Nations Conference on Human Environment (UNCHE), 1972

The United Nations Conference on Human Environment (UNCHE) was held in 1972 at Stockholm, Sweden. Principle 2 of the Stockholm Declaration, of relevance to coastal management, states "*The natural resources of the earth, including the air, water, land, flora and fauna and especially representative samples of natural ecosystems, must be safeguarded for the benefit of present and future generations through careful planning or management, as appropriate*" while Principle 7 states that "*States shall take all possible steps to prevent pollution of the seas by substances that are liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea.*"

In 1981, the then Prime Minister of India issued a directive asking coastal states to take adequate measures to protect the coastal environment by ensuring that no permanent construction should be undertaken within 500 m of the high tide line (MoEF, 2005). This was followed by a set of guidelines to protect the country's beaches but since they had no statutory backing, they were not taken seriously. After the UNCHE, 1972, India enacted the Environment (Protection) Act in 1986. The Preamble of the Act clearly states

> "*Whereas decisions were taken at the United Nations Conference on the Human Environment held at Stockholm in June 1972, in which India participated, to take appropriate steps for the protection and improvement of human environment;*
>
> *And whereas it is considered necessary further to implement the decisions aforesaid in so far as they relate to the protection and improvement of environment and the prevention of hazards to human beings, other living creatures, plants and property;...*"

3.3 The Environment (Protection) Act [E(P)A], 1986

The E(P)A, 1986 is an enabling Act allowing the Central Government '*to take all measures as it deems necessary or expedient for the purpose of protecting and improving the quality of the environment and preventing, controlling and abating environmental pollution.*' It was under Section 3(1) and Section 3(2) (v) of the Environment (Protection) Act, 1986 and Rule 5(3)(d) of Environment (Protection) Rules, 1986, that a Notification was issued on 19th February 1991 related to coastal protection.

3.4 Coastal regulation Zone Notification (CRZ), 1991

The Coastal Regulation Zone Notification (CRZ, 1991) declared '*the coastal stretches of seas, bays, estuaries, creeks, rivers and backwaters which are influenced by tidal action (in the landward side) up to 500 metres from the High Tide Line (HTL) and the land between the Low Tide Line (LTL) and the HTL as Coastal Regulation Zone*'.

It imposed restrictions on the establishment and expansion of industries, operations or processes etc., in the CRZ. The CRZ was further divided into four classes:

CRZ-I: including the ecologically sensitive areas (ESA) such as mangroves, coral reefs and salt marshes along the coast;

CRZ-II: highly developed areas

CRZ-III: the rural areas

CRZ IV: India's island territories

Norms for regulation of activities are provided in the notification. Section 2 of the notification listed prohibited activities in the CRZ, such as setting up/ expansion of new industries (with exceptions) and permitting only those that directly required foreshore facilities. Section 3 provides the regulation mechanism for permissible activities in the CRZ. It specifies that clearance would be given only for those activities requiring shorefront and also lists various activities that require environmental clearance from the Ministry of Environment and Forests. Coastal Zone Management Plans (CZMP) identifying and classifying the CRZ areas were to be prepared by the respective states and within the framework of such approved plans, all development and activities within the CRZ would be regulated as per specified norms.

Annexure I provided details on the coastal area classification and development regulations. CRZ I included not only areas that are ecologically important but also '*areas likely to be inundated due to rise in sea level consequent upon global warming and such other areas as may be declared -by the Central Government or the concerned authorities at the State/Union Territory level from time to time*'.

The eventuality of rising sea levels was clearly recognised in this first of its kind legislation that focused on the coastal zone as a distinct entity. However, the implementation of the CRZ 1991 was poor because of a number of reasons including lack of capacity, the frequent amendments that weakened the Notification (e.g., reducing the buffer zone), lack enforcement of the CRZ and non-preparation of proper CZMP (Ramesh et al., 2010).

3.5 The National Environment Policy (NEP), 2006

In 1986, India brought out a National Environment Policy (NEP, 2006). The section on Coastal Resources refers to the diverse set of natural and manmade assets that provide habitats for marine species, which, in turn comprise the resource base for livelihoods of coastal communities and for sustainable tourism and also serves as protection from extreme weather events. The document also highlights the increasing degradation of coastal resources, indicating the causal factors as poor planning, improper location of industries and infrastructure, pollution from industries and settlements, and overexploitation of living natural resources and indicates the potential adverse impacts of sea level rise due to climate change in the future.

According to the NEP, the deeper root causes of the problems were inadequate institutional capacities and poor participation by local communities in the formulation and implementation of coastal management plans. Hence, though developmental activities are regulated by means of the Coastal Regulation Zone notification and management plans made under them, *there is need to ensure that the regulations are firmly founded on scientific principles, including the physical, natural, and social sciences. This is necessary to ensure effective protection to valuable coastal environmental resources, without unnecessarily impeding livelihoods, or legitimate coastal economic activity, or settlements, or infrastructure development* (NEP 2006, 5.1.3.ii). The NEP also recommended a re-visitation of the CRZ 1991 to ensure a more holistic approach, and also called for the preparation of ICZM Plans with strong basis in science with extensive local participation towards both formulation and implementation.

