ECOLOGY AND CONSERVATION OF ICHTHYOFAUNA IN THE EAST GODAVARI RIVER ESTUARINE ECOSYSTEM (EGREE), ANDHRA PRADESH

Thesis submitted to the
Saurashtra University, Rajkot (Gujarat)

for the award of the Degree of

DOCTOR OF PHILOSOPHY
IN
WILDLIFE SCIENCE

By

PAROMITA RAY

Under the supervision of

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18th July, 2022

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Ms. Paromita has put in more than eight terms of research work, embodied in this thesis, under my supervision. The work presented in this thesis has not been submitted to any other university or institute.

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I hereby declare that the thesis titled "Ecology and conservation of Ichthyofauna in the East Godavari River Estuarine Ecosystem (EGREE), Andhra Pradesh" submitted by me for the degree of Doctor of Philosophy is the record of research work carried out by me during the period from January 2015 to August 2022 under the guidance of Dr. K. Sivakumar, Scientist F, Wildlife Institute of India, Dehradun and co-supervision of Dr. J. A. Johnson, Scientist-F, Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any degree, diploma, associate ship, fellowship, titles in this or any other University or other institution of higher learning. I further declare that the material obtained from other sources has been duly acknowledged in this thesis. I shall be solely responsible for any plagiarism or other irregularities, if noticed in this thesis.

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Chapter 1 Introduction 1.1. Estuaries Estuaries are transitional coastal zones where freshwater and marine water mixes. They act as a dynamic interface between freshwater, marine, and the adjoining terrestrial ecosystems that may be affected by tides (Wolanski & Elliott, 2015). Several authors including Pritchard, 1967; Dalrymple et al., 1992; Perillo, 1995; Potter et al., 2010 have attempted to define an 'estuary'. Later, Wolanski and Elliot (2016) provided a comprehensive description of estuaries incorporating elements from the previous definitions: "…an estuary is a semi-enclosed body of water connected to the sea as far as the tidal limit or the salt intrusion limit and receiving freshwater runoff, recognising that the freshwater inflow may not be perennial (i.e., it may occur only for part of the year) and that the connection to the sea may be closed for part of the year (e.g., by a sandbar) and that the tidal influence may be negligible." The role of estuaries as important habitats for fishes has been well studied and well discussed in the past few decades (Laegdsgaard & Johnson, 1995; Kathiresan & Bingham, 2001; Blaber, 2007). Sheaves (2009) propounded estuaries to be a crucial connecting link between the freshwater, coastal, and marine habitats of fishes. The high productivity of estuaries and high input of nutrients makes them rich feeding grounds for various species. For the diadromous species, they provide a gradual transition state, making it easier for the fishes to migrate through varying salinities. However, the role of estuaries as important nursery grounds for fishes has been recognized by many authors to be a crucial one (Blaber &

Blaber, 1980; Bell et al., 1984; Robertson & Duke, 1987

Acknowledgements

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I am extremely privileged to have received the Future Conservationist Award from the Conservation Leadership Programme, and a small grant from the Rufford's, in 2017 and 2018 respectively, which allowed me to pursue my passion of fish conservation in Andhra Pradesh. While this work was not directly a part of my thesis but these grants helped me immensely to gain valuable experiences and skills in freshwater ecology, thus broadening my understanding of the ecological connectivity within a river basin and the coastal ecosystems. I have to extend my deepest gratitude to the wonderful team of CLP-2017, Christina, Stuart, Laura, Charlotte and Maureen. They believed in the cause of freshwater conservation, which unfortunately is an extremely neglected and under-funded part of the global wildlife community. More importantly they provided me with the opportunity to attend the leadership training organized by CLP in 2017, and multiple other opportunities during my association with them.

Furthermore, CLP also supported with a small grant to participate in an exchange programme with Dr Gustavo Castellanos-Galindo from Colombia. This exchange programme of a few days has helped me gain a friend and a mentor in Gustavo. His work on fish communities in mangroves of Colombia and Brazil has provided me greatly with the necessary direction in my own thesis. He taught me the basics of ecosystem modelling for mangrove habitats and provided me with the basic training in the Ecopath with Ecosim software, which allowed me to successfully complete the second objective of my thesis. I can never thank Gustavo and CLP enough for giving me this opportunity. In this respect, I also want to appreciate Dr Villy Christensen for allowing me to be part of his online course of Ecopath with Ecosim at the University of British Columbia (UBC), Canada in 2021.

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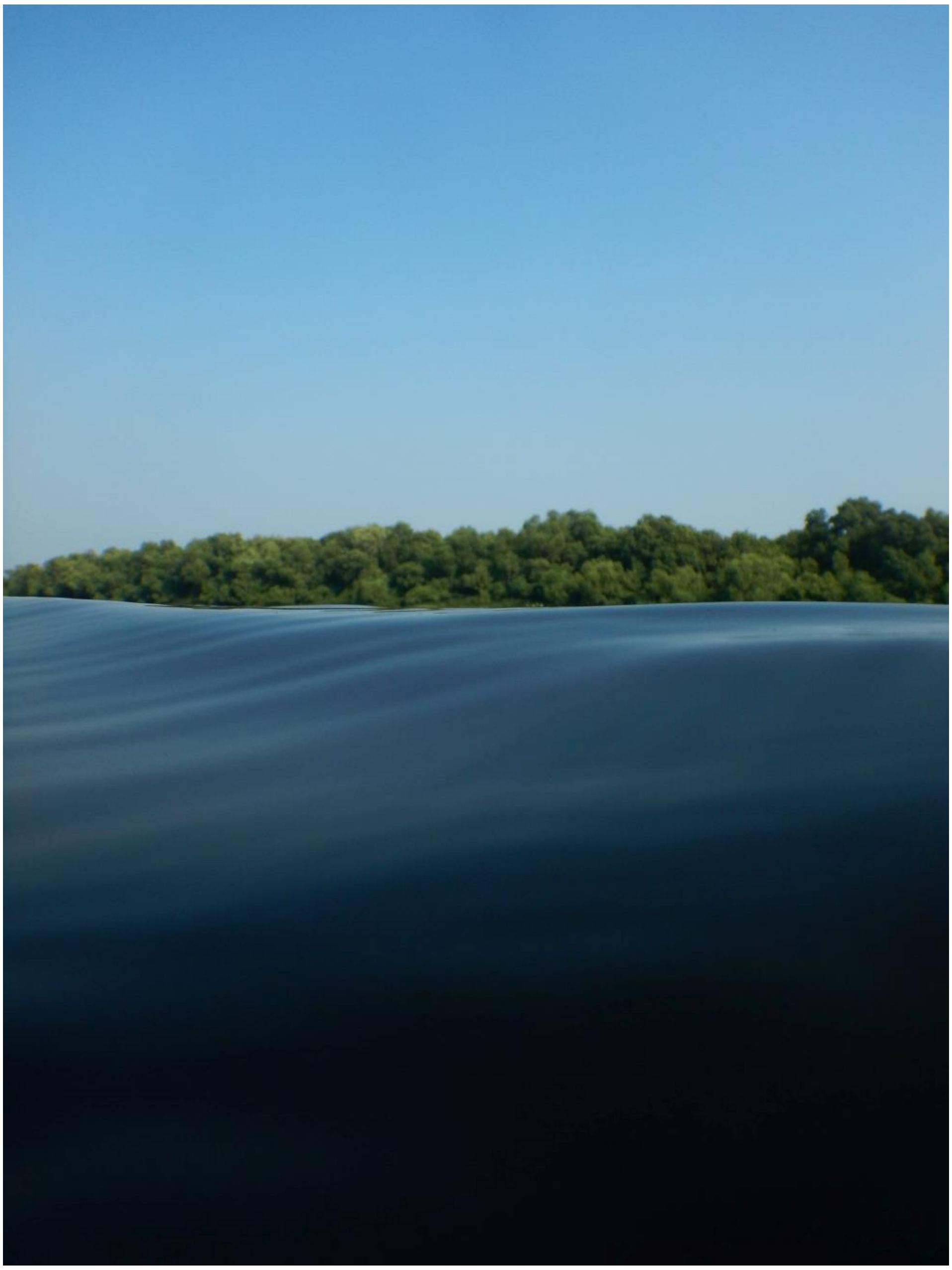


