Auditing Perspectives on Sustainable Marine Fisheries

Image credit: Curt Storlazzi, USGS Pacific Coastal and Marine Science Centre, Public domain, via Wikimedia Commons

Dr. Gulshan Sharma

Research Associate, iCED

Occasional Research Paper Series # 15

Blue Economy Edition, 2024

International Centre for Environment Audit and Sustainable Development (iCED), Jaipur, India

About the Research Paper

Sustainable marine fisheries play a crucial role in maintaining marine biodiversity, supporting the livelihoods of coastal communities and fostering economic growth while preserving the health and resilience of marine ecosystems paving the way for a sustainable Blue Economy.

This research paper is an attempt to explore the practices in sustainable marine fisheries management and navigate through the complex areas of fisheries regulation, ensuring that economic prosperity aligns with the preservation of marine ecosystems. This paper can serve as a valuable resource for policymakers to develop and refine policies that align with global standards while maintaining a balance between economic growth and environmental preservation.

This research paper is part of the Occasional Research Paper Series, started at iCED since May 2022, with a special focus on the Blue Economy sector. This also represents iCED's new pathway of emerging as a Centre of Excellence for Audit of the Blue Economy.

Feedback

We strive for constant improvement and encourage our readers to provide their valuable feedback/suggestions. Please send us your suggestions and comments about this Research Paper to iced@cag.gov.in.

Disclaimer

The facts, opinions and interpretation of primary/secondary data in this paper are solely the personal statements of the author and they do not in any way represent the official position of the Office of the Comptroller and Auditor General of India/Indian Audit and Accounts Department. The contents of this paper are meant for information and knowledge purposes only. They should not be considered as being at par with audit reports, regulations, manuals, or other instructions for audit. iCED disclaims all liability for actions taken or failed to be taken based on any content of the paper.

Declaration by the Research Associate

I, **Dr. Gulshan Sharma** hereby declare that Research Paper titled "**Auditing Perspectives on Sustainable Marine Fisheries**" submitted to iCED is my own work and no part of it has been published anywhere else in the past. The facts and figures given in the paper are true and authentic to the best of my knowledge.

I concur with the modifications/corrections carried out during the report evaluation based on inputs provided by me.

2 July 2024 (**Dr. Gulshan Sharma**)

Jaipur **Research Associate, iCED**

Acknowledgement

I wish to express my deepest gratitude and sincere thanks to Ms. Sayantani Jafa, Additional Deputy Comptroller and Auditor General and Director General, iCED, for giving her invaluable guidance throughout the research work. I would like to express my sincere appreciation to Dr. Nanda Dulal Das, Former Director (Training and Research), iCED and Shri Mehul Grover, Director (Training and Research), iCED for their valuable supervision, guidance and constructive suggestions and in providing inputs for this research work, carried out as a Research Associate at iCED.

I also offer my sincere thanks for the help and feedback offered by Shri Kamal Kumar Sahal, Consultant, iCED and Shri Saurabh Sharma, Assistant Administrative Officer, iCED. This Research Paper would not have been possible without their generous support, constructive feedback, and constant encouragement.

2 July 2024 (**Dr. Gulshan Sharma**)

Jaipur **Research Associate, iCED**

Foreword

Fisheries and aquaculture play a significant role in providing sustenance for billions globally and hold key economic importance for coastal communities in most of the countries. Our present consumption patterns and fishing methods are becoming unsustainable due to acute demand for fish and aggressive changes in fishing patterns. The foremost challenge confronting the fisheries sector is overfishing, leading to the depletion of fish stocks to a level where their rate of recovery struggles to match the rising demand. This challenge is compounded by illegal fishing practices and harmful fishing techniques.

India's vast coastline, rich marine biodiversity and the dependence of a large population on marine fisheries for their livelihoods make sustainable fishing a key imperative for the nation. The state of Indian marine fisheries is characterised by a combination of success stories and significant challenges. On the positive side, India has made substantial progress in recent years by adopting scientific fishing practices, promoting aquaculture, and strengthening the enforcement of regulations. Initiatives such as Pradhan Mantri Matsya Sampada Yojana (PMMSY) and Blue Revolution Scheme for responsible fishing are the important steps taken in this direction. However, there remain persistent challenges such as overfishing in some regions, habitat degradation, bycatch concerns, and impacts of climate change and marine pollution on fish stocks.

The commitment to environmental sustainability places an inherent responsibility on every Supreme Audit Institution (SAI) to continually enhance their audit efforts relating to environmental and sustainable development issues. The role of audits becomes instrumental in ensuring that policies are effectively implemented to address these critical issues, leading to the sustainable management of fisheries and the preservation of marine resources for future generations.

The Hon'ble Comptroller and Auditor General of India, Shri Girish Chandra Murmu also emphasised the same as the Chair of SAI 20 in 2023 and pointed out the need for SAIs to develop comprehensive guidelines and specific toolkits to facilitate audits in this sector. Considering the various dynamics at play and in alignment with iCED's mandate as a Centre of Excellence for Audit of the Blue Economy, we have undertaken the development of this research paper. This paper offers some innovative and insightful approaches based on scientific data interpretations. Its publication is a testament to iCED's overarching commitment to evolve fresh perspectives which may assist audit planning in environmental audit endeavours. Incidentally, this Research Paper is the 15th volume in the Occasional Research Paper Series, undertaken since May-June 2022 at iCED.

I would like to extend my appreciation to the author of this paper, Dr. Gulshan Sharma for her commendable efforts. Furthermore, I wish to acknowledge and commend the dedicated contributions of the entire research team at iCED, whose collective efforts have developed this paper. Needless to say, with this publication, iCED once again reaffirms its dedication to being a specialised hub of dynamic in-house research. It also opens a new pathway into research in the multi-faceted complexity of the Blue Economy and its Audit, where iCED now acts as a Centre of Excellence. We eagerly anticipate and welcome any feedback and suggestions on this Research Paper.

2 July 2024

Jaipur

(Sayantani Jafa)

Additional Deputy C&AG & Director General, iCED

Message from the Director (Training and Research)

Sustainable marine fisheries in the coastal part of India play a vital role in the well-being of communities residing along India's extensive coastline. These regions are endowed with rich marine biodiversity and are home to fishermen whose livelihoods depend on the supplies from the sea. Achieving sustainability in marine fisheries is not just an ecological mandate but also an essential socio-economic necessity. Major efforts to achieve this in the coastal districts include inter alia, the implementation of stringent regulations to prevent overfishing, the protection of critical marine habitats and the promotion of responsible fishing practices. The collaborative efforts involving government agencies, local communities and research institutions can play a pivotal role in resource management and stock assessment. However, ensuring sustainable fisheries in the coastal districts requires continual commitment from the community and policymakers and increased investment in this area. It is crucial to maintain a delicate balance between conserving the marine environment and safeguarding the economic prosperity of the coastal inhabitants.

In light of this, by utilising Geographic Information Systems (GIS) and harnessing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and other reliable sources, this paper is positioned to function as a valuable resource for auditors. I hope that this paper will offer a fresh perspective and approach to provide insights into the potential fishing zones and sustainability in coastal districts. Furthermore, I believe that this would also serve as a compass for audits, facilitating the identification of districts, where fishing sustainability might not be maintained.

I am sincerely grateful to Ms. Sayantani Jafa, Additional Deputy Comptroller and Auditor General and Director General, iCED for leading us with her visionary insights and constant encouragement to take the efforts ahead. I would also like to acknowledge the contributions of all those who directly or indirectly contributed to making this paper a reality and appreciate their efforts. I sincerely believe that this Occasional Research Paper would serve as a good source of information for planning and execution of the audits on “Sustainable Marine Fisheries”.

2 July 2024 **(Mehul Grover)**
Jaipur **Director (Training and Research), iCED**

Abstract

Background: Sustainable management of marine fisheries is crucial for preserving marine ecosystems and the livelihoods of coastal communities. This study explores the integration of Geographic Information Systems (GIS) to analyse multidimensional data. It highlights the analysis of historical fish catch data to observe catch rate trends and overfishing signs, with a focus on Potential Fishing Zones (PFZs) to enhance sustainability. Additionally, the study employs a sustainability framework to pinpoint areas in need of intervention.

Methodology: Geographic Information System (GIS) is employed to integrate and analyse the diverse data, including environmental parameters. Historical catch data, sourced from fisheries statistics, is analysed to notice catch rate trends and potential overfishing indicators. Meanwhile, the sustainability framework provides a holistic assessment of factors, enabling informed decision-making in the pursuit of sustainable fisheries management.

Results: Historical catch data analysis reveals delicate trends in catch rates, allowing for early intervention to prevent overfishing. The identification and utilisation of PFZs enhance fishing efficiency and yield optimisation for fishermen. The sustainability framework, incorporating benchmark values, provides a baseline for assessing fishery status, and trends in fishery improvement or deterioration. This approach offers a promising pathway to sustainable marine fisheries management.

Keywords: Potential Fishing Zones (PFZs), Overfishing, Sustainability Framework, Catch rate trends, Ecological Conservation, Coastal Communities, Data integration, and Fishery audits.

Table of Contents

List of Figures

List of Tables

Abbreviations

CICEF	:	Central Institute of Coastal Engineering for Fishery
CIFNET	:	Central Institute of Fisheries Nautical and Engineering Training
EEZ	:	Exclusive Economic Zone
FIDF	:	Fisheries and Aquaculture Infrastructure Development Fund
FSI	:	Fishery Survey of India
GIS	:	Geographic Information Systems
IUU	:	Illegal, Unreported and Unregulated
MSY	:	Maximum Sustainable Yield
NFDB	:	National Fisheries Development Board
NIFPHATT	:	National Institute of Fisheries Post Harvest Technology and Training
PFZ	:	Potential Fishing Zones
PMMSY	:	Pradhan Mantri Matsya Sampada Yojana
SST	:	Sea Surface Temperature
POC	:	Particulate Organic Carbon

Auditing Perspectives on Sustainable Marine Fisheries

1. Background

The fishing sector in India is a vital component of the country's economy and a significant source of livelihood for millions of people (National Fisheries Development Board 2024), particularly in coastal and rural areas. India has a vast coastline of over 7,500 kilometres (MoES 2024), including islands with an Exclusive Economic Zone (EEZ) of 2.5 million km^2 (ICAR 2024), which is an important area, both for exploration and exploitation of natural resources (Nammalwar, S and Ramesh 2013). The fishing sector contributes to domestic food security (FAO 2019) and also provides employment opportunities as well as contributes to foreign exchange earnings through seafood exports. Fishing, if sustainably managed, plays a crucial role in providing jobs (Directorate-General for Maritime Affairs and Fisheries 2024) and a sustainable supply of food resources to the world (Younes 2023). However, the fisheries resources are under-utilised in some places, while it is overexploited in many other areas (Colloca, Scarcella and Libralato 2017). It is imperative to improve the management of the fishing industry to increase fish production, promote exports and strengthen the national economy (Antonova 2016). The use of technology for identifying Potential Fishing Zones (PFZs) would be of great value to the fishing community, as it would improve overall fishing effectiveness and sustainability (INCOIS 2023).