3.6 United Nations Conference on Environment and Development (UNCED), 1992

The United Nations Conference on Environment and Development (UNCED, also known as the Earth Summit) was held in 1992. One of the major outputs of the conference was Agenda 21, the global action plan for sustainable development into the 21st century. Chapter 17 titled *'Protection of the oceans, all kinds of seas, including enclosed and semi-enclosed seas, and coastal areas and the protection, rational use and development of their living resources'* called for *'new approaches to marine and coastal area management and development, at the national, sub-regional, regional and global levels, approaches that are integrated in content and are precautionary and anticipatory in ambit'*. The first programme area called for states to commit themselves to

a. integrated management and sustainable development of coastal and marine areas under their national jurisdiction
b. ensure balanced use of resources,
c. apply preventive and precautionary approaches in project planning and implementation and
d. provide access, as far as possible, for concerned individuals, groups and organizations to relevant information and opportunities for consultation and participation in planning and decision-making at appropriate levels.

3.7 The First Swaminathan Committee

Between 1991 and 2004, over twenty-five amendments were made to the 1991 CRZ Notification. A number of committees had made recommendations and there had also been some judicial pronouncements as well as representations from various stakeholders (Ramesh et al., 2010). Hence, in the light of these as well as based on suggestions in the NEP, 2006 and the Agenda 21, an expert committee – the Swaminathan Committee was constituted by the MoEF to *"carry out a quick but comprehensive review of the Coastal Regulation Zone Notification, 1991"* and *"if necessary, to make the regulatory framework consistent with well-established scientific principles of coastal zone management"*.

The report of the First Swaminathan Committee (MoEF, 2005) was accepted in 2005, about two months after the 26th December Indian Ocean tsunami of 2004 that devastated large parts of the Indian coastline. The committee examined in great detail the suggestions made by various committees and the amendments to the CRZ Notification that had been carried out. The committee suggested a set of twelve basic guiding principles to govern future decisions in coastal zone management. Emphasis was placed on the regeneration of mangrove wetlands, coral reefs and sea grass beds as well as promotion of coastal forestry and agro-forestry as it would serve for both as carbon sequesters; as bioshields against coastal hazards and support livelihoods of coastal communities.

Based on the Committee's report, a draft notification was issued on 1st May 2008 (draft Coastal Zone Management (CZM) Notification, 2008) by MoEF. According to this notification, the Coastal Zone was defined as *"the area from the territorial waters limit (12 nautical miles measured from the appropriate baseline) including its sea bed, the adjacent land area along the coast, and inland water bodies influenced by tidal action including its bed, up to the landward boundary of the local self-government or local authority abutting the sea coast, provided that in case of ecologically and culturally sensitive areas, the entire biological or physical boundary of the area may be included, as specified under the provisions of Environment Protection Act"*.

3.8 The Second Swaminathan Committee

The issue of draft notification on CMZ was protested especially by the fishing community, as they envisioned large scale uncontrolled development of the coast and their lives and livelihoods imperilled. In June 2009, following a series of consultations across the nine coastal states, and taking into account the report by a Joint Parliamentary Committee investigation, the MoEF constituted a four-member committee to recommend future steps on the draft Coastal Management Zone (CMZ) Notification, 2008, also chaired by Prof. M.S. Swaminathan (and hence referred to as the Second Swaminathan Committee).

In its report titled "Final Frontier" (MoEF, 2009), the four-member committee, pointed out that the Indian coastline was doubly vulnerable today facing threat from development activities on the one hand and from climate related hazards on the other and recommended that the 2008 draft CMZ Notification be allowed to lapse. They suggested strengthening of the CRZ Notification 1991, incorporating the major amendments. An Agenda for Coastal Areas was also highlighted as part of their report. Of specific relevance to climate change and the coast are the following:

- Strengthen protection to mangroves based on clear definitions.
- Include the seaward side to ensure protection from current and future threats, but with safeguards to ensure there is no restriction to livelihoods of fishing communities.
- Introduce measures to greatly strengthen research and regulatory capacity at all levels.
- Introduce policies to cope with, and adapt to, the future dangers from sea level rise and increased vulnerability of the coasts.

The Ministry of Environment and Forests accepted the recommendations of this Report and let the 2008 draft CMZ Notification lapse and prepared the Draft CRZ 2011 Notification keeping suggestions/ recommendation of the Committee. Public opinion was also sought through widespread consultations and finally the CRZ Notification was issued in the Gazette dated 6th January 2011.

3.9 CRZ 2011

The 2011 CRZ Notification was issued with three specific objectives:

i. To ensure livelihood security to fisher communities and other local communities living in coastal areas
ii. To conserve and protect coastal stretches, its unique environment and its marine area
iii. To promote development through sustainable manner based on scientific principles taking into account the dangers of natural hazards in the coastal areas, sea level rise due to global warming.