"Like winds and sunsets, wild things were taken for granted until progress began to do away with them"

-Aldo Leopold

Summary

Estuaries are semi-enclosed, transitional coastal zones where freshwater and marine water mixes. They act as a dynamic interface between freshwater, marine, and the adjoining coastal ecosystems. The role of estuaries as fish habitats is well recognized, and have been subjected to several studies globally. They may act as nursery for juveniles, feeding sites or even as a transitioning habitat for diadromous fish species. A number of tropical and subtropical estuaries are lined by mangroves, which play similar role as fish habitats. India is endowed with a long, indented coastline, which is home to several estuaries that are lined by mangrove forests. One such site is at the confluence of Godavari River with the Bay of Bengal in Andhra Pradesh, which is occasionally known as the East Godavari River Estuarine Ecosystem (EGREE). This estuary plays an important role in supporting thousands of small-scale fishers in the region but is at a tipping point wherein it is constantly being threatened by urbanization and growth in aquaculture on one hand, while on other hand it must adapt to the rising sea surface temperatures and sea level rise.

Understanding the ecological processes and functions of the estuary, including studying the role of the Godavari mangroves as fish habitats, is needed to maintain the various ecosystem services of EGREE. Due to this requirement coupled with a general lack of studies on estuarine fish assemblages in India, this study was carried out and became part of my PhD thesis.

The three main objectives of this thesis are:

1. To study the spatio-temporal changes in fish assemblage across the different habitats in East Godavari Riverine Estuary Ecosystem (EGREE)

2. To study the trophic ecology of ichthyofauna in East Godavari Riverine Estuary Ecosystem

(EGREE).

3. To study the role of mangrove forests in structuring the ichthyofauna in Coringa Wildlife Sanctuary.

This study was conducted between June 2014 and May 2017 in the estuarine zone of the Godavari delta and the mangroves of Coringa Wildlife Sanctuary in Andhra Pradesh. The sanctuary (237.5 sq. km) lies at 16°59’-16°44’ N, 82°15’- 82°20’E, in the northern part of the delta formed by Godavari River at its confluence with Bay of Bengal. These mangrove forests have global importance as they are part of the Central Asian Flyway and have been declared an Important Bird and Biodiversity Area (IBA). Godavari River is the second- longest river in India with a drainage basin of 3.1 × 10 5 sq. km. Its delta is characterised by habitats including mangroves and riparian forests, riverine sandbars, open mudflats, sand spits, and an extensive lagoon termed “Kakinada Bay” towards the north. The region receives an average precipitation of 1000-1100 mm/year and has two monsoon seasons from July to November. The study area has a mostly semi-diurnal tidal cycle with a mean annual tidal amplitude of 0.36m to 1.38m.

The mangrove forests of Coringa WLS are dominated by *Avicennia marina, Avicennia officinalis* and *Excoecaria agallocha*. The creeks at many places are also lined by dense patches of mangrove-associates such as thorny shrub *Acanthus illicifolius* and grass species including *Myriostachya wightiana*. Three major sub-tidal creeks namely Thulyabhaga, Coringa, and Gaderu flow across the sanctuary dividing it into different zones. Another subtidal creek – Giriyampeta drains the southern edge of the sanctuary.

Spatial patterns in the fish community of sub-tidal creeks in Coringa Wildlife Sanctuary.

Assemblage patterns in the fish community were studied in four sub-tidal creeks of the protected mangrove forest in CWS. The role of environmental factors driving these patterns was also identified. Additionally, I also documented the fish diversity of the larger EGREE area including the mangroves, the riverine part of the estuary, and the Kakinada Bay. Fish sampling in three major seasons viz. Winter, Summer and Rainy was done using trammel net at different sampling sites in the four creeks. During each sampling event at a site, the trammel net was deployed for one hour after which the fish species caught were identified and their individuals counted for record.

I documented 231 finfish species from EGREE, of which 150 species were recorded in the Coringa Wildlife Sanctuary. The most speciose order was the Perciformes with 41 species followed by Clupeiformes (25 species), and then Carangiformes (18 species). Among the families, Carangidae was represented by the highest number of species (16 species) followed by Gobiidae and Sciaenidae (both represented by 12 species). Nearly 67% of the overall species occurred in at least two habitat types showing a high degree of overlap between the different estuarine habitats. Four species recorded during this study are listed threatened in the IUCN Red List, while three Near Threatened and 11 Data Deficient species were also recorded. Additionally, five non-native species were recorded in EGREE, of which *Oreochromis mossambicus* was found to have established a wild population in parts of Coringa and Thulyabagha creeks.

The fish community of the mangrove lined creeks of CWS was dominated by five species that contributed over 50% to the overall fish catch. *Mystus gulio* was among the most abundant species in the Thulyabhaga (42.7%) and Coringa (21%) creeks, Arius sp. (33.5%) and *Dendrophysa russelii* (18.8%) in Gaderu, and *Dichotomyctere fluviatilis* (13%) and *Ambassis gymnocephalus* (10.4%) in Giriyampeta creek. No effect of season or creeks was detected in the species community variables, including species diversity and species evenness. Though the observed number of species was higher in Giriyampeta and Gaderu (creeks with higher salinity) than Thulyabagha and Coringa (creeks with lower salinity). The environmental variables were also relatively stable except for salinity, which was found to be an important factor explaining ~85% of the differences in the species assemblages between the four creeks. These results suggest that the fish community of the sub-tidal creeks in the sanctuary includes two main spatial assemblages- one in creeks with relatively lower salinity values (Thulyabagha and Coringa) that included presence of a few freshwater species, and the other in creeks with higher salinity values (Gaderu and Giriyampeta) that was dominated by euryhaline and marine species.

Trophic ecology of ichthyofauna in East Godavari Riverine Estuary Ecosystem (EGREE)

In order to explore the trophic dynamics between the various functional groups occurring in the mangrove-lined creeks of Coringa Wildlife Sanctuary (CWS), a mass-balanced preliminary trophic model was created using the Ecopath with Ecosim (EwE) software. Based on the observations made during the fishing surveys in 2015-2017, a total of 21 functional groups (single species or groups of species), including detritus, were defined. For each of the functional groups, five input parameters were used that included biomass (B), diet composition (DC), annual production per unit of biomass (P/B), annual consumption per unit of biomass (Q/B), and annual fisheries yield (Y).

The trophic levels in the system varied from 1.0 for primary producers and detritus to 3.7 for the piscivorous fishes. The total biomass of the system (excluding detritus) was calculated as 939 t/km^2, of which 96% was due to the mangroves while ~1% each of the total biomass was contributed by window-pane oysters and blood cockles. The total catch for the sampling year was 84.1 t/km^2/year, and the mean trophic level for the catch was 2.5.

Significant degree of niche overlap was found among a number of functional groups, especially among the blood cockles and the window-pane oysters, both in terms of their prey and their potential predators. These two groups also shared similar prey resources with planktivorous fishes, and thus had high prey overlap as well as occupied the same trophic level within the food web. *Oreochromis mossambicus,* a non-native species showed a high degree of prey overlap with penaeid shrimps and benthic macrofauna, though other indicators from the model did not reveal any major impact of this species on other functional groups. The other finfish groups did not show any prey overlap among each other, suggesting certain degree of niche segregation between each other.

The Keystonness index identified Fishing cats as a keystone species, followed by phytoplanktons and zooplanktons. CWS is a low-productivity system, which is still in an immature state. It has a high catch rate (84.1 t/km^2/year) for an estuarine ecosystem coupled with the dominance of lower trophic levels in the fisheries of the sanctuary (mean trophic level of catch was 2.5). While a high relative ascendancy value is indicative of a stable ecosystem, lower relative overhead value and Finn's Cycling Index suggest high vulnerability to external disturbances. This is an important outcome considering the very high fishing pressures inside CWS, and its vulnerability to sea level rise.