1.1 Understanding the Significance of Potential Fishing Zone

The PFZs are specific areas in any sea for a particular time span where there is forecast of various fish accumulation (ICAR 2014). They are intricately linked to fishing sustainability as they guide fishing activities to areas of natural abundance (INCOIS 2023). By concentrating efforts in these zones, overexploitation is minimised (Thakare 2021), bycatch is reduced, and ecosystems remain balanced, contributing to the long-term health of fisheries and marine environments (Negi and Mamgain 2013). However, the spatial distribution and fish community structure are continuously changing and vulnerable (Frelat, et al. 2018) to various dynamic factors, such as the environment, Climate Change (Nye, link and Hare 2009) and other human-induced alterations to the coastal landscapes, pollution, habitat destruction, and overfishing (Perry, Low and Allis 2005). In a recent research of World Resources Institute (WRI), Food and Agriculture Organisation (FAO) stated that 33 per cent of marine fish stocks (FAO 2019) were overfished in 2015, and another 60 per cent were overfished at maximum benchmark levels. One World Bank study found that global fishing effort needs to decline by 5 per cent every year for a 10-year period for allowing fish stocks to rebuild (WRI 2024).

These complexities make it difficult for fishermen to determine the optimal fishing zones using traditional experimental techniques (Younes 2023). Thus, it is necessary to find better solutions that fully exploit the richness of the oceans by identifying the best PFZs (Ghorai, Patra and Bhattacharya 2015).

1.2 Mapping Potential Fishing Zones using Remote Sensing data and Geographic Information System

Geographic Information System (GIS) is a valuable application of modern technology that aids in optimising fishing efforts (ICAR 2009) and promoting sustainable fisheries management (Nammalwar, S and Ramesh 2013). GIS combines the power of satellite imagery and spatial analysis to identify and locate areas with favourable conditions for fishing activities (Paolo, et al. 2024). Traditional potential fishing ground identification often relies on historical knowledge, local experience and trial-and-error methods (Negi and Mamgain 2013). This has proven to be effective only in some areas, with the risk of over or under-exploitation in many fishing areas (Bose, Bose and Das 2019). At present, fishing activities are concentrated on a narrow belt of inshore waters up to a depth of about 50 metres (Namallwar, Satheesh and Ramesh 2013). Identifying and knowing details of PFZs can enhance fishing safety by helping fishermen avoid hazardous areas such as regions with adverse weather conditions or dangerous sea currents (Bundy 2016). While short-term zones optimise immediate catch efficiency based on transient conditions, by considering factors such as environmental variability, a year-long assessment underscores the commitment to sustainable fishing (Negi and Mamgain 2013). By identifying and focusing on areas with higher fish abundance and suitable environmental conditions, fishermen can optimise their efforts, reduce fuel consumption, and minimise the by-catch (Frank Asche 2024) of non-target species. This approach helps in maintaining fish stocks, preventing overfishing, and preserving the marine ecosystem (Bundy 2016).

In the recent past, mapping of Sea Surface Temperature (SST), Chlorophyll concentration (Chl-a) and Particulate Organic Carbon (POC) using satellite remote sensing as a tool to study the distribution of fish resources is gaining momentum (INCOIS 2023). Fishes are known to respond well to changes in temperature i.e., they are known to gather within certain temperature ranges. The SST is the most easily observed environmental parameter (Huang, et al. 2021) and it has been frequently used in correlation with fish availability.

1.3 Potential Fishing Zone Forecasting System - Marine Fishery Advisories

The Indian National Centre for Ocean Information Services (INCOIS) has taken up this activity and brought many improvements in the generation as well as the dissemination of these activities (INCOIS 2023). PFZ-along the Indian coastline are identified using data on SST and Chlorophyll that are regularly retrieved from NOAA-AVHRR (USA) thermal-infrared channels and Eumetsat satellites along with optical bands of Oceansat-II (India) and MODIS Aqua (USA) satellites (Moderate Resolution Imaging Spectroradiometer 2023). The marine region of India's coastline, consisting of all coastal states and island territories, has been divided into about 12 sectors viz., Gujarat, Goa, Maharashtra, Karnataka, Tamil Nadu, Kerala, Andhra Pradesh, Odisha, West Bengal, Andaman and Nicobar Islands, and Lakshadweep. PFZ advisories are brought separately for each of these 12 sectors (Chakraborty, et al. 2019). However, fishing vessels owned by government organisations such as the Central Marine Fisheries Research Institute (CMFRI), Fishery Survey of India (FSI), National Institute of Ocean Technology (NIOT) and National Institute of Oceanography (NIO) etc., are equipped with fishing aids for identifying PFZs (INCOIS 2023). PFZ advisories are communicated by INCOIS on Mondays, Wednesdays and Fridays covering the entire coastline of India. Using remotely sensed data from numerous satellites, the ESSO-Indian National Centre for Ocean Information Services (INCOIS) allocates these advisories to fishermen on a daily basis, with particular references to 586 landing regions throughout the Indian coast (ICAR 2014). ESSO-INCOIS provides this service throughout the year, with the exception of periods when the Government of India issued a fishing ban and during periods of adverse situations such as cyclones, high waves, tsunamis, etc. (Ministry of Ocean Development 2006).

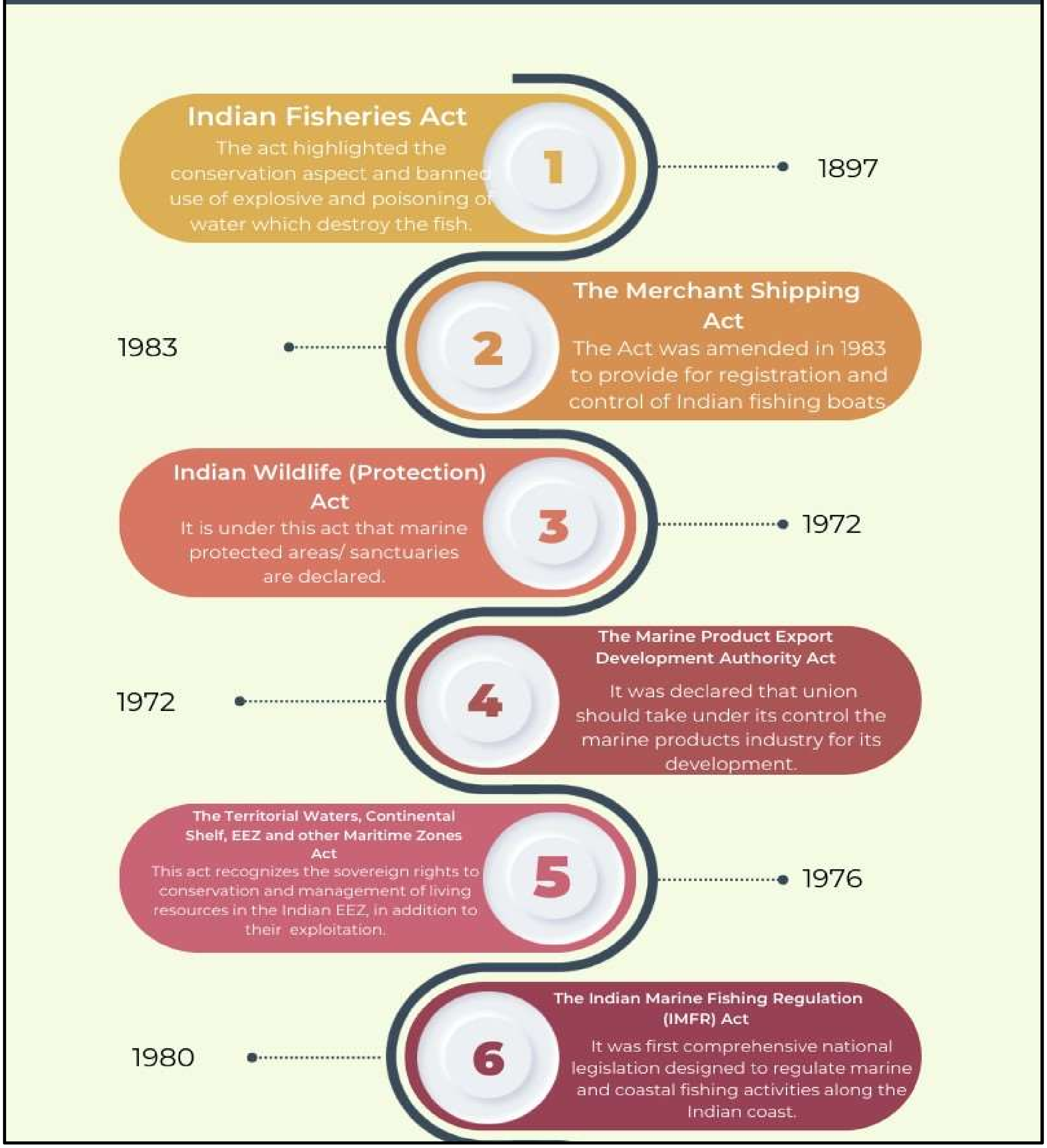
2. India: A Global Player in the Fisheries Sector

According to the Indian Constitution, fisheries in the territorial seas, which reach a distance of twelve nautical miles from the coast, is a State subject, and the state governments are primarily responsible for its development. All fishing operations beyond this limit, known as the deep sea or EEZ (ICAR 2024), which extends up to a distance of 200 nautical miles, are under the control of the Central Government (Stavridis 2023). The State Government is in charge of the fisheries, which are in the 12-nautical mile territorial seas, as well as the local communities that depend on the local fisheries and marine resources (Edwin 2022).

2.1 Casting the Net of Sustainability: Mapping India's Fisheries Landscape with Acts and Schemes

The need of fisheries legislation was emphasised long back as in 1873 when the government's attention was brought to the depletion of fishery resources in the dams and reservoirs (Datta 2024). The Ministry of Fisheries, Animal Husbandry and Dairying has undertaken extensive efforts to promote sustainable practices and boost the fisheries sector, including implementing conservation measures and supporting aquaculture development (Ministry of Fisheries, Animal Husbandry & Dairying 2023). Figure 1 provides a comprehensive overview of Fisheries Management in India, highlighting key Acts and Schemes. It showcases the intricate web of regulations and initiatives undertaken for sustainable fisheries development.