The CRZ 2011 extended the coastal regulation zone seaward to the 12 nautical mile territorial limit. In addition, the CRZ 2011 included the concept of a hazard line. Within the CRZ, four zones were demarcated as follows:

i. **CRZ-I:** Areas that are ecologically sensitive and geomorphological features which play a role in maintaining the integrity of the coast; and area between HTL and LTL
ii. **CRZ –II:** Areas that have been developed up to or close to the shoreline
iii. **CRZ – III:** Areas that are relatively undisturbed
iv. **CRZ – IV:** Water area from the Low Tide Line to twelve nautical miles on the seaward side; and the water area of the tidal influenced water body from the mouth of the water body at the sea up to the influence of tide which is measured as five parts per thousand during the driest season of the year.
v. **Areas requiring special consideration:** CRZ areas within municipal limits of Greater Mumbai, CRZ areas of Kerala and CRZ areas of Goa; Critically Vulnerable Coastal Areas (CVCA) such as Sunderbans region of West Bengal and other ecologically sensitive areas identified as under Environment (Protection) Act, 1986 and managed with the involvement of coastal communities including fisherfolk.

For island territories, along with CRZ Notification 2011, the Island Protection Zone (IPZ) Notification 2011 was issued. This declared the coastal stretches of Middle Andaman, North Andaman, South Andaman and Greater Nicobar and entire area of the other islands of Andaman and Nicobar and the Lakshadweep and their water area up to territorial water limit as the Island Protection Zone, putting restrictions on the setting up and expansion of industries, operations or processes. Apart from the standard restrictions and prohibitions, the IPZ calls for disaster risk reduction through bioshields with local vegetation (mangroves) and other soft protection measures, and the conservation of beaches and sand dunes.

3.10 Climate Change and CRZ 2011

The significance of the CRZ Notification, 2011 with respect to climate change are classified into three aspects:

i. The 500 m distance from the HTL functions like a buffer from ocean-based threats such as sea level rise due to thermal expansion of water resulting in coastal inundation,

ii. The hazard line, a combination of 1 in 100-year flooding and predicted 100-year erosion line, identifies the areas that are likely to be inundated due to climate related threats such as storm surges – and therefore calling for appropriate adaptation measures to be put in place, and

iii. Zoning of the CRZ takes into account the ecologically sensitive nature of the coast and tries to control activities that can have adverse impacts on functioning of these ecosystems. The states are to prepare Coastal Zone Management Plans which are essentially maps of the CRZ demarcating the four zones and indicating the permitted/ prohibited activities. Even where activities are permitted, Environmental Impact Assessment (EIA) needs to be conducted following the procedure laid down in the 2006 Environmental Impact Assessment (EIA) Notification. Here also, climate change aspects would be considered while carrying out the assessment to propose appropriate mitigation measures though it has not been explicitly stated in the EIA 2006 Notification, especially as part of the disaster management component.

CRZ-I: The Notification provides for special protection and conservation measures for the coastal ecologically sensitive areas (ESAs) and the eco-morphological features which play a role in the maintaining the integrity of the coasts. No management action would be possible unless the area is clearly mapped and delineated based on scientific criteria and the boundaries are clearly defined. The CRZ Notification, 2011 clearly lists out the areas that fall within the category of CRZ-IA. It includes Ecologically Sensitive Areas (ESAs) and a buffer zone of 50m for around mangrove which covers an area >1000 Sq.m. Ecologically sensitive areas and the geomorphological features that play a primary role in maintaining the integrity of the coast. CRZ-I includes the following,

i. Mangroves, in case mangrove area is more than 1000 square metres, a buffer area of 50 metres shall be provided;
ii. Corals and coral reefs and associated biodiversity;
iii. Sand Dunes;
iv. Mudflats which are biologically active;
v. Salt Marshes;
vi. Turtle nesting grounds;
vii. Horse shoe crabs habitats;
viii. Sea grass beds;
ix. Nesting grounds of birds;
x. Areas or structures of archaeological importance and heritage sites.
xi. National parks, marine parks, sanctuaries, reserve forests, wildlife habitats and other protected areas under the provisions of Wild Life (Protection) Act, 1972 (53 of 1972), the Forest (Conservation) Act, 1980 (69 of 1980) or Environment (Protection) Act, 1986 (29 of 1986); including Biosphere Reserves.

Mapping over 34,000 sq. km of ESAs along the mainland coast and islands of India has been completed by the National Centre for Sustainable Coastal Management, MoEFCC and the extent of each ESA is given in Figure 3.