Role of mangroves in structuring the ichthyofauna in Coringa Wildlife Sanctuary

The structural complexity of a habitat is one of the fundamental factors shaping a biological community and driving habitat usage by taxa. The structural complexity in mangrove forests, as a result of their unique root systems and other variables, provides excellent refuge and feeding habitats for fishes. In this chapter, I set out to examine the potential role of microhabitat features in the structuring of the fish assemblages within the small, intertidal creeks of CWS. The influence of other factors, including the diel, tidal cycles, and seasons are also studied. For this, I identified four intertidal creeks within the larger system of the Coringa creek based on various factors including differing management types, and ease of accessibility. Two of the four creeks were natural creeks while two others were artificial or created by the forest department for the purpose of mangrove replanting. This study was carried out from 2016 to 2017 in the three major seasons. In each season, an equal number of sampling surveys were carried out in the spring tides and neap tides during which, block nets of mesh sizes 20mm were set across the mouth of the intertidal creeks just before the onset of low tide. Thereafter, the fishes remaining in the emptied creek were identified and recorded. A total of 18 finfish species were recorded belonging to 16 families, of which Polynemidae and Cichlidae were the most speciose. Among the species, *Mugil cephalus, Mystus gulio* and *Dichotomyctere fluviatilis* dominated the overall fish abundance. A closer look at the species composition of these intertidal creeks in Coringa revealed that they are perhaps a smaller subset of the overall fish composition of the Coringa subtidal creek.

Further, the species composition of these intertidal creeks was dominated by marine migrants and estuarine species, with each contributing ~40% of the fish abundance. The freshwater migrant was the next important ecological guild, contributing ~19% to the fish abundances in the intertidal creeks. This was unlike the general pattern in tropical estuaries where marine migrants are significantly more dominant while freshwater migrants are fewer in numbers. However, this could be a result of a lower influence of marine waters, and a higher influence of freshwater due to direct connections with the Godavari River. Lack of the larger marine predators made the conditions more favourable for the estuarine species, leading to greater numbers when compared with other estuaries. Notably, the top five species contributing over 50% to the fish abundance included two estuarine species and two freshwater migrants.

The multivariate analyses revealed the presence of two main seasonal assemblages- the first group specific for the rainy season, and the second group for winter and summer seasons. No major effects of other temporal factors (tides or diurnal cycle) were observed. Spatially, the natural creeks had higher species diversity and evenness than artificial creeks but these differences were not statistically significant. Overall, these results suggest that in case of intertidal creeks, seasons instead of spatial differences are the major driving forces in structuring the fish assemblages. The monsoonal rainfall brings in higher discharge of freshwater into the Coringa creek system, thus lowering the salinity values, and potentially creating favourable conditions for estuarine species than the marine ones.

Perceptions of local fishers towards mangrove conservation in East Godavari River Estuarine Ecosystem (EGREE)

Among the various services provided by mangrove forests, fisheries have direct implications for the local communities. The artisanal fishery practiced inside the Coringa Wildlife Sanctuary and surrounding mangroves provides livelihood to ~44 fishing villages in the region. A semi-structured questionnaire survey was conducted from September 2016 to January 2017 in 417 households across 14 villages directly abutting the sanctuary. The main objective was to estimate the non-use value attached by local fishers through their stated preference for willingness-to-pay a yearly amount to protect and restore the mangroves (and therefore, their fishery) in the region.

During the survey, 92.7% of the respondents agreed to pay an amount for protecting the mangroves. The best-approximating probit model revealed that a person with higher number of years of education, a lower household income, and an awareness of climate change is more willing than others to pay for mangrove protection. Additionally, when asked of their perception of the changing climate pattern in their area, nearly every respondent noticed an increase in ambient temperatures and rise in sea level in the past 10 years, but only 41.7% of the respondents were aware of the concept of "climate change" and its impacts on coastal areas. Results of this study added to the earlier evidences of the positive importance attached by local communities to mangrove forests. However, raising awareness about their vulnerability to drivers of climate change is an essential step to help them in adopting to the future changes.

Recommendations

In order to protect the aquatic ecosystems of the East Godavari district, it is crucial to understand and acknowledge the importance of ecological connectivity between the different coastal habitats. Among other factors, habitat connectivity plays an essential role in driving several ecological processes and flows in the ecosystem. While CWS do provide a crucial refuge for estuarine and juvenile marine fishes, adoption of a holistic approach of sustainability is recommended in EGREE.

The government bodies need to take immediate steps to address the various issues impacting the integrity of EGREE including the proliferation of aquaculture ponds in the region, release of untreated effluents from the aquaculture ponds and other industries, destructive activities such as sand mining, etc. Stocking of non-native fishes in the reservoir, canals or aquaculture ponds in the district should be prohibited, and the fisheries department encourage protection of the native fishes of the Godavari River basin. A minimum buffer should be allowed around the mangrove forests and the creeks, to allow them to maintain their structural integrity and landward shift driven by sea-level rise. Some recommendations for the proliferating aquaculture pond in the district include allowing a minimum gap between the ponds and adjoining mangroves and creeks, stricter monitoring of the ponds to prevent flouting of rules by them, and carrying out a scientific study to assess the carrying capacity of the estuary for the aquaculture industry.

Polavaram Dam will also lead to widespread ecological changes in the estuary. The minimum freshwater flows to the downstream habitats must be ensured by the dam authorities, taking in consideration the river's natural pattern of seasonal variation in freshwater discharge. Based on the results of this thesis, mapping of unprotected and degraded patches of mangroves and coastal water bodies in EGREE is recommended followed by prioritization for focused conservation efforts. Such highly degraded and vulnerable habitats may be declared as 'eco-sensitive zones' or 'community reserves', providing them with minimum protection from future conversions and losses.

It is crucial to garner support of the local communities and other stakeholders, and to focus on their awareness of the climate change impacts on their lives and livelihoods. Regular and focused campaigns would be helpful to improve awareness among the stakeholders including authorities, policy makers, and the various industries of the region. Finally, further inter- disciplinary studies are recommended to understand the different complexities existing at various levels in EGREE including biological, ecological, social, cultural and economic complexities.

Conclusion

CWS is located close to Kakinada city- an important marine fishery centre on the east coast of India. The mangroves of Godavari River (EGREE region) act as an important connecting link between the freshwater and marine ecosystems. Yet the mangroves possess a relatively distinct fish assemblage comprising mainly of euryhaline species. Although these mangrove forests are particularly known to support a productive prawn fishery in the region (Mohan et al., 1997), several finfishes (except the pufferfishes) recorded during our study also have high commercial value and contribute to the artisanal fishery practiced by the locals. Salinity gradients existing within and between the different mangrove lined creeks have been found to be structuring the fish assemblages. Low salinity in certain creeks of CWS allows freshwater and euryhaline species such as *M. gulio* and *O. mossambicus* (a non-native species) to not just establish themselves as residents in the mangroves but also dominate the overall fish abundances.

The preliminary Ecopath model of CWS suggested the fragility of this ecosystem to external factors including the high fishing pressure (mainly due to unregulated fisheries) existing within the creeks, and climate change drivers. Based on the results of earlier studies coupled with my results and observations, the mangroves in EGREE are vulnerable to coastal squeeze and further degradation due to sea level rise.

Considering these threats, the information collected during my thesis, and the studies carried out by Wildlife Institute of India (WII) will serve as a baseline to monitor future changes in the estuarine community of this region.

Chapter 1

Introduction

1.1. Estuaries

Estuaries are transitional coastal zones where freshwater and marine water mixes. They act as a dynamic interface between freshwater, marine, and the adjoining terrestrial ecosystems that may be affected by tides (Wolanski & Elliott, 2015). Several authors including Pritchard, 1967; Dalrymple et al., 1992; Perillo, 1995; Potter et al., 2010 have attempted to define an 'estuary'. Later, Wolanski and Elliot (2016) provided a comprehensive description of estuaries incorporating elements from the previous definitions:

"…an estuary is a semi-enclosed body of water connected to the sea as far as the tidal limit or the salt intrusion limit and receiving freshwater runoff, recognising that the freshwater inflow may not be perennial (i.e., it may occur only for part of the year) and that the connection to the sea may be closed for part of the year (e.g., by a sandbar) and that the tidal influence may be negligible."