FISHING REGULATIONS IN INDIA



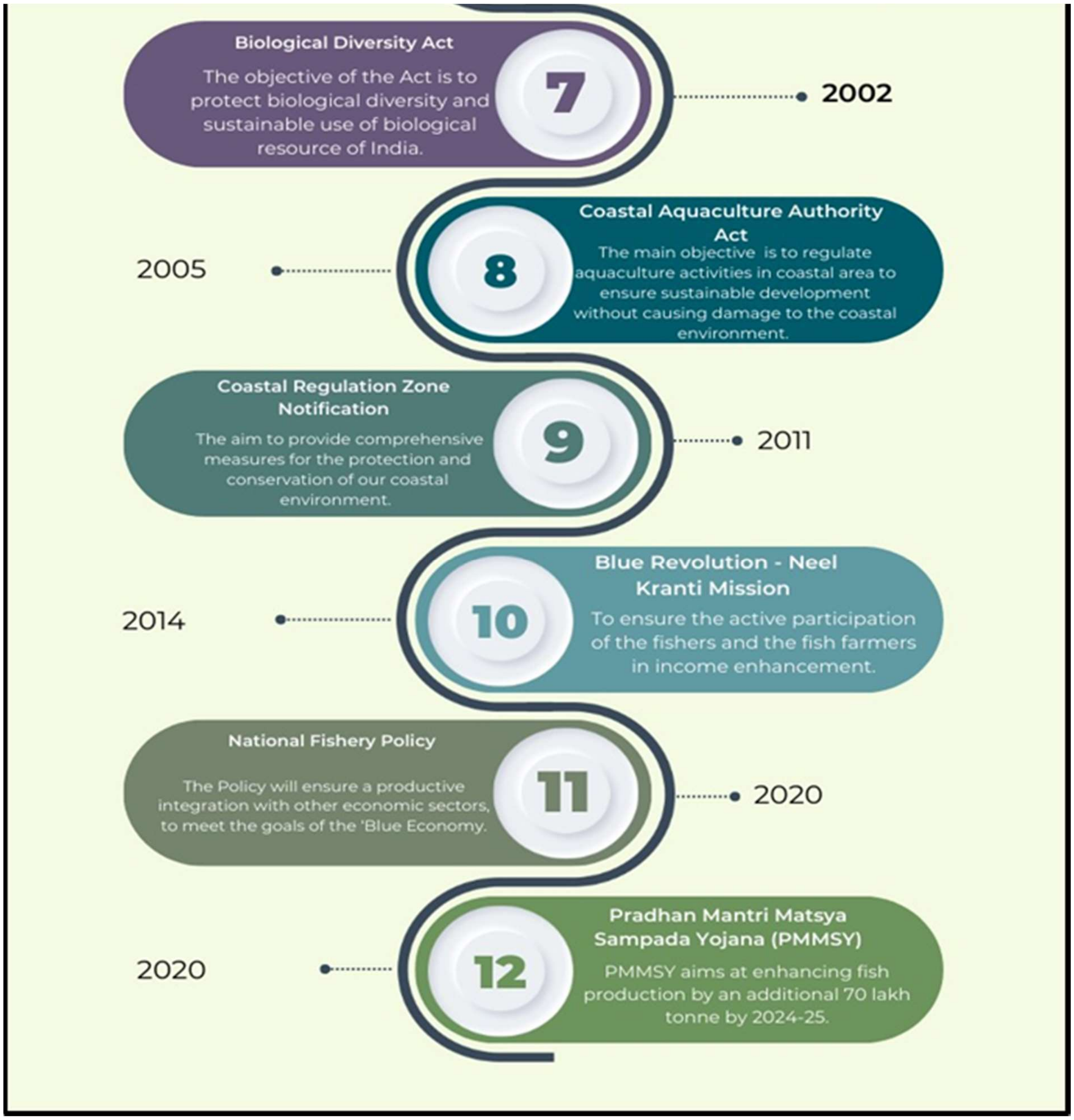


Figure 1: A Timeline of Fisheries Management Acts and Schemes in India *(Ministry of Fisheries, Animal Husbandry and Dairying 2024)*

The timeline of legislative acts and policies in India reflects India's evolving commitment to comprehensive fisheries and maritime management. These milestones underscore India's dedication to sustainable practices, responsible resource management, and the conservation of marine ecosystems (Edwin 2022). These legislative acts and policies represent India's continuous efforts to balance economic growth, environmental conservation, and sustainable resource management within the fisheries and maritime sectors.

2.2 Year-wise expenditure for development of fisheries sector under Blue Revolution Scheme 2015-16 to 2019-20

In India, the Blue Revolution is also referred to as Neel Kranti. It was first implemented between 1985 and 1990, under the seventh five-year plan (Ministry of Fisheries, Animal Husbandry and Dairying 2024). The "Blue Revolution" and the "Pradhan Mantri Matsya Sampada Yojana (PMMSY)" are two distinct (Ministry of Fisheries, Animal Husbandry and Dairying 2024) but closely related initiatives in India, both focusing on the development and growth of the fisheries sector. The Blue Revolution serves as the overarching strategy, while PMMSY is one of the prominent schemes operating under this strategy. They both share the common objective of fostering sustainable growth in the fisheries sector, but PMMSY provides more specific and detailed guidelines and funding for achieving this goal (NFDB 2021).

Figure 2 provides a yearly breakdown of expenditures allocated to the development of the fisheries sector under the Blue Revolution Scheme from 2015-16 to 2019-20 (Ministry of Fisheries, Animal Husbandry and Dairying 2020). The main aim of the Blue Revolution was to enhance aquaculture in India through the adoption of new techniques of fish breeding, marketing, and exporting (Hi Pro Feeds 2024). The Neel Kranti Mission Blue Revolution has the vision to attain economic success for the country and the fishers as well as contribute towards nutritional security by using the full potential of water resources towards fisheries development in a sustainable way (Department of Animal Husbandry, Dairying & Fisheries 2018).

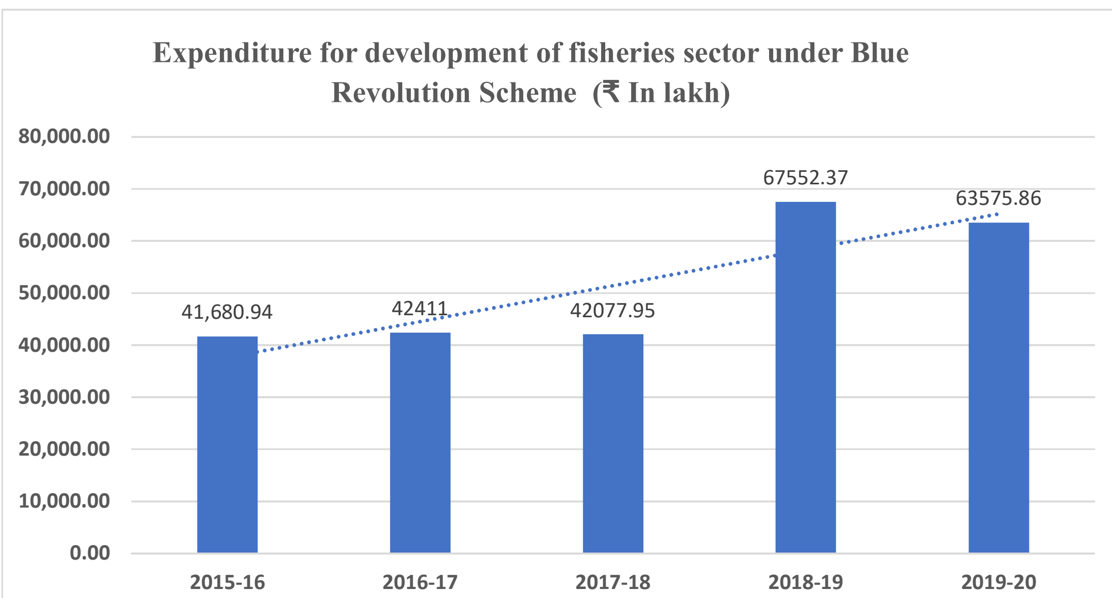


Figure 2: Diving into Progress: Charting the Financial Tide of the Blue Revolution Scheme *(Ministry of Fisheries, Animal Husbandry and Dairying 2020)*

The data shows a consistent financial commitment to the growth of the fisheries sector, with fluctuations in expenditure. In 2018-19, there was a significant increase in expenditure, reaching ₹ 67,552.37 lakh, showcasing a substantial allocation in the sector. A steadily higher level of financial allocations signify the government's dedication to promoting sustainable fisheries development in India (Ministry of Fisheries, Animal Husbandry and Dairying 2020).

"PMMSY - A scheme to bring about Blue Revolution by sustainable development of fisheries sector in India", was launched in 2020 as part of the 'Atma Nirbhar Bharat' (Kalita 2020) implemented as umbrella scheme to strengthen the value chain which include quality improvement and post-harvest management to double the income of fish farmers and to generate meaningful employment (Department of Fisheries 2020). Figure 3 presents a year-wise breakdown of expenditures dedicated to the development of the fisheries sector under the PMMSY for the years 2020-21 and 2023-24.

The data reflects a substantial increase in the expenditure of ₹ 699.72 crore in 2020-21, which saw further growth to ₹ 1,169.19 crore in 2021-22 followed by ₹ 1,500 crore in 2024. This noteworthy surge in expenditure illustrates the government's commitment to fostering the sustainable development and growth of the fisheries industry in India (Ministry of Fisheries, Animal Husbandry and Dairying 2023).

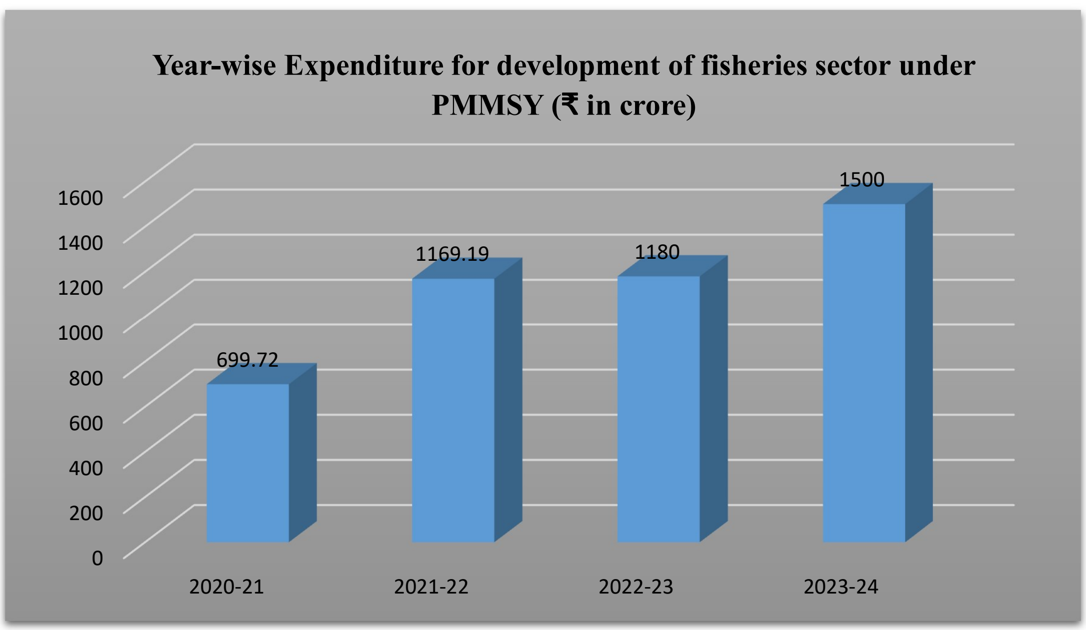


Figure 3: Navigating Growth: Annual Expenditure for Fisheries Development under PMMSY *(Ministry of Fisheries, Animal Husbandry and Dairying 2023)*

Furthermore, the annual expenditure for FIDF[1] showed a noteworthy rise, escalating from ₹ 1.00 crore in 2018 to ₹ 9.50 crore in the year 2020 (Ministry of Fisheries, Animal Husbandry and Dairying 2020). These expenditures play a crucial role in enhancing the livelihoods of fisherfolk and the overall prosperity of the fisheries sector.