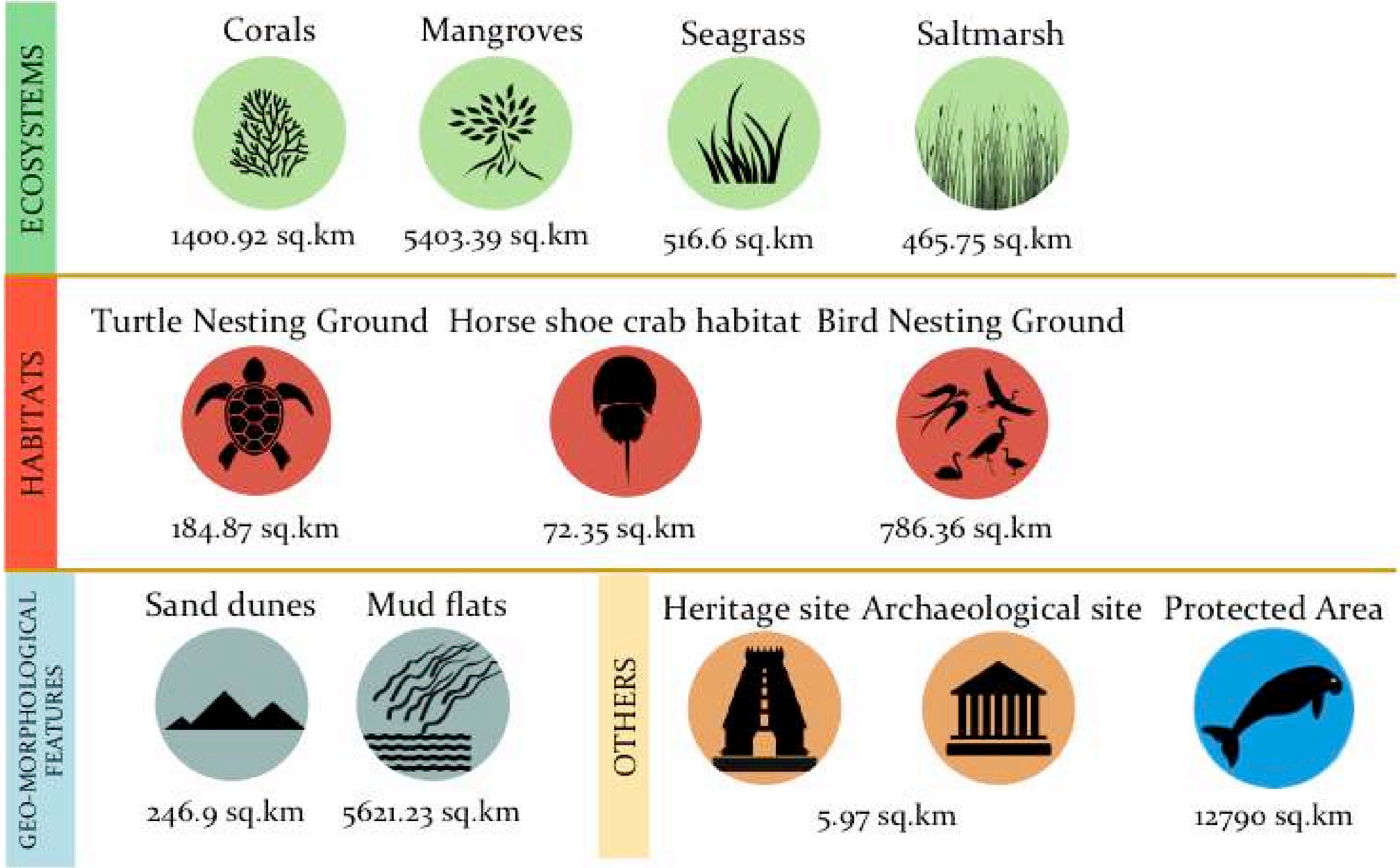

Figure 3: Coastal/ Marine Ecologically Sensitive Areas of India

In addition, a new category has been listed in the CRZ 2011, namely the CVCA or Critically Vulnerable Coastal Areas. Such areas are to be protected through involvement of the local communities who depend on such ecosystems for their sustenance. The rationale being that ecosystems are better protected by communities who benefit directly from the ecological services and thus have a stake and ownership in safeguarding the environment. Moreover, local communities have a better understanding of the changes in the ecosystems and can draw on their traditional knowledge for adaptation, conservation and governance systems for effective management.

The Coastal Regulation Zone (CRZ) Notification, 2011 has identified 12 sites along the coast of India as Critically Vulnerable Coastal Areas (CVCAs) for promoting conservation and sustainable use of coastal resources and habitats (Figure 4). A scientific assessment of the extent of community dependence on the ESAs and their governance ability has been completed for all the 12 CVCA sites along the country's coast.