The role of estuaries as important habitats for fishes has been well studied and well discussed in the past few decades (Laegdsgaard & Johnson, 1995; Kathiresan & Bingham, 2001; Blaber, 2007). Sheaves (2009**)** propounded estuaries to be a crucial connecting link between the freshwater, coastal, and marine habitats of fishes. The high productivity of estuaries and high input of nutrients makes them rich feeding grounds for various species. For the diadromous species, they provide a gradual transition state, making it easier for the fishes to migrate through varying salinities. However, the role of estuaries as important nursery grounds for fishes has been recognized by many authors to be a crucial one (Blaber & Blaber, 1980; Bell et al., 1984; Robertson & Duke, 1987; Laegdsgaard & Johnson, 1995).

1.2. Mangroves and fishes

Mangroves are among the dominant vegetation of the tropical and sub-tropical estuaries (clubbed as tropical estuaries henceforth); therefore, studies of fish assemblages in most tropical estuaries are invariably linked with mangrove forests (Blaber, 2007). Unique root system of these plants assists them to grow in hypoxic soil conditions and to resist the diurnal fluctuations in the tide. This above-ground root structure along with other structural features of mangroves provide suitable habitats for several organisms including fishes (Nagelkerken et al., 2008). In this regard, three main reasons proposed (Cyrus & Blaber, 1987; Laegdsgaard & Johnson, 1995; Sheaves, 2005a; Blaber, 2007) are: 1) decrease in risk from predation due to structural complexity and turbidity; 2) increased nutrient input; and 3) stable environment for larvae and juveniles.

In terms of species diversity, the tropical Indo-West Pacific region shows the highest diversity with 600 fish species recorded(Blaber, 2007). In some estuaries such as the Embley in Australia (Blaber et al., 1989) and Vellar in India (Krishnamurthy et al., 1984) nearly 200 species have been recorded. At the local scale, the species diversity of fishes in mangroves vary according to the degree of habitat heterogeneity, salinity regime and other hydrological parameters (Blaber, 2007).

India is endowed with a long, indented coastline, dotted with several estuaries. A number of these estuaries, especially the ones at the confluence of large rivers, are mainly lined by mangrove forests. The most notable of the mangrove forests in India is the Sundarbans in West Bengal, which is known for its umbrella species- the Royal Bengal Tiger. Pichavaram in Tamil Nadu, Godavari in Andhra Pradesh, and Zuari in Goa are some of the other important mangroves occurring in India.

Krishnamurthy et al., 1984, reported around 350 species of ichthyofauna from the Indian mangroves; out of this they reported 197 species from the Pichavaram mangroves while 168 from Sundarbans. They also reported 223 species from the Godavari mangroves, which was subsequently updated to a list of over 300 fish species by Krishnan and Mishra (2001). However, most of the studies on ichthyofauna of Godavari estuary either focus on enlisting the number of species or on ecology of one species or taxa. There are still very few comprehensive studies to understand the fish community in an estuary or a mangrove forest in India. The Godavari River basin contributes greatly towards the country's fishery sector, particularly to small-scale fisheries, but a huge knowledge gap exists on the essential ecological processes and the factors driving these fisheries.

1.3. Anthropogenic impacts on estuaries

Coastal ecosystems are one of the most densely populated areas across the world (Small & Nicholls, 2003). Twenty out of 33 megacities that have population over 10 million are situated within 100 km from the sea (Griggs & Reguero, 2021). Rapid urbanization, economic growth, coastal pollution due to sewage discharge and fertilizers run-off, land-use changes into agriculture and aquaculture, extractive industries such as oil and natural gas, sand mining, and overfishing are some of the several ways humans are altering the coastal ecosystems.

Unfortunately, estuaries are among the most vulnerable ecosystems of the world (Elliott & Whitfield, 2011), being impacted by both upstream (river-based) and downstream (marine) threats. At the same time, given the complex nature of estuaries it becomes difficult to differentiate between the direct impacts of climate change and other anthropogenic disturbances due to rapid urbanization and economic activities (Elliott et al., 2019).

1.4. Need for the study

The scenario for the Godavari River basin, more specifically the East Godavari River Estuarine Ecosystem (EGREE), is not quite different from other coastal zones in the country. EGREE is at a tipping point wherein it is constantly being threatened by urbanization and growth in aquaculture on one hand, while on other hand it must adapt to the rising sea surface temperatures and sea level rise. Regulation of freshwater flow by the Polavaram Dam, which will soon be operational, will pose further pressures on the estuary as the river's existing annual discharge pattern gets altered. However, this estuary accrues significant ecological and economic benefits to the local stakeholders such as livelihood sustenance, carbon-sink services, shoreline protection, storm protection etc. EGREE is also rich in coastal and marine biodiversity, home to rare and threatened species including Fishing Cat (an elusive small cat species) and Smooth-coated Otter, and a recognized Important Bird Area (IBA) of the eastern coast of India.

Information on the ecological processes and functions of any ecosystem is crucial for its long-term conservation, and for a dynamic ecosystem like EGREE, it becomes even more important. Considering the different issues, this study was carried out to understand the assemblage patterns of the ichthyofauna of EGREE, and the important ecological processes and factors shaping them, mainly in the mangrove-lined creeks of the estuary. Fishes are an important part of an estuarine ecosystem upon which livelihoods of thousands of fishers are dependent. Any disturbance can bring rapid changes in their assemblage patterns (Whitfield & Elliott, 2002; Breine et al., 2010), and thereby on the fish stocks. Therefore, studying them will also help in assessing the ecological status and resilience of the estuary.

1.5. Literature Review

1.5.1 Ichthyofaunal assemblage structure in estuaries and mangrove creeks

Coastal ecosystems such as estuaries and mangroves are known to support rich and unique biodiversity, which may vary on various scales of time and space. The Indo-West Pacific zoogeographical area is a hotspot for marine and coastal fauna, supporting the highest species richness (around 600 species) when compared with the other zoogeographical areas (Blaber, 2007). This biodiversity decreases latitudinally while moving away from the equator in Southeast Asia. Inger, 1955 was among the first authors to study fish diversity associated with mangroves. Likewise, (Blaber & Blaber, 1980) are perhaps pioneers in contemporary fish assemblage studies of estuaries and mangroves. Other important studies on ecology of fish communities associated with estuaries and mangroves have been conducted in Brazil (Barletta et al., 2003; Barletta & Saint-Paul, 2010) and Australia (Blaber et al., 1989; Laegdsgaard & Johnson, 1995; Laegdsgaard & Johnson, 2001a).

In the mangrove estuaries, most ubiquitous fishes would be the gobies (Gobiidae family), which are represented by around 110 species (Krishnamurthy & Jeyaseelan, 1984). However, estuaries provide habitats for several other fish species including those having high commercial value. With high species diversity, characterizing Indo-West Pacific estuarine fishes into a single general assemblage structure would be futile since many species are restricted to a few regions or certain basins; on the other hand, species such as *Mugil cephalus* have circumtropical distribution (Blaber, 1997; Laroche et al., 1997), and may occur in majority of the coasts and estuaries. Blaber (1997) gives examples of some species commonly found across the Indo-West Pacific zone, which include *Ambassis gymnocephalus, Caranx sexfasciatus, Elops machnata, Gerres filamentosus, Leiognathus equula, Terapon jarbua, Platycephalus indicus,* and *Sillago sihama*. In case of Indo-Malayan mangroves, (Krishnamurthy & Jeyaseelan, 1984) noted that carnivorous fish families like Ariidae, Polynemidae, Pomadasiydae and Sciaenidae are common with 56 species being recorded. The diversity is more in case of the mangroves of Indian Ocean than those of Pacific Ocean, possibly due to greater discharge of freshwater (Krishnamurthy et al., 1984) from huge river basins of Ganges, Godavari etc.