3. Objective

The objective of this paper is to use GIS and Remote Sensing data and advanced satellite image processing techniques to review the fish catch practices in the coastal regions in India, and their correlation with sustainability trends over time.

4. Methodology

Firstly, the data of core indicators like SST, Chl-a, and POC was collected using the GIS imagery and QGIS software. The study uses data spanning five years for coastal districts in India, to calculate the values of SST, Chl-a and POC and the range for the components based on Indian scenario to delineate suitable ranges for PFZs. Secondly, the raw data for fish catch was gathered from a wide range of sources. The benchmark range was used to analyse the fishing sustainability in various coastal areas of the state of Maharashtra.

4.1 Study Area and Temporal Coverage

This study covered five consecutive years i.e. 1st April 2017 to 31st March 2022, for analysing data on SST, Chl-a and POC in coastal districts of Maharashtra.

The satellite data used in this study has a spatial resolution of 4 km. Satellite imageries have been obtained from the website of NASA MODIS web (www.oceancolor.gsfc.nasa.gov). In this study, District-wise (Ratnagiri, Mumbai City, Sindhudurg, Thane, Raigad, Mumbai Suburban) fish catch was derived from fisheries statistics of respective States (Statistics Department of Fisheries 2023). Quantum Geographic Information System (QGIS) Software was used for analysing the data along the Maharashtra coastal districts and displaying the results.

Broadly, the methodology is divided into two steps: (1) Data Collection; and (2) Data Range Identification.

[1] Fisheries and Aquaculture Infrastructure Development Fund

4.2 Data Collection

The data of core indicators like SST, Chl-a, and POC was collected for the coastal regions spanning over five years- from 2017-18 to 2021-2022- using the GIS imagery and QGIS software**.**

1. Chl-a (µg/L): Phytoplankton is the base of the food chain due to which Chl-a is produced to show the ocean and water colour, allowing life in the ocean to flourish (Antonova 2016). Numerous studies (Younes 2023) have underscored that the Zooplankton eats phytoplankton and small fishes eat zooplankton and phytoplankton (Ali, Zanaty and Magd 2022). Hence, the greater the concentration of Chl-a, the greater will be the number of fishes in the ocean (Behrenfeld, and Falkowski 2003). Extensive literature highlights the pivotal role of Chl-a as a vital indicator of fish potential and species diversity in the marine ecosystem (Platt and Sathyendranath 2008).

2. SST (°C): The appropriate habitat for fishes is determined by the temperature of the sea (Chakraborty, et al. 2019). It is a major geophysical parameter. In the past, SST was only measured by traditional methods, which had restricted coverage. While Remote sensing technology allows us to measure SST with global coverage (Daqamseh, et al. 2019).

3. POC (mg/m3): POC is the major pathway by which organic carbon generated by phytoplankton is exported from the surface to sediments and acts as a major component of the biological production of fish (Steinberg and Landry 2017). Studies have highlighted the significance of POC in influencing fish foraging behaviour and ecosystem structure (Perry, Low and Allis 2005) and highlighted its link as an indicator of organic matter availability that affects prey abundance and distribution, thereby influencing the distribution and behaviour of fish species (Solanki, et al. 2008).

The concentration of SST, Chl-a, and POC in the waters is gathered from 1st April 2017 to 31st March 2022 based on MODIS satellite image. With the help of QGIS, the mean value of the selected polygon (112 km buffer area and district coastline) was extracted by the zonal statistical analysis for SST, Chl-a, and POC for the six districts (Ratnagiri, Mumbai City, Sindhudurg, Thane, Raigad, and Mumbai Suburban) shown in Tables 3 to 8.

Finally, these indicators were combined to create a fishing sustainability framework as shown in Figure 4 below:

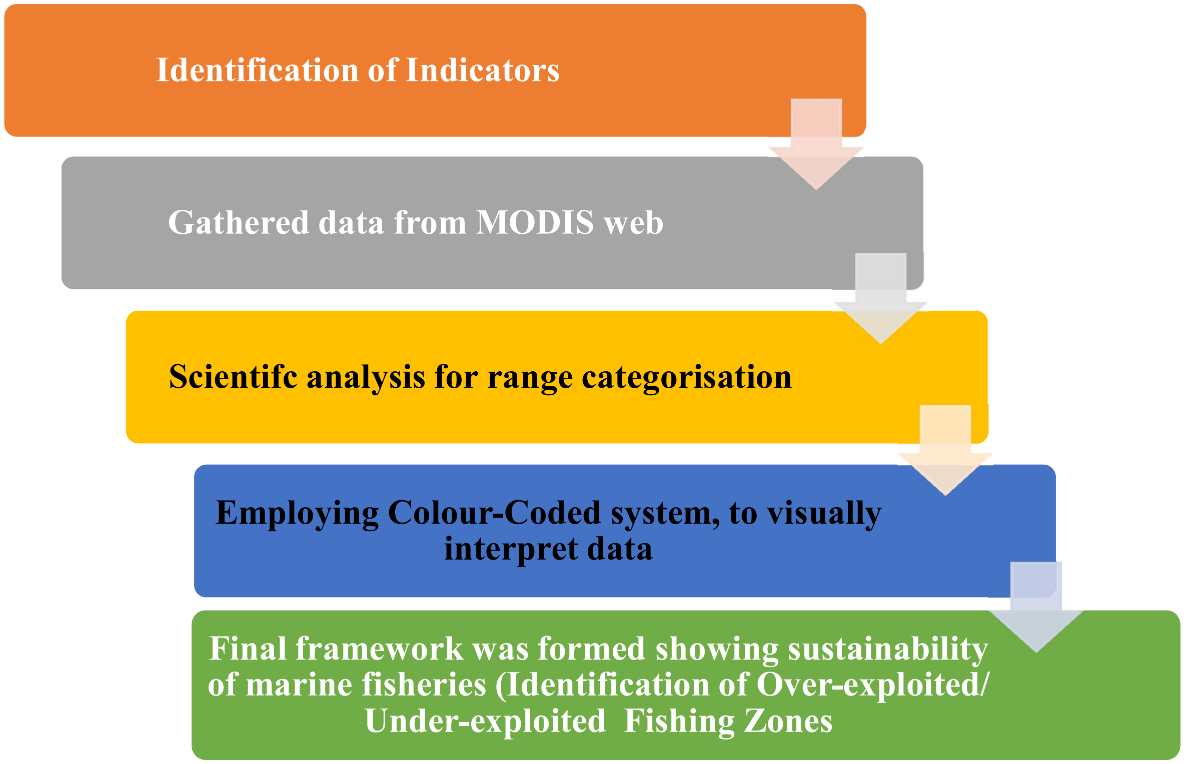


Figure 4*: *Methodology for construction of the framework

4.3 Data Range Identification

Each parameter has been segmented into four ranges, while **SST** has been segmented into three ranges due to its parabolic nature. The range for the SST framework is formulated based on a literature review (Younes 2023). The classification of **Chl-a, and POC** has been determined using their values for the years 2020 and 2021 (Table A2 and Table A3), by the author by utilising the mu-sigma analysis for each framework score, as depicted in Table 1.

A mu-sigma analysis based on the deviations from the average performance of the indicators has been performed to classify their range, identify any trend towards clusterisation, and the potential gaps in performance across these classes. Table 1 shows the final range obtained for the Index. It also classifies the indicators range into five distinct categories. This enables us to identify any trend towards clusterisation or performance. Insights for the analysis are drawn from the (Sarkar 2023).

The classification is based on the following criteria, based on a mu-sigma analysis (assuming that the scores are normally distributed):

Premium: Index scores > μ + σ
Good: μ + 0.5*σ < Index scores < μ + σ
Medium: μ – 0.5*σ < Index scores < μ + 0.5*σ
Low: μ - σ < Index scores < μ – 0.5*σ
Bad: Index scores < μ - σ

Where:

μ is the mean of the indicators across the districts;

σ is the standard deviation of the indicators across the district.

4.3.1 Potential Fishing Zone Classification

Table 1: Framework for Potential Fishing Zones

Indicator	Category	Framework range
SST (Younes 2023)	Risk zone	28.9 ≥
	Best suitable	26.1 - 28.9
	Risk zone	26.1 <
POC	Premium	≥343.5
(Range criteria decided by the author using mu-sigma analysis)	Good	283.6 - 343.5
	Moderate	163.7 - 283.6
	Low	103.7 - 163.7
	Bad	<103.7
Chl-a	Premium	≥ 3.30
(Range criteria decided by the author using mu-sigma analysis)	Good	1.92 - 3.30
	Moderate	1.78 - 1.92
	Low	0.40 - 1.78
	Bad	<0.4

Water with an SST range between 28.9 ≥ is considered a Risk zone, 26.1-28.9 is considered as Best suitable, and 26.1 < is considered a Risk zone. In instances where SST demonstrates parabolic behaviour, both high and low temperatures are identified as Risk zones specifically concerning fish populations. While SST can have both positive and negative impacts on fish behaviour and distribution, there's a critical threshold beyond which rising SST can indeed start to have detrimental effects on fish sustainability. As SST rises, fish may need to migrate to cooler waters or deeper depths to find suitable temperature ranges, while low temperatures within the parabolic pattern may indicate suboptimal conditions affecting fish physiology and behaviour. Fish tend to be more active and feed more actively in temperatures that fall within their preferred range. Muhammad et al. also analysed the parabolic behaviour of the SST range (<24 - >30) and validated it with data from the fishing operation in Aceh Besar (Muhammad, et al. 2022) On the other hand, Sayad in 2021 examined the PFZ in Moroccan waters and recorded that the Premium SST for fishes was 24-30 and less than 22 was considered bad for fish abundance (Younes 2023).