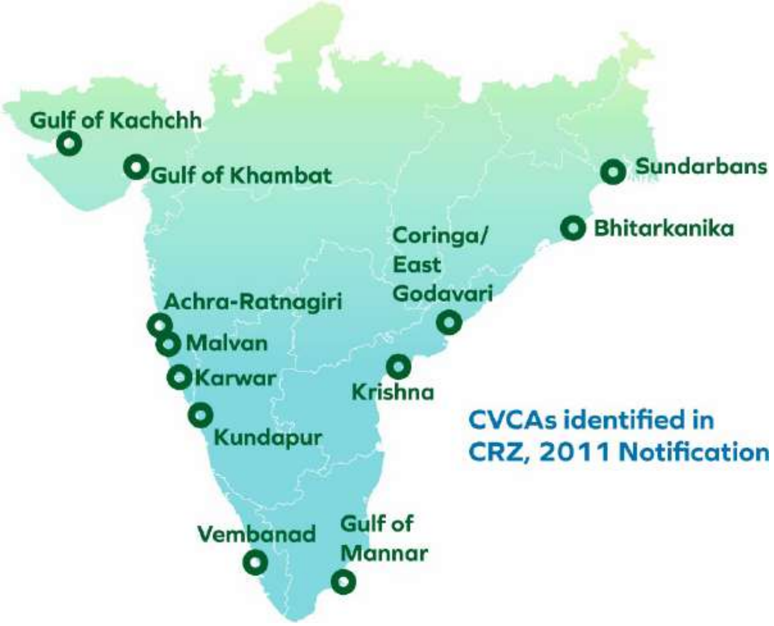

Figure 4: Critically Vulnerable Coastal Areas (CVCA) of India

Similar to CRZ 2011 for the mainland coast, an Island Protection Zone (IPZ) Notification 2011 was issued for the islands of Andaman and Nicobar and the Lakshadweep. Through this, the coastal stretches of Middle Andaman, North Andaman, South Andaman and Greater Nicobar and entire area of the other islands of Andaman and Nicobar and the Lakshadweep and their water area up to territorial water limit was declared as Islands Protection Zone regulating activities that could be carried out in these zones except in the manner provided in the Island Coastal Regulation Zone (ICRZ) and Integrated Islands Management Plans (IIMPs).

In April 2018, MOEFCC issued a draft CRZ Notification 2018 seeking comments from all stakeholders. The draft is now under consideration. This draft incorporates some changes in the way the CRZ zones are defined, taking into account population densities and needs of eco-tourism in ecologically sensitive areas. It also includes islands along the mainland coast under areas requiring special consideration in the CRZ. A notable addition with relevance to climate change is the Annex I of the draft notification which provides a ‘Conservation, Protection and Management framework for Ecologically Sensitive Areas’. In the section on demarcation of the hazard line, it states that *‘with a view to reduce the vulnerability of the coastal communities and ensuring sustainable livelihood, while drawing the CZMPs, the land use planning for the area between the Hazard line and HTL shall take into account such impacts of climate change* *and shoreline changes.'* Similarly, a draft Island Coastal Regulation Zone Notification was issued in August 2018 increasing the number of islands that come under the classification of ICRZ.

3.11 Other Legislation relevant to Coastal Areas

The Wildlife (Protection) Act (WLPA), 1972 provides for both species-specific and spatial conservation strategies. Specifically, Chapter IV of the WLPA provides details of the declaration of sanctuaries, national parks and closed areas. Under the WLPA, currently, there are 24 Marine Protected Areas (MPA) in peninsular India and more than 100 MPAs in the country's islands. The 24 MPAs of the mainland have a total area of about 8214 km^2, which is about 5% of the total protected area network of India and represents 0.25% of the total geographic area of the country (Sivakumar et al., 2014). Some of the important designated MPA in mainland India are the Gulf of Kachchh Marine National Park, the Gulf of Mannar Marine National Park, Bhitarkanika National Park, Coringa Wildlife Sanctuary, Chilika Wildlife Sanctuary and Sundarban National Park. Since these are also included under CRZ-I of the CRZ 2011 Notification, development regulations apply to these too.

The Forest Conservation Act, 1980 prevents conversion of forest land for other purposes except through permission of the Central Government. The Biological Diversity Act, 2002, contains provisions that aim at preserving biodiversity as well as establishing a system for equitable sharing of benefits arising from the use of traditional biological resources and knowledge. Biodiversity Heritage Sites (BHS) may be declared under this Act (Section 37) and Biodiversity Management Committees (BMC) shall be constituted not only for biodiversity conservation but also for documentation and chronicling of biodiversity related knowledge. With respect to climate change, this would refer to knowledge on land races, cultivars etc., that can be used under different climate regimes.

The Environment (Protection) Act also allows areas to be designated with varying degrees of protection when designated as ecologically sensitive zones/ eco-sensitive zones, though as of now, no such designation has been made with specific reference to climate change. Two areas along the coast that have been designated as eco-sensitive are Dahanu and Murud-Janjira in Maharashtra.

The overarching goal of the National Policy on Marine Fisheries, 2017 (NPMF, 2017) is to ensure the health and ecological integrity of the marine living resources of India's Exclusive Economic Zone (EEZ) through sustainable harvests for the benefit of present and future generations of the nation. Specifically, it calls for implementation of the Ecosystem Approach to Fisheries Management as well as area specific management plans. With reference to Climate Change, the policy refers to encouragement of green fisheries by reducing GHG emissions from fishing and fishing-based activities.

4. Multiple Activities and Sectoral Management in the Coastal Zone

The heavy economic investment in coastal areas and growing conflicts among users of the coastal zone has resulted in a demand for better management of this fragile ecosystem. Traditionally, coastal areas have been managed sectorally, apart from division of activities/ geographical jurisdictions between the Centre and States. Figure 5 provides listing of some of the important ministries at the Centre that are involved in managing various activities on the coast. Each ministry has its own set of Acts, Rules and other instruments for implementation (Figure 6).

Inter-ministerial coordination for coastal developmental activities are essential to safeguard the sensitive coastal/ marine ecosystems. Although Environmental Impact Assessments for such projects are mandatory, and often good mitigation measures are recommended, implementation and monitoring needs to be further strengthened. In fact, the MoEFCC are emphasizing on cumulative Impact Assessment of coastal areas, which considers impacts due to existing and future developmental pressures through carrying capacity analyses.