Mangroves in India are home to over 3000 faunal species, making them the most diverse mangrove systems of the world (Kathiresan et al., 2015). Despite this, very few Indian studies have focused attention on studying the ecology of fishes in mangrove creeks. Only since the last few years, authors have begun to give greater consideration in this regard. Some important works include those by Sreekanth et al. (2020) in Mandovi-Zuari estuaries in Goa, (Roshni et al., 2021) in Vembanad estuary;

Bijukumar & Sushama (2000) in Ponnani, and Mohanty et al. (2015) in Chilika Lake. Nevertheless, information about estuaries of eastern coast still appears to be sparse and limited to a few sites.

Generally, the fish assemblage of an estuary is usually composed of varying proportions of marine, estuarine, and freshwater species. The earliest works on classifying estuarine fishes were mainly based on studies limited to temperate regions of Europe and America (Blaber, 1997). Day et al. (1981) attempted to develop a classification system which would be universal in nature. In recent times, use of functional guilds to classify fish diversity in estuaries has gained importance. Elliot and Dewailly (1995) proposed 29 functional guilds for 186 estuarine species under various categories such as ecological types, vertical distribution, diet preferences, etc. Under the ecological guilds, they identified six groups *viz*. ER or Estuarine Resident (those species which spend their entire life cycle in the estuary), MA or Marine Adventitious (irregular presence in the estuary with no apparent requirements), CA which includes all Diadromous migrants, MS or Marine Seasonal (seasonally visiting species to the estuary), MJ or Marine Juvenile which use the estuary as nursery or spawning ground, and FA or Freshwater Adventitious (freshwater species which occasionally enters estuary with no apparent requirements). Potter et al. (2015) modified this classification, and proposed four categories, each consisting of multiple guilds six functional groups in an estuary.

Another defining aspect of estuarine fish assemblages is their diel and seasonal variability. Coastal estuaries like mangroves are highly unstable in terms of their physico-chemical properties. Due to the tidal influence, the water may enter the mangroves and intertidal creeks during high tide while they may get partially or completely flushed during ebb tide. Several species tend to move with the tidal waters into the mangrove creeks and move out into the main channel or Bay with the receding tide (Robertson & Blaber, 1992). Similarly, seasonal variations in the physico-chemical parameters can also bring about changes in the fish assemblage of an estuary. Davis (1988) studied the temporal changes in fish fauna of a tidal swamp in Australia and found that the species composition varied between late dry, early wet, and late wet seasons. He noted that the movement of fishes into the estuary was linked more to their breeding requirements than on salinity or temperature. In one study in a tropical mangrove forest of Madagascar, Laroche et al. (1997) found the fish species richness, abundance, and biomass to be lower during winter months because of reduced availability of some benthic shrimps. In a similar study of mangrove creeks of Caete estuary in Brazil, (Barletta et al., 2003) found significant differences in total fish biomass across the seasons but a stable species composition. The author also observed that the fish assemblage in the main channel and intertidal creeks was concentrated in the lower estuary during the rainy season, a phenomenon which had also been reported by Blaber et al. (1989). They believed that this could possibly be due to indirect influence of rainfall, reproduction, and recruitment of estuarine, marine, and freshwater species.

Though the seasonal distribution of fishes in tropical estuaries might be influenced by food availability or breeding patterns, salinity in combination with other factors plays an important role in structuring the fish distribution (Barletta et al., 2008). Most tropical estuaries experience a dry season when a well-defined salinity gradient develops in the estuary with lower salinities in the upper estuary and higher salinities (>25 psu) in lower parts. And during rainy season, due to heavy discharge of freshwater, the entire estuary experiences lower salinities enabling certain freshwater species to enter (Barletta et al., 2008; Barletta & Saint-Paul, 2010).

In Vellar estuary in the eastern coast of India, (Murugan et al., 2014) found significant seasonal variations in species diversity of fishes, possibly influenced by monsoons. Roshith et al. (2013) in Hooghly estuary also detected significant differences in the different community variables, and deduced the role of monsoonal floods in structuring the fish assemblages. Recent studies by Sreekanth et al. (2020) in Goa's estuaries, and by Roshni et al. (2021) in Vembanad lake, Kerala also found salinity to be an important factor governing the fish assemblage structure, which can be linked to the seasonal rains experienced by the Indian subcontinent. Sreekanth et al. (2020) also compared four estuaries in the western coast, and suggested a positive role of mangrove cover in determining fish diversity.

1.5.2 Habitat complexity of mangroves

Habitat heterogeneity and architectural complexity in an ecosystem is essential for its ecological functioning (Ryder and Kerr, 1989; Peters and Cross, 1992). Studies on coral reefs and seagrass habitats have indicated a possible influence of habitat complexity in structuring the fish communities and other invertebrates (Luckhurst & Luckhurst, 1978; Rozas & Odum, 1988; Jenkins & Sutherland, 1997). In similar ways mangroves, through factors including their root structure, pneumatophore density, overhanging vegetation, shade availability, and depth, can influence species assemblages (Thayer et al., 1987; Nagelkerken et al., 2010; Vorsatz et al., 2021). The emerging or overhanging roots also harbour several other organisms such as algae, barnacles, tunicates, crabs, and gastropods etc., which not only act as prey for the fishes but can also bring about further modifications in the root microhabitats of mangroves (MacDonald and Weis, 2013). Field studies on role of mangrove microhabitats in fish community are few and employ a wide variety of sampling techniques, ranging from visual observations to modified trap nets, stake nets (Robertson & Duke, 1987; Thayer et al., 1987; Adams & Tobias, 1999; Rönnbäck et al., 1999; Zhang et al., 2019). Hence it is difficult to compare their results and generalize the patterns in fish assemblage.

In a study of mangrove prop root habitats, (Adams & Tobias, 1999) employed 2 different sampling methods- baited fish traps and visual transects. Most common families in case of both the sampling techniques were Gerreidae, Lutjanidae and Pomadasyidae. They also found that the fish composition was dominated by juveniles. Another important study of mangrove root habitat was carried out by Rönnbäck et al. (1999), where they also discussed the sampling strategies for assessing mangrove root-microhabitats. They used stake nets for sampling four different habitats with pure stands of *Avicennia* spp. and *Rhizophora* sp., and found that the fishes preferred the pneumatophores of *Avicennia* than the prop roots of the latter. They also found the highest fish abundance and biomass in the more inland habitats, which is in contrast with an earlier study by (Vance et al., 1996).

1.6.3 Trophic linkages in a mangrove ecosystem: Role of fishes

To study the ecological role of an organism, it is futile to study them as a discrete entity of the ecosystem. As part of the natural order every living organism are interrelated to each other in form of a complex process of energy transfer from one trophic level to another. Thus, to study the important factors governing the fish assemblage patterns and their resource utilization, it is essential to study their relationship among each other as well as with other taxa present in the ecosystem. As it is true for other organisms, success of a fish species will depend on how efficiently it utilizes the available resources (such as food, space, time etc.) in presence of other competing organisms. This is known as resource partitioning (Toft, 1985).

In his study on resource partitioning in animals, (Schoener, 1974) postulated that if the number of species increases in a species assemblage, the different species must either segregate along more resource dimensions or decrease their niche breadth. The author found that for most metazoans niche segregation on basis of habitat is most important when compared to food resource or temporal resource. But in case of fishes, (Ross, 1986) found that segregation based on food i.e., trophic segregation was more pronounced than habitat segregation, especially in a fluctuating coastal ecosystem like mangroves where habitat availability may be temporally and spatially limited (Perkins, 1974). Estuaries are greatly subsidized ecosystems with external transfer of nutrients and energy in form of nutrient import from freshwaters mainly during floods (Day et al., 2012), export of mangrove nutrients to adjoining coastal and marine habitats during ebb tide (Alongi, 1996) or by migrating fishes and other aquatic organisms (Sheaves & Molony, 2000), input of mangrove litter and debris in the tidal channels, etc. This makes the estuaries highly productive ecosystems (Costanza et al., 1997).