In the case of the parameter Chl-a, if its value is greater than ≥ 3.30 mg/m3, it has been categorised as premium zone. Range between 1.92 mg/m3 - 3.30 mg/m3 as a good potential zone, and the content 1.78mg/m3 - 1.92 mg/m3 categorised as moderate. If the Chl-a content is less than 0.40-1.78 mg/m3 it has been categorised as less potential zone. Higher chlorophyll levels are associated with increased fish abundance. Muhammad, 2021 also noted that Chl-a levels >0.2 mg/m^3 concentration (Muhammad, et al. 2022) 2-95 mg/m^3 are considered as a (Younes 2023) potential zone for fisheries (Ali, Zanaty and Magd 2022).

For the POC, if the range is greater than ≥ 343.5 mg/m3, it has been categorised as premium potential. The POC range 283.6 mg/m3 - 343.5 mg/m3 is categorised as good potential and the POC range 163.7 mg/m3 - 283.6 mg/m3 is categorised as moderate and the POC content is less than 103.7 mg/m3 is categorised as less potential as shown in Table 1. Higher POC levels are associated with increased fish populations. Higher POC levels are associated with increased fish abundance. Sayad 2023 also recorded that POC levels (400-1000 mg/m^3) concentration considered as a (Yones 2023) potential zone for fisheries (Bose, Bose and Das 2019).

The High, Moderate and Low Potential Fishig Zones may be identified on the basis of the following combinations of the parameters (as formulated by the author):

High Potential Fishing Zones: Warm waters (SST), High productivity (Chl-a), and High POC

Moderate Potential Fishing Zones: Moderate waters (SST), Moderate productivity (Chl-a), and Moderate POC

Low Potential Fishing Zones: Cold waters (SST), Low productivity (Chl-a), and Low POC (Younes 2023).

4.4 Fish Catch Data Collection

The raw data for fish catch was gathered from a wide range of sources. The benchmark range was used to analyse the fishing sustainability in Maharashtra.

5. Results and Analysis

The present study conducts a five-year analysis of fish catch data, using key indicators of fish abundance. The five-year analysis focused on districts like Thane, Mumbai Suburban, Ratnagiri, Mumbai City, Sindhudurg and Raigad in Maharashtra. In the context of the table where different colours represent varying conditions, the colour red typically signifies a risk zone, indicating high-risk conditions. Green is used to denote premium conditions, signifying highly favourable circumstances. Orange is associated with good conditions, showing positive or satisfactory zones. Yellow is used for moderate conditions, indicating average or intermediate levels. Blue is utilised to represent low conditions, showing below-average situations. By employing this colour-coded system, it becomes easier to visually interpret and categorise the different levels of conditions or risks presented in the data. Given below is a legends table for the colour-coded zones:

Table 2: Legends table for the colour-coded zones

Colour	Risk Zone
Red	High Risk
Orange	Best Suitable Zone
Green	Premium Zone
Blue	Low Risk
Yellow	Moderate

The analysis reveals that Ratnagiri District maintains favourable conditions for fishing activities based on the SST, POC, and Chl-a indices. The SST data indicates that the district falls within the "Best Suitable" category for fishing activities. The POC levels in Ratnagiri District vary across the years, with values placing it in the "Good" to "Premium" categories as shown in Table 3. Elevated Chl-a values in 2021-22 suggest ample food sources for fish, contributing to increased fish catch potential indicates a healthy environment for fishing activities in the region. After conducting a five-year analysis of Mumbai City, it was found that there were challenges related to the suitability of fishing activities. In 2018-19 and 2020-21, the SST was not suitable for fishing, falling outside the "Best Suitable" range as per the provided framework. Additionally, the POC levels during 2017-19 were below the suitable threshold for fishing. Despite these unfavourable conditions, the fish catch reported in these years exceeded 104105, indicating potential issues with sustainable fishing management practices.

Table 3 illustrates the fishing performance in Ratnagiri City, as determined by the PFZ framework

District - Ratnagiri				
Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	172.19 Moderate	1.548 Low	28.84 Good	80340
2018-19	227.39 Moderate	4.32 Premium	28.45 Good	73738
2019-20	215.87 Moderate	1.619 Low	28.51 Good	66173
2020-21	341.32 Good	5.39 Premium	27.32 Good	65374
2021-22	301.11 Good	4.208 Premium	28.89 Good	101228

Table 4 illustrates the fishing performance in Mumbai City, as determined by the PFZ framework

District- Mumbai City

Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	157.99 Low	2.49 Good	27.92 Good	104105
2018-19	86.876 Low	4.05 Premium	29.05 Bad	152557
2019-20	484.68 Premium	3.169 Good	28.64 Good	153353
2020-21	397.33 Premium	4.22 Premium	29.39 Bad	133212
2021-22	219.78 Moderate	3.79 Premium	28.9 Good	160708

According to a report by the CMFRI in 2019 revealed an alarming rise in overfishing and the killing of juvenile fish along the Maharashtra coast, leading to an estimated economic loss of over ₹ 686 crore in 2018 (Hindustan Times 2023). However, the CMFRI study also found that over 8.2 per cent of the stocks were overfished, including varieties of catfish, sharks, and lobsters. The CMFRI report recommends measures such as imposing a minimum legal size and changing the mesh size of nets to reduce catch of juveniles and bycatch (The Times of India 2023).

Table 5 illustrates the fishing performance in Sindhudurg, as determined by the PFZ framework

District - Sindhudurg				
Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	245.91 Moderate	5.92 Premium	28.96 Good	20582
2018-19	217.84 Moderate	3.99 Premium	28.99 Good	19054
2019-20	196.84 Moderate	0.357 Bad	29.045 Bad	18713
2020-21	399.67 Premium	2.782 Good	29.91 Bad	17311
2021-22	305.99 Good	2.529 Good	29.31 Bad	10046

During a five-year analysis in Sindhudurg District, Maharashtra, it was revealed that there were challenges related to the sustainability in fishing activities. In 2019 and 2022, the SST were not suitable for fishing, falling outside the optimal range as per the provided framework. Additionally, the Chl-a levels in 2019 were below the suitable threshold (Table 5) for supporting marine life. Despite these unfavorable environmental conditions, the fish catch reported in these years exceeded 10046, indicating issues with sustainable fishing management practices in Sindhudurg District.

Table 6 illustrates the fishing performance in Thane, as determined by the PFZ framework

District - Thane				
Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	238.66 Moderate	4.74 Premium	28.93 Good	114399
2018-19	103.98 Low	0.3244	29.23 Bad	99461
2019-20	180.48 Moderate	0.477 Low	29.19 Bad	86225
2020-21	427.84	1.29 Low	26.98 Good	67547
2021-22	198.76 Moderate	3.9233 Premium	29.9 Bad	58392

The analysis of Thane District in Maharashtra also reveals some concerning trends. In 2018-2020, the SST was not suitable for fishing. Additionally, the levels of Chl-a, and POC were low, especially in 2018-2020 as shown in Table 6. Despite these unfavourable environmental conditions, the reported fish catch was very high in 2018-19, reaching over 99461. However, in the following years, the catch decreased to over 58392 as shown in Table 6. This suggests that the high fishing during the unsuitable environmental conditions was likely unsustainable and could have harmed the marine ecosystem.

In contrast, during 2017-18, when the environmental conditions were moderate, the fish catch rose significantly to 114,399, highlighting the importance of aligning fishing activities with favourable environmental factors to ensure the long-term sustainability of the marine resources in Thane District.

Table 7 illustrates the fishing performance in Raigad, as determined by the PFZ framework

District – Raigad				
Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	245.98 Moderate	2.57 Good	28.41 Good	53338
2018-19	227.56 Moderate	4.36 Premium	28.34 Good	58847
2019-20	398.83 Premium	2.788 Good	28.65 Good	41797
2020-21	185.67 Moderate	2.43 Good	28.32 Good	38019
2021-22	287.99 Good	4.885 Premium	28.31 Good	40601

In Raigad District, during 2017-18 there was a moderate level of POC and Chl-a, with a suitable range of SST, correlating with a fish catch of 53338. The following year, 2018-19, saw a decrease in POC but an increase in Chl-a, and SST, leading to a higher fish catch of 58847. In 2019-20, there was a significant rise in POC, a decline in Chl-a, and a suitable range of SST, reducing the fish catch to 41797 as shown in Table 7. However, in 2020-21, there was a drop in POC and Chl-a, along with a suitable range of SST, resulting in a reduced fish catch of 38019. While, during 2021-22, we witnessed an increase in POC, Chl-a, and SST, leading to a rise in fish catch to 40601. These fluctuations highlight the role of these environmental factors and fish catch in Raigad District, showing the importance of monitoring and managing these parameters for marine ecosystem health.

Table 8 illustrates the fishing performance in Mumbai Suburban, as determined by the PFZ framework

District - Mumbai Suburban				
Year	**POC**	**Chl-a**	**SST**	**Fish Catch**
2017-18	321.98 Good	0.649 Low	26.05 Bad	66228
2018-19	221.9 Moderate	3.82 Premium	27.22 Good	63575
2019-20	267.78 Moderate	1.729 Low	29.38 Bad	76332
2020-21	337.3 Good	3.55 Premium	27.94 Good	77048
2021-22	185.07 Moderate	3.64 Premium	28.47 Good	61773

After a five-year analysis in Mumbai Suburban District, it was found that there were challenges regarding the sustainability of fishing activities. In the years 2017-18 and 2019-20, the SST was outside the optimal range for fishing, indicating unfavourable conditions. Additionally, Chl-a levels were consistently below the necessary threshold from 2017-18 and 2019-20, and POC levels were found to decline in 2018-20 and 2021-22. Despite these unfavourable conditions, the reported fish catch exceeded in 2019-20 and remained above 66228 in subsequent years as shown in Table 8. This discrepancy shows that fishing activities during these periods may have been unsustainable, leading to the depletion of marine resources. It is crucial for fishermen in Mumbai Suburban District to consider halting fishing during times when environmental conditions are not favourable to ensure the sustainability of the marine ecosystem in the region.

The data revealed that during certain years, the SST, Chl-a levels, and POC content were not optimal for healthy fishing activities. However, despite these unfavourable environmental conditions, the reported fish catch remained high in some of these districts. This discrepancy revealed that the fishing practices during those periods were unsustainable and could have led to the depletion of marine resources. Conversely, when the environmental conditions were more favorable, the fish catch also increased, highlighting the importance of aligning fishing activities with the ecological needs of the marine ecosystem.