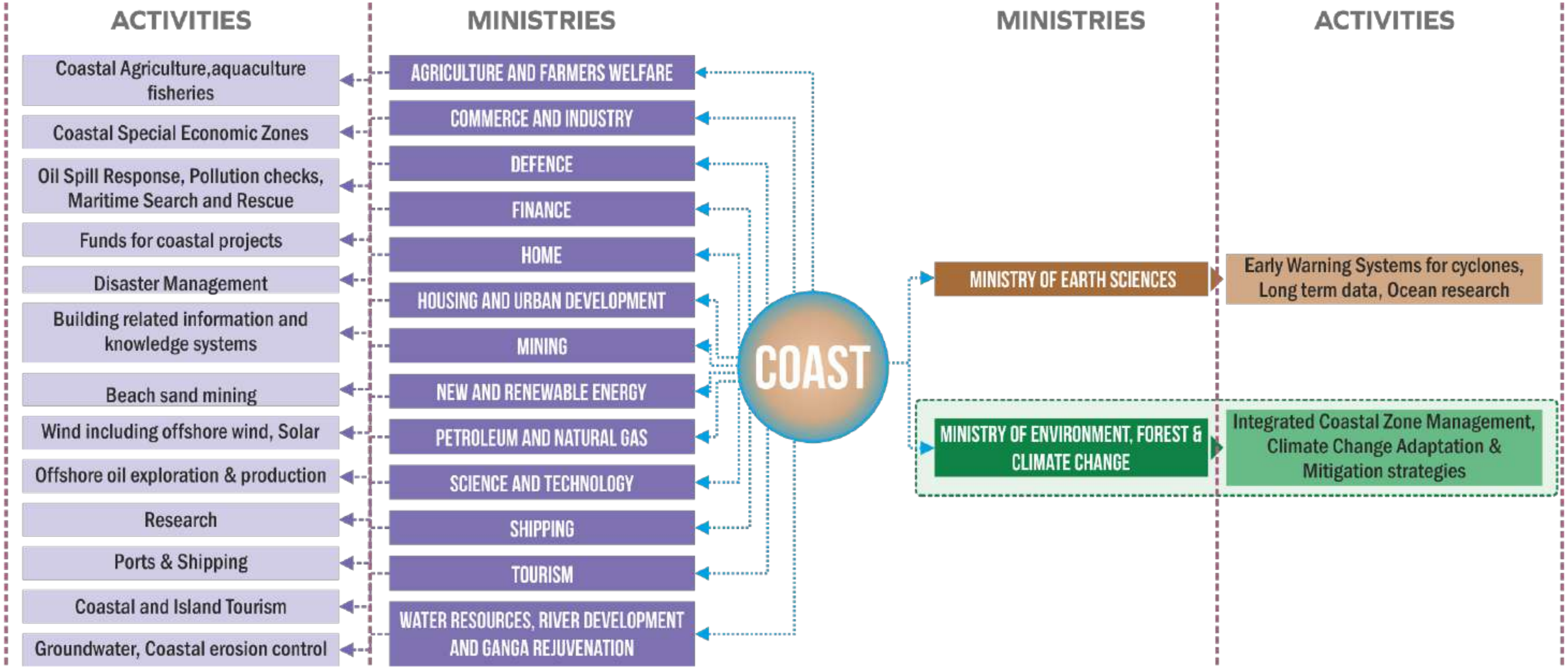

Figure 5: Overview of Ministries/ Agencies with core coastal mandates

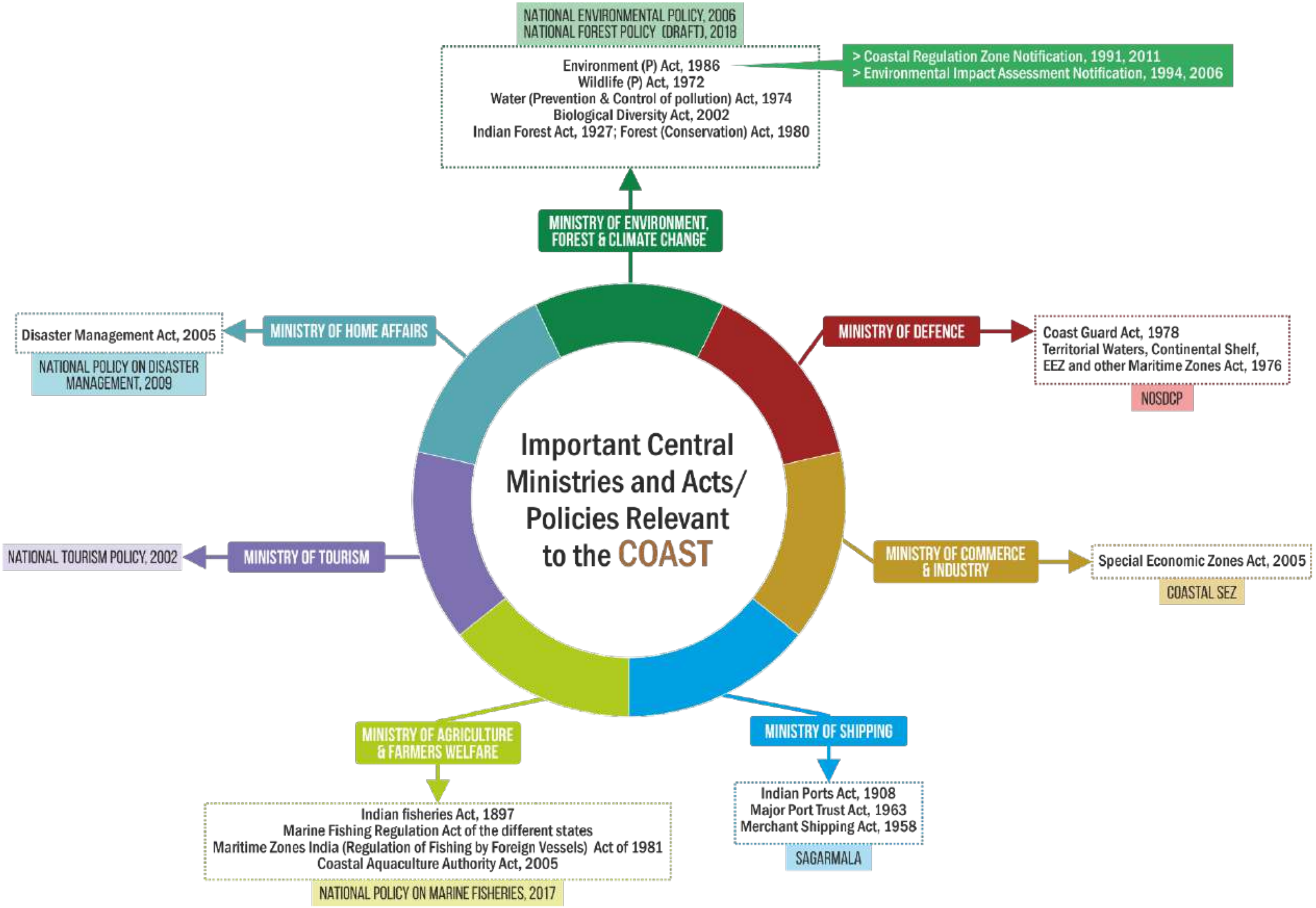

Figure 6: Important Central Ministries and Acts/ Policies Relevant to the Coast

4.1 Integrated Coastal Zone Management (ICZM)

India's coastline has so far been regulated as per the provisions under CRZ Notification, 2011. It is increasingly recognized that Indian coastal/ marine systems are highly productive with valued ecosystem goods and services and serve as lifeline for coastal livelihoods. Conventional sectoral planning has been practiced so far, however, a broader management perspective, integrating the sectors across disciplines has become necessary. Realizing this, the Government of India (GoI) initiated the Integrated Coastal Zone Management Project (ICZM) with assistance from the World Bank.

The major objectives of India's ICZM Programme is to build the national capacity towards implementation of a comprehensive ICZM approach and piloting it in the selected states of India. The project envisages achieving (i) security of lives and property/ assets in disaster-prone coastal zones; (ii) conservation, preservation, restoration and development of coastal resources and ecosystems; (iii) security of livelihood of coastal communities and overall food security; (iv) security of cultural and heritage sites; and (v) goals of national development and growth in such ways that the development is sustainable.

In the first phase of the ICZM Project, three coastal states i) Gujarat ii) Odisha and iii) West Bengal were chosen based on varying levels of development, industrialization and nature of coastal zone management challenges. The uniqueness of the ICZM Programme is in addressing