Ross (1986) noted that fishes are difficult organisms to study for resource partitioning since they exhibit variable preference for food items at different life stages. As juveniles they may depend more on planktons, which they may outgrow of as they increase in size. Similarly, changes in habitat may result in changes in food patterns (Sheaves, 2009). Therefore, in a highly variable habitat like mangroves, the food of a fish species might change with the tides as well as along seasons. Important theories such as member-vagrant hypothesis (Sinclair & Iles, 1989) and match-mismatch hypothesis (Cushing, 1990) emphasize the importance of connectivity between spawning and nursery grounds of fishes, and between juveniles and their prey. In this context, roles of estuaries and mangroves as part of the Coastal Ecosystem Mosaic (Sheaves, 2009), and as nursery grounds of fishes becomes vital (Robertson & Duke, 1987).

1.6. Objectives

Following are the objectives of the proposed study:

1. To study the spatio-temporal changes in fish assemblage across the different habitats in East Godavari Riverine Estuary Ecosystem (EGREE)
2. To study the trophic ecology of ichthyofauna in East Godavari Riverine Estuary Ecosystem (EGREE).
3. To study the role of mangrove forests in structuring the ichthyofauna in Coringa Wildlife Sanctuary.

1.7. Thesis overview

The thesis is organized into seven chapters.

Chapter 1: provides a background to the importance of tropical estuaries and mangroves in shaping fish communities and supporting small-scale fisheries. It sets out to review the existing literature on the ichthyofaunal assemblages in estuaries and mangroves, particularly in the Indo-pacific region including India. Various other aspects of fish communities within mangrove forests are also reviewed in this chapter.

Chapter 2: describes the study area in the Coringa mangroves located in the East Godavari River Estuarine Ecosystem (EGREE), giving details of the landscape, geographical setting, dependence of local communities, and major stressors present in the landscape.

Chapter 3: gives a brief overview of the general spatial and temporal changes recorded in fish communities studied across the different mangrove forests and tropical estuaries of the world. It then discusses the methods adopted to carry out this study in the mangrove habitats of EGREE and the results of the same.

Chapter 4: discusses the emergence of the Ecosystem-based approach for fisheries management. Further the chapter discusses the importance of studying the trophic ecology or trophodynamics of ichthyofauna in estuaries, which helps to expand the knowledge base on the ichthyofauna of mangroves so as to minimize the harmful impacts of overexploitation on the fisheries as well as on the overall ecosystem. The methods to develop an ecosystem model of Coringa Wildlife Sanctuary.

Chapter 5: gives the details of the methods on and preliminary results of the study to understand the role of different mangrove types (based on the management systems- artificially created creeks with natural, intact mangrove-lined creeks) in shaping the fish communities at smaller scales within the intertidal creeks.

Chapter 6: gives details of the methods on and the results of the study to assess the perspectives, attitudes of local fisher communities on mangrove conservation in EGREE.

Chapter 7: concludes the thesis with a brief discussion on the main outcomes along with the conservation implications and recommendations.

Chapter 2

Study area

2.1 Location and topography

The Godavari River is the second longest river and one of the major rivers in India with a watershed area of more than 14,000 sq.km (Figure 2.1). The river originates near Triambakeshwar, Nasik in Maharashtra and flows into Bay of Bengal at East Godavari district of Andhra Pradesh after traversing around 1456 km. From its origin to its confluence with Bay of Bengal the river travels through some of the fossil rich areas of Deccan traps, Central Indian grasslands, mineral rich Eastern Ghats, alluvial flood plains and East Coast teeming with unique marine life. Throughout its course it gets ample water from tributaries like Waingangā, Pedhavagu, Pranahita, Indravathi, Sabari, Sileru. After traversing a distance of 1465 kms, it empties to sea in form of two major distributaries namely Vasista-Godavari and Gouthami-Godavari rivers. Godavari River has a drainage basin of 310,000 km^2 (Rao et al., 2010), and is one of the most turbid rivers of the world, particularly during monsoon seasons (Syvitski & Saito, 2007). The sanctuary (237.5 sq.km) lies at 16°59’-16°44' N, 82°15'-82°20'E in the northern parts of the delta formed by Godavari River at its confluence with Bay of Bengal (Figure 2.2). These mangrove forests also have global importance as they are part of the Central Asian Flyway and have been declared as an Important Bird and Biodiversity Area (IBA) (Ramasubramanian et al., 2006; Rahmani and Islam, 2016).

This ecosystem encompassing the Godavari mangroves is the second largest area of mangroves along the east coast of India after the Sundarbans.

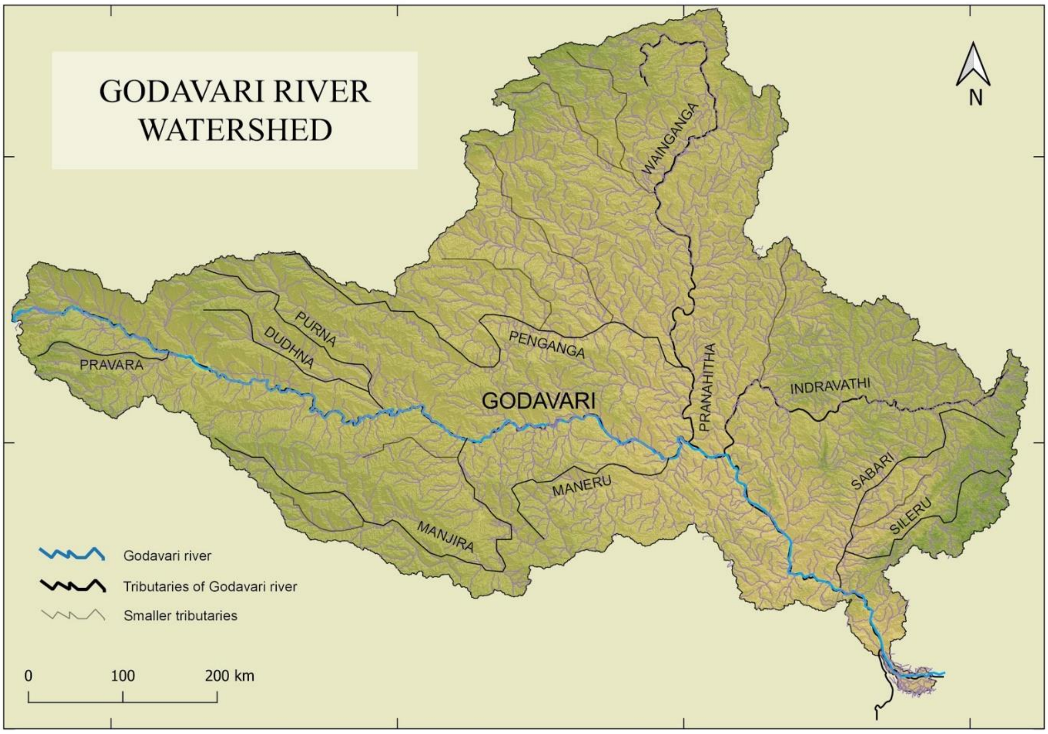


Figure 2.1. Watershed map of the Godavari River Basin including the main tributaries

EGREE is a highly dynamic landscape. Due to the high sediment load from Godavari River and frequent cyclones, this landscape continually undergoes changes. Studies have shown that after 1889 the river has changed its main course from Kakinada Bay in north to its present mouth near Bhairavapalem village. Similarly, the sand spits present along the Kakinada Bay and at the mouth of the river also keep changing in their morphology and length. The sand spit along the Bay, known as Hope Island, has increased from its small size in 1864 to a 17 km-long spit now. Hope Island provides natural shelter to the mangroves and villages along the Bay and has allowed the establishment of a major fishing harbour as well as Kakinada Port, thereby having high economic value for the region. However, extensive patches of mangrove forests are the main features of this landscape. After the Sundarbans in West Bengal, the Godavari mangroves of EGREE are the largest mangrove forests in east coast of India.