Maximum Sustainable Yield and Sustainable Fishing

Implementing sustainable fishing criteria is essential to ensure that we harvest fish at a rate that allows populations to replenish, safeguarding long-term resource availability (National Geographic 2024). By adhering to Maximum Sustainable Yield (MSY), we strike a balance between meeting current fishing needs and preserving the health and productivity of marine ecosystems for future generations (Our world in data 2024). The concept of MSY is that it is the largest yield (or catch) of a species that can be taken on a sustainable basis, for an indefinite period. In India, there are various criteria and guidelines for sustainable fishing practices (Encyclopedia of Ecology, 2008 2008). The FSI, an agency of the Government of India, plays a key role in assessing and regulating the marine fishery potential of the Indian EEZ (Fishery Survey of India 2023). The MSY of fish stocks from the Indian EEZ has been assessed at 3.9 million tonnes, providing a crucial benchmark for sustainable harvest levels (Sathiadhas, Ramachandran and Aswathy 2010). The Government of India have imposed a uniform ban on marine fishing along the east coast from April 15 to May 31 and along the west coast from June 10 to August 15 every year in order to maintain fish stocks (INCOIS 2023) at a sustainable level and conserve fishery wealth. The Government of India has enacted fishing regulations outlined in The National Fisheries Policy 2020 and The Marine Fisheries Regulation Act, 1983, with subsequent amendments reinforcing this regulatory framework (Datta 2024). These regulations aim to prevent overfishing by establishing specific quotas for various fish species, implementing seasonal restrictions, and setting minimum legal size limits to protect juvenile fish and ensure their successful reproduction (Edwin 2022). Additionally, the Act outlines enforcement mechanisms and penalties for violations, underscoring the government's commitment to responsible fishing practices (FAO 2019). By adhering to these quotas and regulations, India strives to strike a balance between the economic needs of its fishing communities and the long-term sustainability of its marine ecosystems (Fishery Survey of India 2023).

6. Way forward in sustainable fisheries management

The way forward in sustainable fisheries management involves a multifaceted approach addressing ecological, economic, and social dimensions. Key strategies may include:

- Implementing fisheries management policies grounded in scientific research and data to ensure accurate assessments of fish stocks, ecosystem health, and sustainable catch levels. Enhance transparency in reporting data and management actions to build trust.
- Emphasising the impacts of Climate Change by integrating climate resilience strategies into fisheries management plans.
- Strengthening specialised training for auditors on sustainable fisheries management principles, practices, and regulations.
- Familiarise auditors with advanced technologies used in fisheries monitoring, such as satellite tracking and remote sensing.
- Integrating sustainable fisheries practices into national and international policy frameworks.
- Educating fishing communities about the long-term benefits of conservation and sustainable management.

By integrating these strategies, a balance is aimed between meeting current human needs, and ensuring the well-being of fishing communities for future generations.

Bibliography

Ali, Elham M, Nagalla zanaty, and Islam abou Magd. 2022. "Potential Efficiency of Earth Observation for Optimum Fishing Zone Detection of the Pelagic Sardinella aurita Species along the Mediterranean Coast of Egypt." *Fishes* 3 (7). Accessed January 2, 2024. doi:https://doi.org/10.3390/fishes7030097.

Antonova, Anna s. 2016. "The rhetoric of "responsible fishing": Notions of human rights and sustainability in the European Union's bilateral fishing agreements with developing states." 70: 77–84. Accessed August 8, 2023. doi:https://doi.org/10.1016/j.marpol.2016.04.008.

Behrenfeld,, Michael J, and Paul G. Falkowski. 2003. "Photosynthetic rates derived from satellite-based chlorophyll concentration." Edited by Limnology and Oceanography. *Limnology and Oceanography* 42 (1): 1-20. Accessed July 20, 2023. doi: https://doi.org/10.4319/lo.1997.42.1.0001.

Bose, Ridhi, Arun Bose, and Archan Das. 2019. "Fish Diversity and Limnological Parameters Influencing Fish Assemblage Pattern in Chambal River Basin of Madhya Pradesh, India." Edited by India, Sect. B Biol. Sci Proc. Natl. Acad. Sci. *Proceedings of the National Academy of Sciences* 89: 461–473. Accessed July 11, 2023. doi:https://doi.org/10.1007/s40011-017-0958-5.

Bundy, Alida. 2016. "Strong fisheries management and governance positively impact ecosystem status." *Fish and Fisheries* 18: 412–439. Accessed July 2, 2023. doi: https://doi.org/10.1111/faf.12184.

CAG. 2018. *Performance Audit of Economic Sector for the year ended 31 March 2017.* Performance Audit, Comptroller and Auditor General of India. Accessed 2024 17. file:///C:/Users/EDP/Downloads/Report_No1_of_201 8_Economic_Sector_Government_of_Gujarat%20(1).pdf.

Chakraborty, Kunal , Sourav Maity, Aneesh A Lotliker, Alakes Samanta, Jayshree Ghosh, and Nagaraja Masuluri. 2019. "Modelling of marine ecosystem in regional scale for short term prediction of satellite-aided operational fishery advisories." Edited by Ralph Rayner. *Journal of Operational Oceanography* (Taylor & Francis) 157-175. Accessed January 5, 2024. doi:https://doi.org/10.1080/1755876X.2019.1574951.

Chen, Qi , Weiteng Shen, and Bing Yu. 2018. "Assessing the Vulnerability of Marine Fisheries in China: Towards an Inter-Provincial Perspective." *Sustainability* 101 (11): 4302. Accessed July 4, 2023. doi:https://doi.org/10.3390/su10114302.

Colloca, Francesco, Giuseppe Scarcella, and Simone Libralato. 2017. "Recent Trends and Impacts of Fisheries Exploitation on Mediterranean Stocks and Ecosystems." *Sec. Marine Fisheries, Aquaculture and Living Resources* (Frontiers) 4. Accessed January 4, 2024. doi:https://doi.org/10.3389/fmars.2017.00244.

Comptroller and Auditor General of India. 2012. "Audit Report on Social, General and Economic (NonPSUs) Sectors." Accessed September 27, 2023. https://cag.gov.in/uploads/download_audit_report/2013/Assam_Report_2_2013_Exe_Sum.pdf.

Daqamseh, Saleh T. , A'kif Al Fugara, Biswajeet Pradhan, and Anas Al Oraiqat. 2019. "MODIS Derived Sea Surface Salinity, Temperature, and Chlorophyll-a Data for Potential Fish Zone Mapping: West Red Sea Coastal Areas, Saudi Arabia." *Advanced Applications of Remote Sensing in Monitoring Marine Environment* 19 (9). Accessed January 9, 2024. doi:https://doi.org/10.3390/s19092069.

Datta, Subhendu. 2024. *Fisheries Legislation in India.* Central Institute of Fisheries Education. Accessed January 4, 2024. https://www.academia.edu/74051339/Fisheries_Legislation_in_India.

Department of Animal Husbandry, Dairying & Fisheries. 2018. *Centrally Sponsored Scheme (CSS) on Blue Revolution.* Department of Animal Husbandry, Dairying & Fisheries, 60. Accessed January 11, 2024. https://fisheries.maharashtra.gov.in/sites/default/files/Revised_Blue_Revolution_Guidelines.pdf.

Department of Fisheries. 2020. "Pradhan Mantri Matsya Sampada Yojana." Ministry of Fisheries, Animal Husbandry and Dairying , 237. Accessed September 29, 2023. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://nfdb.gov.in/PDF/ PMMSY- Guidelines24-June2020.pdf.

Department of Fisheries. 2023. Department of Fisheries. Accessed September 26, 2023. https://dof.gov.in/sites/default/files/2021-10/Draft_Indian_Marine_Fisheries_Bill_ 2021.pdf.

Department of Fisheries. 2023-2024. "Ministry of Fisheries, Animal Husbandry and Dairying." Demand No. 43 Notes on Demands for Grants, 2023-2024, Ministry of Fisheries, Animal Husbandry and Dairying, Department of Fisheries. Accessed September 26, 2023. https://www.indiabudget.gov.in/doc/eb/sbe43.pdf.

Department of Fisheries, Government of Telangana. 2023. *Government of Telangana Fisheries Department.* Edited by Government of Telangana Department of Fisheries. Accessed September 26, 2023. https://fisheries.telangana.gov.in/ifd.php.

Directorate-General for Maritime Affairs and Fisheries. 2024. *European Commission* . Accessed January 11, 2024. https://oceans-and-fisheries.ec.europa.eu/facts-and-figures/facts-and-figures-common-fisheries-policy/employment_en.

Edwin, Leela. 2022. "Fishing Regulations in India." *Training Manual: ICAR* 14. Accessed January 4, 2024. https://krishi.icar.gov.in/jspui/bitstream/123456789/78263/1/3_Fishing%20Regulations%20in%20India.pdf.

Encyclopedia of Ecology, 2008. 2008. "Maximum Sustainable Yield." *Encyclopedia of Ecology.* Accessed January 11, 2024. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/maximum-sustainable-yield.

FAO. 2019. *Food and Agriculture Organisation of the United States Aquatic Sciences and Fisheries Abstracts (ASFA).* France Société Française d'Ichtyologie. Accessed January 2, 2024. https://www.fao.org/fishery/en/openasfa/29a26546-dc4a-4136-a3e2-365377575027.

Fisheries and fishermen welfare. 2021-2022. "Animal Husbandry, Dairying, Fisheries and Fishermen Welfare Department." Demand No. 7, Fisheries and Fishermen Welfare.

Accessed September 26, 2023. https://cms.tn.gov.in/sites/default/files/documents/fisheries_e_pn_2021_22.pdf.

Fishery Survey of India. 2023. *Fishery Survey of India Government of India.* Accessed September 27, 2023. https://fsi.gov.in/LATEST-WB-SITE/fsi-main-pg-frm.htm.

Frank Asche. 2024. *Green Growth in Fisheries and Aquaculture.* Organisation for Economic Co-operation and Development, OECD Organisation for Economic Co-operation and Development. Accessed January 6, 2024. https://www.oecd.org/greengrowth/sustainable-agriculture/48258799.pdf.

Frelat, Romain , Alessandro Orio, Michele Casini, Andreas Lehmann, Bastien Mérigot, and Christian Möllmann. 2018. "A three-dimensional view on biodiversity changes: spatial, temporal, and functional perspectives on fish communities in the Baltic Sea." *ICES Journal of Marine Science* (Oxford university press) 75 (7). Accessed January 11, 2024. doi:https://doi.org/10.1093/icesjms/fsy027.

Ghorai, Mrinmay, Bidhan Patra, and Manojit Bhattacharya. 2015. "The impact of coal fly ash power station on distribution and biodiversity of freshwater fishes in rupnarayan river, West Bengal, India." *International Journal of Current Research* 7: 23954-23961. Accessed July 21, 2023. https://www.journalcra.com/article/impact-coal-fly-ash-power-station-distribution-and-biodiversity-freshwater-fishes-rupnarayan.

Hi Pro Feeds. 2024. "Blue Revolution." Hi Pro Feeds. Accessed January 9, 2024. https://hiprofeeds.in/blog/blue-revolution-revolutionizing-fish-farming-in-india/.