common coastal issues by all sectoral line departments, agencies and coastal community. Based on the issues identified through ICZM project, appropriate interventions are integrated with the ongoing development plans of the line departments. The ICZM Plan considers a larger plan area/ boundary that extend beyond the regulatory 500 m from the HTL.

Further, a large number of pressures on the coast have origin further upstream. Thus, planning for development and conservation needs to be more integrated and coherent, cutting across various landscape activities and sectoral interests.

5. India's International Commitments

At the global level, India has been proactive in contributing to international deliberations towards conservation and management of ecosystems, biological diversity and sustainable utilisation of resources. India is a signatory to various conventions related to environment (Table 1) and in this context, India has also enacted and implemented appropriate legislations and action plans for carrying out its international commitments. As part of these commitments, a number of locations have been identified as sites for special protection; some such well- known protected sites located on the Indian coast include the Ramsar sites of Chilika lagoon and Vembanad Kol and Biosphere Reserves such as the Sunderban (also a natural World Heritage site) and Gulf of Mannar.

India's national development goals are also reflected in the Sustainable Development Goals (SDG) and in fact, India has been in the forefront of meeting up these global goals towards ending poverty, protecting the planet and ensuring peace and poverty. India has taken concrete steps and strategized on a long term basis towards protecting its biodiversity.