The delta is characterized by different types of habitats including mangroves and riparian forests, riverine sandbars, open mudflats, sand spits and an extensive lagoon termed as "Kakinada Bay" towards the north. The region receives an average precipitation of 1000-1100 mm/year and has two monsoon seasons from June to August and September to November. The summers are extremely hot with temperatures above 40°C and experience extended heat wave conditions, while the winters are mild with minimum temperatures from 17 °C to 19°C. The study area has mostly semi-diurnal tidal cycle with a mean annual tidal amplitude of 0.36m to 1.38m (Dehairs et al., 2000; Rao et al., 2015). The mangrove forests of Coringa WLS are dominated by *Avicennia marina*, *Avicenna officinalis* and *Excoecaria agallocha*. The creeks at many places are also lined by dense patches of mangrove-associates such as thorny shrub *Acanthus illicifolius* and grass species like *Myriostachya wightiana*. Three major subtidal creeks namely Thulyabhaga, Coringa and Gaderu flow across the sanctuary dividing it into different zones. The southern part of the delta also has mangrove patches but with a lower degree of legal protection and higher anthropogenic influence. The mangroves of Godavari delta have been estimated to be providing ecosystem services of nearly 90,000 USD/annum to the local communities (Dehairs et al., 2000).

This study was conducted between June 2014 and May 2017 in the mangrove forests of Coringa Wildlife Sanctuary (hereafter CWS), which is a protected area located in the state of Andhra Pradesh, at the eastern coast of India (Figure 2.3). The total area of Godavari delta, according to the Forest Department is 316 km^2, of which 235.7 km^2 is under the Coringa Wildlife Sanctuary (Sivakumar et al., 2017). The sanctuary has three Reserve forests (RF) – Corangi, Corangi Extn and Bhairavapalem. The other six reserve forests - Rathikalava, Masanitippa, Malatippa, Balusitippa, Kothapalem and Kandikuppa are an extension of the Coringa Wildlife Sanctuary. Coringa Wildlife Sanctuary is named after a tiny village "Korangi" and is located between 16°44' to 16° 53' N and 82° 14' to 82° 22' E in East Godavari District of Andhra Pradesh. The mangrove forests of this region were among the first 17 regular reserve forest blocks declared in Madras presidency on 1st January 1883 when Madras Forest Act came into force following which any type of felling was stopped inside the mangroves (Management Plan Coringa Wildlife Sanctuary, 1993). To enhance protection, it was subsequently declared as "Coringa Wildlife Sanctuary" under sec. 18 of the Wildlife Protection Act 1972 (Central Act No. L III of 1972) through G.O.Ms.No. 484 Forests and Rural Development (For.III) Department in 1978. Coringa Wildlife Sanctuary now spans across an area of 235.70 sq. km.

2.2 Climate

The Coringa Wildlife Sanctuary and the surrounding areas experience typical coastal climate with high humidity, often above 80% and a mean annual temperature of 25^{o} C. Summers are extremely hot and humid whereas light winter ranges from November to February. The region experiences two monsoon seasons: Southwest monsoon extends from July to October while the Northeast Monsoon occurs from October to November.

2.3 Hydrology

Godavari River branches into two rivers named as Vasista and Gauthami near Dowlaiswaram, of which the Gauthami branch flows in eastern direction and opens into Bay of Bengal at two places, namely Bhairavapalem and Kothapalem villages. The Gauthami River is also connected to Kakinada Bay by two major channels namely, the Coringa River arising at Yanam and the Gaderu River arising at Bhairavapalem. There are many other channels and creeks such as Chollangi creek, Matlapalem channel and many other creeks which ultimately flow into the Kakinada Bay in the northern part of the sanctuary or join the two main channels i.e., Coringa and Gaderu, which cut across the entire sanctuary and ultimately join the sea. Vashista branch of Godavari flows south-east and gets divided into two branches namely Vashista and Vainateyam and opens into Bay of Bengal at two places namely Antarvedi and Karawaka near Gogannamatam and Odalarevu respectively. Near the confluence (Karawaka) muddy and swampy regions exists, harbouring the mangrove and halophytic vegetation from Karawaka to Gogannamatam. In Gogannamatam on either side of the river some muddy platforms occur, which harbours both mangrove and halophytic vegetation. Height and growth of the mangroves are reduced towards the Gogarnamatam. The Godavari empties large volume of fresh water, loaded with sediments, flows through a number of distributaries into the Godavari delta (Rao et.al 2010).

The river Godavari originates near Nasik, Maharashtra, and travels 1465 km before flowing into the sea near Bhairavapalem village. As it enters the state of Andhra Pradesh it meanders through the steep valleys of Eastern Ghats, finally emerging into a vast flood plain after Polavaram village in West Godavari district. It then branches into two distributaries named as Vasistha and Gouthami near the Dowlaiswaram Barrage. The Gouthami River flows in eastern direction and meets the Bay of Bengal at two places, namely Bhairavapalem and Kothapalem villages. Similarly, the Vasistha River flows slightly in the south-eastern direction and drains into the sea at Antervedi and Odalarevu village. This project mainly focused on the Gouthami River and its distributaries. Godavari River empties huge amount of water each year into the Bay of Bengal. This large volume of fresh water, loaded with silt and sediments, flows through many distributaries into the Godavari delta (Rao et al., 2010). River flow peaks during the months of August and September that also corresponds with the south-west monsoons in India, while discharge is very low in the dry season from January to May.

The two of the major rivers or creeks of CWS include:

Coringa River: This is a small river originating at the town of Yanam and enters the sanctuary area near Coringa village. It travels north to join the Kakinada Bay. Since it receives freshwater from Godavari River, salinity is relatively low but increases towards the mouth near Kakinada Bay. Major part of this river flows through the town of Yanam and other villages. Number of industries such as lime and cement manufacturing units, boat construction units and aquaculture ponds are also present along its banks. Therefore, anthropogenic influence on this river is higher than Gaderu.

Gaderu: Gaderu river arises about 5 Km below Yanam, near Bhairavapalem village. It enters the sanctuary at the southern tip and nearly bisects the sanctuary into two. It also travels north and ultimately joins the Kakinada Bay. There are smaller sub-tidal and inter-tidal creeks that originate from this river and meet the Bay of Bengal. Salinity in this channel and its creeks are relatively higher than other creeks of CWS due to the direct connection with sea at several points. A locally important landing centre for both estuarine and marine fishes is present at Bhairavapalem village along this river. The entire sanctuary is tide-influenced with two cycles of high and low tides. During high tide water flows from north to south through Gaderu and Coringa, enters the sanctuary submerging the mudflats through the innumerable network of creeks. In the spring tides, several parts of the mangrove forests also get submerged especially in the monsoon season. During low tide, water drains out from the sanctuary from south to north direction exposing the mudflats situated in western and southern parts of the Bay. In simple words, the drainage can be described from North to South during high tide and from South to North during low tide through the two major rivers Gaderu and Coringa.