Hindustan Times. 2023. *'Overfishing, killing of juvenile fish on rise along Maharashtra coast'.* July 2. Accessed April 28, 2024. https://timesofindia.indiatimes.com/city/mumbai/sharks-and-lobsters-among-stocks-overfished-study/articleshow/101426760.cms.

Huang, Minrui , Liuyong Ding, Jun Wang , Chengzhi Ding, and Juan Tao. 2021. "The impacts of climate change on fish growth: A summary of conducted studies and current knowledge." *Ecological Indicators* (Elsevier) 121 (106976). Accessed January 6, 2024. doi:https://doi.org/10.1016/j.ecolind.2020.106976.

Huot, Yannick, M Babin, and F Bruyant. 2007. "Does chlorophyll-a provide the best framework of phytoplankton biomass for primary productivity studies?" *Biogeosciences Discussions* 707-745. Accessed January 6, 2024. https://www.researchgate.net/publication/29620069_Does_chlorophyll_a_provide_the_best_framework_of_phytoplankton_biomass_for_primary_productivity_studies.

ICAR. 2009. *Application of Geographic Information System in Fisheries Management.* Indian Council of Agricultural Research, 10. Accessed January 7, 2024. https://krishi.icar.gov.in/jspui/bitstream/123456789/8728/1/Application%20of%20geographic%20information%20system%20in%20fisheries%20management.pdf.

—. 2024. *Indian Council of Agricultural Research.* Accessed January 5, 2024. http://ecoursesonline.iasri.res.in/mod/page/view.php?id=91735.

ICAR. 2014. *Potential Fishing Zone Advisory.* Indian Council of Agricultural Research. Accessed January 5, 2024. https://ccari.icar.gov.in/Extension%20Folder%20No.%2070.pdf.

INCOIS. 2023. *ESSO-INCOIS-Indian National Centre for Ocean Information Services.* Accessed November 2, 2023. https://incois.gov.in/portal/aboutus.

INTOSAI. 2023. *Key Findings and Recommendations from the Performance Audit on the Fisheries and Agriculture Diversification Programme (FADIP).* INTOSAI Working Group on Environmental Auditing (WGEA), INTOSAI Working Group on Environmental Auditing (WGEA), 2. Accessed January 17, 2024. https://www.environmental-auditing.org/media/tkbl3ixy/fadip_summary.pdf.

INTOSAI. 2022. *Member States need to step up fight against illegal fishing.* INTOSAI Working Group on Environmental Auditing (WGEA), 2. Accessed January 8, 2024. https://www.environmental-auditing.org/media/y1poe5uy/illegal_fishing_en_press_release.pdf.

INTOSAI. 2020. *Performance Audit of Illegal Fishing Prevention.* INTOSAI Working Group on Environmental Auditing (WGEA), 1. Accessed January 17, 2024. https://www.environmental-auditing.org/media/4xqhvsul/2020_-_illegal_fishing.pdf.

Jishad, M, Ranjeet sarangi, Smitha Ratheesh, Syed Ali, and Rashmi Sharma. 2021. "Tracking fishing ground parameters in cloudy region using ocean colour and satellite-derived surface flow estimates: A study in the Bay of Bengal." Edited by Ralph Rayner. *Journal of Operational Oceanography* 14 (1). Accessed January 7, 2024. doi:https://doi.org/10.1080/1755876X.2019.1658566.

Kalita, Prabin. 2020. *PM Modi launches Pradhan Mantri Matsya Sampada Yojana (PMMSY).* The Times of India, September 10. Accessed January 4, 2024. https://timesofindia.indiatimes.com/india/pm-modi-launches-pradhan-mantri-matsya-sampada-yojana-pmmsy/articleshow/78045273.cms?from=mdr.

Karuppasamy, S, TP Ashhitha, R Padmanabhan, M Shamsudeen, and Silva JMN. 2020. "Validation of integrated potential fishing zone (IPFZ) forecast using satellite based chlorophyll and sea surface temperature along the east coast o." *Indian Journal of Geo Marine Sciences* 49 (3): 1025-1030. Accessed January 2, 2024. https://nopr.niscpr.res.in/handle/123456789/54934.

Malakar, Krishna , Trupti Mishra, Vittal Hari , and Subhankar Karmakar. 2021. "Risk mapping of Indian coastal districts using IPCC-AR5 framework and multi-attribute decision-making approach." *Journal of Environmental Management* 294. Accessed January 3, 2024. doi:https://doi.org/10.1016/j.jenvman.2021.112948.

2023. *Maps of India.* August 25. Accessed 2023. https://www.mapsofindia.com/lat_long/.

Ministry of Agriculture . 2004. "Marine Fishing Policy." Ministry of Agriculture, Department of Animal Husbandry & Dairying, 6. Accessed September 27, 2023. https://smallscalefishworkers.org/wp-content/uploads/2019/01/MARINE-FISHING-POLICY-2004.pdf.

Ministry of Fisheries, Animal Husbandry & Dairying. 2023. "Allocation in Budget FY 2023-24 for Department of Fisheries marks an overall increase of 38.45% over the Budget of FY 2022-23." Accessed September 27, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1896462.

Ministry of Fisheries, Animal Husbandry and Dairying. 2024. *Department of Fisheries.* Accessed January 4, 2024. https://dof.gov.in/blue-revolution.

Ministry of Fisheries, Animal Husbandry and Dairying. 2020. "Handbook on Fisheries Statistics." Accessed November 2, 2023. https://dof.gov.in/sites/default/files/2021-02/Final_Book.pdf.

—. 2023. *Ministry of Fisheries,Animal Husbandry & Dairying.* Accessed September 26, 2023. https://dahd.nic.in/related-links/centrally-sponsored-national-scheme-welfare-fishermen.

—. 2024. *National Fisheries Development Board.* Accessed January 9, 2024. https://nfdb.gov.in/welcome/PMMSY.

Ministry of Ocean Development. 2006. *Annual report.* Ministry of Ocean Development, 86. Accessed January 7, 2024. https://www.moes.gov.in/sites/default/files/inline-files/ar05-06.pdf.

2023. *Moderate Resolution Imaging Spectroradiometer.* Accessed 2023. https://modis.gsfc.nasa.gov/.

MoES. 2024. *Ministry of Earth Sciences.* Accessed January 11, 2024. https://moes.gov.in/about-us-0?language_content_entity=en.

Muhammad, Muhammad, Agus Widi Priana, Junaidi M. Affan, Haekal Azief Haridhi, and Irwan Irwan. 2022. *Mapping potential fishing zones based on sea surface temperature and Chlorophyll-A in the Waters of Aceh Besar, Indonesia.* Accessed October 2, 2023. doi:10.1051/e3sconf/202233902002.

NABARD . 2023. *National Bank for Agriculture and Rural Development.* Edited by NABARD. Accessed September 26, 2023. https://www.nabard.org/PressReleases-article.aspx?id=25&cid=554&EID=68#:~:text=The%20Union%20Budget%20for%20FY,computerisation%20of%2063%20thousand%20PACS.

Namallwar, Satheesh, and Ramesh. 2013. "Applications of Remote Sensing in the validation of Potential Fishing Zone (PFZ) along the coast of North Tamil Nadu, India." *Indian journal of Geo Marine Sciences* 283-292. Accessed January 4, 2024. http://eprints.cmfri.org.in/9578/1/IJMS_42%283%29_283-292_Nammalwar.P.pdf.

Nammalwar, P , Satheesh S, and R Ramesh . 2013. "Applications of remote sensing in the validations of potential fishing zones (PFZ) along the coast of North Tamil Nadu, India. Indian Journal of Geo-Marine Sciences,." *Indian Journal of Geo Marine Sciences* 42 (3): 283-292. Accessed January 2, 2024. http://eprints.cmfri.org.in/id/eprint/9578.

NASA MODIS. 2023. *Ocean colour level 3 & 4 browser.* Accessed August 11, 2023. https://oceancolor.gsfc.nasa.gov/l3/.

National fisheries development board . 2020-21. *Annual report.* National Fisheries Development Board, Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. Accessed September 26, 2023. https://nfdb.gov.in/PDF/ANNUAL%20REPORTS/AR2021F.pdf.

National Fisheries Development Board. 2024. *Introduction to Fish and Fisheries.* National Fisheries Development Board, 36. Accessed January 7, 2024. https://nfdb.gov.in/PDF/Fish%20&%20Fisheries%20of%20India/1.Fish%20and%20Fisheries%20of%20India.pdf.

National Fisheries Policy. 2020. "National Fisheries Policy, 2020." 45. Accessed September 27, 2023. https://dof.gov.in/sites/default/files/2020-12/Policy_0.pdf.

National Geographic. 2024. *Sustainable Fishing.* Accessed January 11, 2024. https://education.nationalgeographic.org/resource/sustainable-fishing/.

Negi, Ram, and Sheetal Mamgain. 2013. "Species Diversity, Abundance and Distribution of Fish Community and Conservation Status of Tons River of Uttarakhand State, India."

Journal of Fisheries and Aquatic Science, 8 (5): 617–626. Accessed July 21, 2023. doi:https://doi.org/10.3923/jfas.201.

NFDB. 2021. "Training manual on recent advances on fish harvest and post harvest technologies." National Fisheries Development Board, 270. Accessed January 6, 2024. file:///C:/Users/EDP/Downloads/PMMSY%20Training%20manual%20MRC%20CIFT%202021.pdf.

Nilanjan Ghosh, Roshan Saha and Soumya Bhowmick. 2019. "SDG Framework and Ease of Doing Business in India: A Sub-National Study", ORF Occasional Papers, Observer Research Foundation,." Accessed September 27, 2023. https://www.orfonline.org/research/sdg-framework-and-ease-of-doing-business-in-india-a-sub-national-study-52066/.

Nye, Janet, Jason link, and Jon Hare. 2009. "Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United Sates continental shelf." *MARINE ECOLOGY PROGRESS SERIES* 393: 111-129. Accessed January 5, 2024. doi:10.3354/meps08220.

Our world in data. 2024. *Fish and Overfishing.* Accessed January 11, 2024. https://ourworldindata.org/fish-and-overfishing.

Paolo, Fernando, David Kroodsma, Jennifer Raynor, and Tim Hochberg. 2024. "Satellite mapping reveals extensive industrial activity at sea." *Nature* (Nature) 625: 85-91. Accessed January 7, 2024. doi:https://doi.org/10.6084/m9.figshare.24309475 .

Perry, Allison L, Paula Low, and Jim Allis. 2005. "Climate change and distribution shifts in marine fishes." *Science* 308 (5730): 1912-5. Accessed August 1, 2023. doi:10.1126/science.1111322.

PIB Delhi. 2023. *Allocation in Budget FY 2023-24 for Department of Fisheries marks an overall increase of 38.45% over the Budget of FY 2022-23.* February 05. Accessed September 26, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1896462.