Specifically, Goal 14 which seeks 'preserving life below water' calls for sustainable management of coastal and marine ecosystems through reduction of pollution and impact of ocean acidification, enhancing conservation and sustainable use of ocean based resources, increasing scientific knowledge, developing research capacity, transfer of marine technology, supporting artisanal fishers with resources and markets, replace harmful subsidies that damage biodiversity with those that will recognise differential treatment for developing and least developed countries, implement science based management practices, increase economic support to small developing islands and least developed countries to develop their marine resources etc. Finally, the target is to enhance the conservation and sustainable use management by implementing the international law as in UNCLOS, pertaining to coastal ecosystems as detailed in paragraph 158 of 'The






Future We Want' the outcome document of the United Nations Conference on Sustainable Development. As per the voluntary national review to UN, India highlighted its progress the steps taken towards Blue Revolution, preservation and management (http://www.undp.org/content/undp/en/home/sustainable-development-goals.html).

India's Intended Nationally Determined Contribution (INDC) is balanced and comprehensive as, towards its plan for adaptation to climate change particularly in vulnerable ecosystems including coastal, India has been proactive by setting up missions and targets which includes strategies, initiatives and missions. India is working towards reduction in the emissions intensity of its GDP by 33 to 35 per cent by 2030 from the 2005 level and creation of an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.

In 2018, Prime Minister Narendra Modi was conferred the Champions of the Earth award, the UN's highest environmental honour for his work (along with French President Emmanuel Macron) in championing the International Solar Alliance and promoting new areas of levels of cooperation on environmental action and for taking a pledge to eliminate all single-use plastic in India by 2022. India was the global host to the World Environment Day 2018 with the theme 'Beat Plastic Pollution'.

This has high relevance to both marine biodiversity and climate change. Plastics are typically manufactured from petroleum by-products as a product of refining fossil fuels for energy. Plastics, especially those manufactured from Low Density Polyethylene (LDPE) widely used in single-use items, are exposed to sunlight and degrade; they produce methane and ethylene, the former a potent GHG. India notified the Plastic Waste Management Rules in 2016 extending the jurisdiction of applicability to rural areas and bringing in the responsibilities of producers and generators apart from phasing out the use of certain kinds of plastics. Reduction in production of single-use plastics along with move to renewable energy (and hence, reduction in fossil fuel usage) will contribute towards mitigating climate change. Moreover, plastic pollution entering the oceans harms not just the marine life forms but increasingly microplastics have far reaching repercussion entering tap water and the food chain. Thus, India has been taking initiatives to introduce new legislations to support its commitment to safeguard the environment.

Conclusions

Coastal areas are complex considering a wide variety of activities and uses they offer to the country's economy and livelihood. Through the evolution of coastal governance, several acts, laws and notifications have provided a buffering protection to the coast of India, including its island territories. The recent increase in interest on the coastline and the islands have prompted a coupled management-regulatory approach such as the CZMP and ICZM to better manage and conserve the fragile coast. This also significantly safeguards climate change induced pressures at the land-sea interface. This integrated approach would ensure three important pillars of sustainable development goals: (a) environmentally sustainable, (b) economically viable; (c) socially acceptable. This would ensure long- term sustainable development of India's coastal and islands, that balances conservation and sustainable coastal development.

Table 1: Environment related international conventions to which India is a signatory

S.No.	Name of Convention/ Treaty Expanded Title	Acronym	Date of Adoption	Entry into force	Date signed by India
1	United Nations Framework Convention on Climate Change	UNFCCC	9 May 1992	21 Mar 1994	10 Jun 1992
2	Convention on Biological Diversity	CBD	22 May 1992	29 Dec 1993	5 Jun 1992
3	Convention on Wetlands of International Importance especially as Waterfowl Habitat	Ramsar	2 Feb 1971	21 Dec 1975	1 Feb 1982 (entry into force)
4	Convention concerning the Protection of the World Cultural and Natural Heritage	WHC	16 Nov 1972	17 Dec 1975	14 Nov 1977
5	Convention on International Trade in Endangered Species of Wild Fauna and Flora	CITES	3 Mar 1973	1 Jul 1975	20 Jul 1976
6	Convention on the Conservation of Migratory Species of Wild Animals	Bonn Convention	23 Jun 1979	1 Nov 1983	1 Nov 1983
7	United Nations Convention on the Law of the Sea	UNCLOS	10 Dec 1982	16 Nov 1994	10 Dec 1982
8	United Nations Fish Stocks Agreement	UNFSA	4 Aug 1995	11 Dec 2001	19 Aug 2003 (accession)
9	Vienna Convention for the Protection of the Ozone Layer	Vienna Convention	22 Mar 1985	22 Sep 1988	18 Mar 1991
10	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal	Basel Convention	22 Mar 1989	5 May 1992	15 Mar 1990
11	Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade	PIC	10 Sep 1998	24 Feb 2004	24 May 2005 (accession)
12	Stockholm Convention on Persistent Organic Pollutants	POPS/ Stockholm Convention	22 May 2001	17 May 2004	14 May 2002
13	International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 relating thereto	MARPOL	2 Nov 1973	2 Oct 1983	Ratified Annexes I - VI

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