—. 2023. *Ministry of Fisheries, Animal Husbandry & Dairying.* Edited by PIB Delhi. Accessed September 26, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1654543#:~:text=Government%20has%20decided%20for%20introducing,with%20the%20elements%20of%20Post.

PIB. 2023. *Press Information Bureau Ministry of Earth Sciences.* Accessed September 26, 2023. https://pib.gov.in/newsite/PrintRelease.aspx?relid=193703.

Platt , Trevor , and Shubha Sathyendranath . 2008. "Ecological indicators for the pelagic zone of the ocean from remote sensing." *Remote Sensing of Environment* (Elsevier) 112: 3426-3436. Accessed July 11, 2023. doi:https://doi.org/10.1016/j.rse.2007.10.016.

PRS Legislative Research . 1983. "The Tamil Nadu Marine Fishing Regulation Act." Accessed September 27, 2023. Marine Fisheries Regulation Act, 1983 (MFR Act).

Sathiadhas, R. , C. Ramachandran, and N. Aswathy. 2010. *Conservation of Fisheries Resources in India Economic an livelihood issues.* Accessed January 11, 2024. http://eprints.cmfri.org.in/8757/1/R_Sathiadhas.pdf.

Solanki, HU, Pradeep Mankodi, Shailesh Nayak, and Rashmin Dwivedi. 2008. "Satellite observations of main oceanographic processes to identify ecological associations in the Northern Arabian Sea for fishery resources exploration." *Hydrobiologia* 612 (1): 269-279. Accessed January 9, 2024. doi:10.1007/s10750-008-9496-8.

2023. *Statistics Department of Fisheries.* Accessed August 5, 2023. https://dof.gov.in/statistics.

Stavridis, Admiral . 2023. "CHAPTER 2: MARITIME ZONES." In *Law of the Sea*. Accessed December 4, 2023. https://sites.tufts.edu/lawofthesea/table-of-contents/.

Steinberg, Deborah K. , and Michael R. Landry. 2017. "Zooplankton and the Ocean Carbon Cycle." *Annual Review of Marine Science* 9: 413-444. Accessed January 11, 2024. https://www.annualreviews.org/doi/10.1146/annurev-marine-010814-015924.

Survey of India. 2024. *Survey of India.* Accessed April 4, 2024. https://www.surveyofindia.gov.in/.

Thakare, Lalit. 2021. "Vulnerability assessment of the Ratnagiri coast (Maharashtra, west coast of India." *Journal of Coastal Research* 421-432. Accessed June 22, 2023. doi:https://doi.org/10.2112/JCOASTRES-D-19-00190.1.

The Times of India. 2023. *Sharks and lobsters among stocks overfished: Study.* July. Accessed April 27, 2024. https://timesofindia.indiatimes.com/city/mumbai/sharks-and-lobsters-among-stocks-overfished-study/articleshow/101426760.cms.

WRI. 2024. *World Resources Institute Course 4 Increase Fish Supply (Synthesis).* Accessed January 5, 2024. https://research.wri.org/wrr-food/course/increase-fish-supply-synthesis.

WWF. 2024. *WWF.* Accessed March 2, 2024. https://www.worldwildlife.org/industries/sustainable-seafood.

Younes, Oulad Sayad . 2023. "Mapping Potential Fishing Zones Using Remote Sensing Data and GIS: A Case Study of Moroccan Waters." *Multimedia Research,* 6 (2): 1–13. Accessed July 21, 2023. doi:https://doi.org/10.46253/j.mr.v6i2.a1.

Appendix

A. Description of Indicators

For the purpose of computation of the proposed PFZ framework, three indicators were identified. The latest available data for each variable were collected for Maharashtra districts. Table A1 summaries the chosen indicators and the sources of data.

Table A1: Description of Indicators

Indicator	Methodology	Unit of measurement	Data source	Type of Indicator
SST (Sea Surface Temperature)	Zonal statistics in QGIS	Degrees Celsius (°C)	(NASA MODIS 2023)	Parabolic behaviour indicator
POC (Particulate Organic Carbon)	Zonal statistics in QGIS	(mg/L)	(NASA MODIS 2023)	(P)
Chl-a (Chlorophyll-a)	Zonal statistics in QGIS	(µg/L)	(NASA MODIS 2023)	(P)

Here, (P) stands for progressive indicator. Progressive indicators always show improvement or advancement. The value of the indicator increases over time as positive changes occur. While SST shows parabolic behaviour describes a situation in which the SST indicator displays a curved, parabolic pattern in its data. Categorisation of SST behaviour based on specific temperature ranges mentioned below:

1. **Sea Surface Temperature ≥ 28.9°C:** Regressive Behaviour
   - When the sea surface temperature is above or equal to 28.9°C, it exhibits regressive behaviour.
2. **Sea Surface Temperature between 26.1°C and 28.9°C:** Progressive Behaviour
   - When the sea surface temperature falls within the range of 26.1°C to 28.9°C, it indicates progressive behaviour.
3. **Sea Surface Temperature 26.1°C < :** Regressive Behaviour
   - When the sea surface temperature is less than or equal to 26.1°C, it displays regressive behaviour.

Table A2: Raw data for Sea Surface Temperature (SST), Chlorophyll-a (Chl-a), Particulate Organic Carbon (POC) Concentrations, and Fish Catch - Year 2020

S. No.	District	Chl-a value	SST	POC 2020	Marine Fish catch 2020 (Quantity in tonnes)
1.	Amreli	0.0000	28.0500	471.3900	1716.0200
2.	Bhavnagar	3.1100	28.3300	390.5900	392.0000
3.	Jamnagar	2.4300	28.6600	245.9100	1218.0000
4.	Junagadh	0.0000	28.0600	381.5900	15329.0000
5.	Kachchh	4.4600	26.5250	416.9900	420.0000
6.	Surat	0.9400	28.0000	228.0000	3208.0000
7.	Valsad	1.3700	27.0900	350.0000	87594.0000
8.	Mumbai	6.0050	28.5100	547.1900	154353.0000
9.	Raigad	6.3900	28.6300	535.0900	41797.0000
10.	Ratnagiri	2.9000	29.0100	199.5900	66173.0000
11.	Sindhudurg	0.3200	28.9300	146.1900	18713.0000
12.	Thane	6.3660	28.6050	479.9900	86225.0000
13.	North Goa	0.4000	28.9600	349.5900	48081.0000
14.	South Goa	5.8000	28.8900	240.9100	47945.0000
15.	Dakshin Kannada	0.5500	29.3900	157.9900	163096.0000
16.	Uttar Kannada	0.6330	29.1050	106.9900	108500.0000
17.	Alappuzha	0.2500	29.4250	159.1900	12534.0000
18.	Ernakulam	0.3500	29.2950	172.1900	97703.0000
19.	Kannur	0.3400	29.9800	167.1900	9519.0000
20.	Kasaragod	0.3678	29.2750	168.9900	19259.0000
21.	Kollam	1.2500	28.0000	226.0000	97346.0000
22.	Kozhikode	0.3660	29.1250	261.7900	53766.0000
23.	Malappuram	0.3400	29.0700	177.7900	24203.0000
24.	Thiruvananthapuram	0.2500	28.3350	378.5900	57426.0000
25.	Thrissur	0.6500	29.0800	235.9900	19927.0000
26.	Kanniyakumari	0.1100	28.0000	231.0000	69686.0400
27.	Pudukkottai	1.0800	28.0000	271.0000	42609.0000
28.	Ramanathapuram	0.4730	28.7600	184.9900	3450.1700
29.	Thanjavur	2.4300	28.7400	139.1900	28049.9300

Table A3: Raw data for Sea Surface Temperature (SST), Chlorophyll-a (Chl-a), Particulate Organic Carbon (POC) Concentrations, and Fish Catch - Year 2021

S.No.	Districts	Chl-a value	SST	POC 2021	Marine Fish catch 2021 (Quantity in tonnes)
1.	Amreli	4.744744534	24.71	396.92	60576
2.	Bhavnagar	4.890775205	25.095	396.92	2640
3.	Jamnagar	1.93	25.63	333.22	67146
4.	Junagadh	1.930671897	25.72742653	350.53	280897
5.	Kachchh	2.715292711	25.795	395.69	72897
6.	Surat	4.535297095	25.83171313	398.79	3208
7.	Valsad	4.552970948	25.85	373.36	87594
8.	Mumbai	4.283719897	25.97	405.68	133212
9.	Raigad	2.769549988	26.36	360.599	38019
10.	Ratnagiri	1.753	26.44999941	337.11	65374
11.	Sindhudurg	3.205592161	26.54499941	362.19	17311
12.	Thane	3.205592161	26.55499941	371.79	67547
13.	North Goa	1.69710913	26.6499994	340.133	54265
14.	South Goa	1.563853172	26.76	342.16	53976
15.	Dakshin Kannada	0.8430155	26.77	272.665	163096
16.	Uttar Kannada	1.358867413	26.82	280.67	108500
17.	Alappuzha	2.78	26.8399994	74.83	16979
18.	Ernakulam	2.281	26.98	118.35	152368
19.	Kannur	0.95	26.9999994	71.986	10711
20.	Kasaragod	0.25	27.125	69.075	12364
21.	Kollam	0.414	27.16499939	169.73	96662
22.	Kozhikode	1.7	27.18999939	160.79	122639
23.	Malappuram	1.885	27.44999935	221.19	32532
24.	Thiruvananthapuram	0.362	27.63657635	61.59	64047
25.	Thrissur	1.125	27.8	227.39	58297
26.	Kanniyakumari	0.31	27.98	86.834	7112.17
27.	Pudukkottai	2.9233	28.01	211.8	42609
28.	Ramanathapuram	2.123	28.18999	217.84	3450.17
29.	Thanjavur	2.795888	28.22	138.4	28049.93
30.	East Godavari	0.3949	28.2875	103.81	111724
31.	Guntur	0.3583	28.305	91.49	40912
32.	Krishna	0.3583	28.38	90.49	41229
33.	Nellore	0.546226	28.44999	121.19	91332
34.	Prakasam	0.6303	28.64999343	146.13	41284
35.	Srikakulam	0.2578	28.96	81.55	59839
36.	Vishakhapatnam	0.2983	29.16	75.67	103973
37.	Vizianagaram	0.3282	29.175	80.52	17506
38.	West Godavari	0.346	29.31	97.5	12475
39.	Baleshwar	1.171	29.48742653	219.971	38690
40.	Puri	0.422	29.49	142.969	31127
41.	Ganjam	0.401	29.664999	118.79	10062
42.	Purba Medinipur	4.75	29.83499933	300.11	51889
43.	South 24 Parganas	2.508449339	29.89	301.11	124637
44.	North 24 Parganas	2.804631954	30.4499	319.85	0