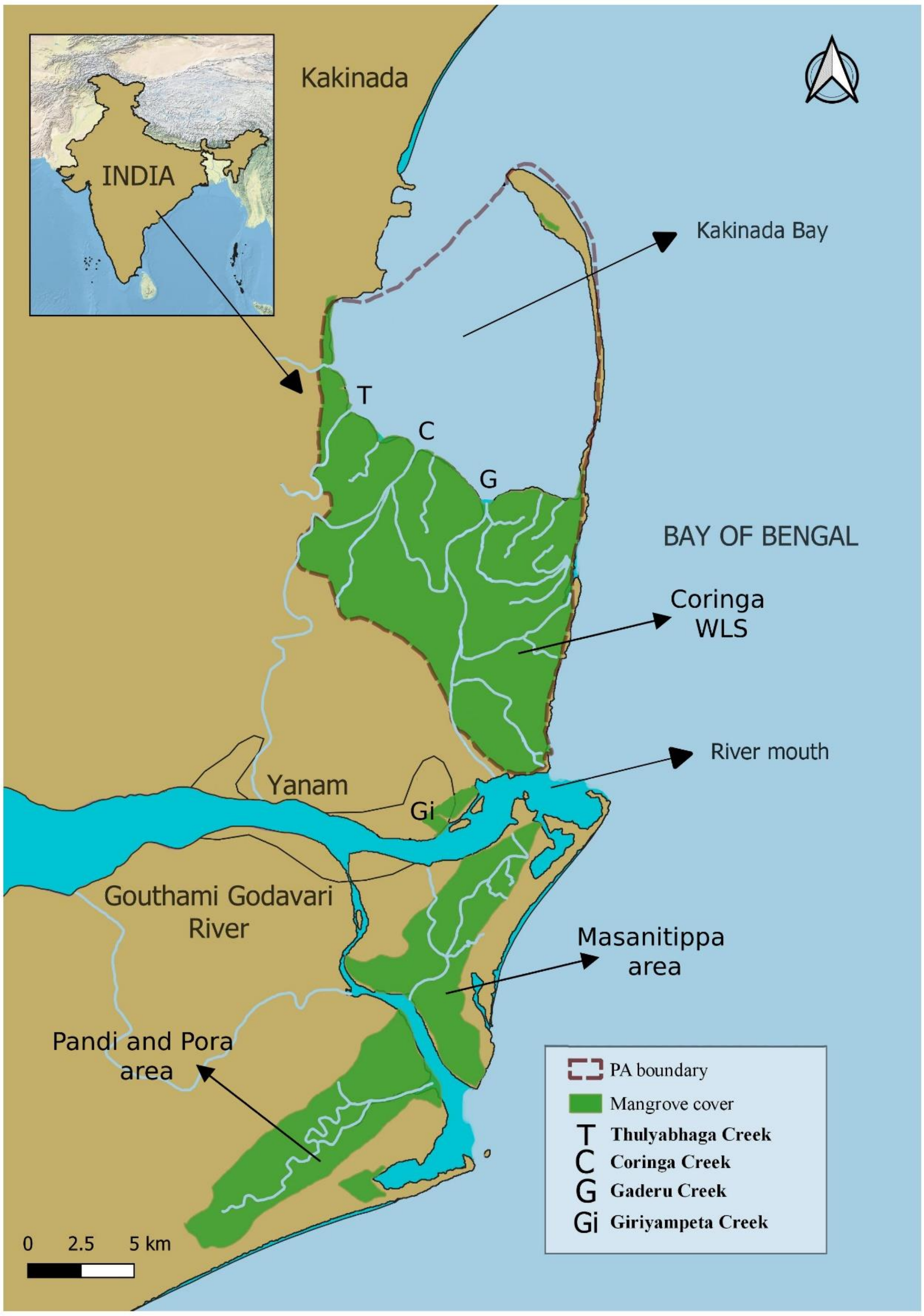


Figure 2.2. Map showing the location of Coringa Wildlife Sanctuary (CWS) and other mangrove patches in the East Godavari district, Andhra Pradesh, along with all the major subtidal creeks draining the sanctuary.

2.4 Flora

The sanctuary itself has a long history behind it. Since 1893, the mangrove forests of this region were subjected to heavy exploitation to meet local demands of fuel wood. The area was under working from 1893 till 1978 (almost for a century continuously) by the Forest Department without any standards or proper scientific protocols. In addition, dependence of heavily populated villages and cities on the mangroves led to heavy felling and grazing which also added to widespread habitat degradation and fragmentation. Coringa was one of the first 17 regular reserve forest blocks declared in Madras presidency on 1st January 1883 when Madras Forest Act came into force. Therefore, for more than 100 years the forests of Coringa Wildlife Sanctuary are being protected. Subsequently, any type of felling was stopped inside these mangroves. Later in 1978 to further enhance protection, it was declared as "Coringa Wildlife Sanctuary". Coringa Wildlife Sanctuary comprises 235.70 sq.km of mangrove forests in EGREE.

The mangrove forests of the Godavari delta are inter-tidal, dominated mainly by *Avicennia marina*, *Avicenna officinalis*, *Excoecaria agallocha*, *Rhizophora mucronata, Ceriops decandra*, *Sonneratia apetala, Sonneratia caseolaris and Xylocarpus granatum.* In addition, mangrove associates like *Acanthus ilicifolius, Derris trifoliata, Myriostachya whightiana*, *Caesalpinia crista, Ipomoea tuba, Hibiscus tiliaceus, and Thespesia poulneoides* were also commonly recorded along the creeks of the sanctuary and other mangrove areas of the delta. As per earlier reports, there are 35 species, of which 16 are true mangroves, and the rest are associated mangrove species. This includes one nearly threatened species (*Ceriops decandra*) and three rare species. *Ceriops decandra*, a Near Threatened species (IUCN), has been flowering and fruiting throughout the year, while for the three *Avicennia* spp., flowering was observed between April and August.

2.5 Fauna

In terms of faunal diversity this ecosystem is highly blessed. It is an Important Bird Area (IBA), with a recorded population of 236 bird species, of which 88 are migratory, including several that are threatened. More than 20,000 waders use this area in a year. Places such as Sacramento Island, Hope Island, Masanitippa, Yellayapeta serve as important nesting sites for migratory turtle species, notably the endangered Olive Ridley turtle and green turtle. Mangroves of Godavari delta are also home to one of rare and elusive cats- the Fishing cat *Prionailurus viverrinus*. In addition to that, Smooth coated otters *Lutrogale perspicillata* are also present in good population. Golden Jackal, Palm civet, Rhesus macaque are other mammals present in the mangrove forests and surrounding areas. The rich aquatic fauna is the mainstay of this region which is evident in the fact that it is one of the important fishing grounds in the eastern coast of India. In a survey by Zoological Survey of India in 2001, around 2 species of sponges, 6 species of jelly fishes, 29 species of polychaetes, 21 species of crabs, and 64 species of molluscs were reported. In addition, the same report listed around 314 species of fishes from the region.

2.6 Socio- Economic Status

These mangrove forests support a population of more than 79,400 people belonging to 44 mangrove-abutting villages. These villagers, mostly who are traditional fishers, are directly dependent on the mangroves for their livelihoods as well as for firewood, fodder, and timber. Other villages and cities situated in the East Godavari district are also indirectly dependent on the mangroves due to the immense ecological services provided by this ecosystem. These fishing communities majorly use the mangroves for their artisanal fishing (Figure 2.4). These mangroves are rich in crustacean, molluscs, finfish, bivalves, and gastropods, which also provide an alternate source of livelihood for the fishermen and villagers. Kakinada bay, which is rich in bivalve resource like *Anadara granosa, Placuna placenta, Meretrix meretrix* etc are used in lime making and are transported to other states for ornamental making. Associated mangrove *Porteresia coarctata* grass is used as fodder and the *Myriostachya wightiana* is used as thatching material (Figure 2.5), while the bark of *Ceriops deccandra* is used for colouring the fishing nets.

2.7 Threats

In the last few decades this region has witnessed rapid economic changes and emergence of large-scale production activities. Currently the main production sectors operating in the landscape/ seascape are fisheries, aquaculture, salt pans, manufacturing activities such as, oil and gas exploration, fertilizers, edible oil, rice products, tourism, and ports. In addition, dependence of heavily populated villages and cities on the mangroves and over-exploitation of the natural resources are also cause for widespread habitat degradation and destruction in EGREE. Climate change is also an imminent threat to this highly vulnerable ecosystem. The four main drivers viz. increasing temperatures, sea level rise, rise in salinity, and ocean acidification have the potential to drastically change the dynamics of the ecosystem and its associated flora and fauna. Since the local community is so inherently dependent on the estuary and mangroves, any impacts on them will have profound impacts on the local community too. With this background the current study focuses on studying the impacts of climate change as well as other threats on EGREE and subsequently to develop a conservation strategy and adaptation and mitigation plan for the region.

In order to fill the huge blank areas inside CWS, Forest Department has been resorting to artificial regeneration of mangrove species since 1991 (Sivakumar et al., 2017). With the assistance of M.S. Swaminathan Research Foundation and the local communities, large parts of Coringa Wildlife Sanctuary have since been restored successfully using the fishbone technique. Additionally, 20 eco-development societies were also constituted to involve the local villagers in preserving and protecting the flora and fauna of CWS. A tourist facility also exists which plays an important role in disseminating the role and values of these mangroves to the local people and other tourists. However, the Forest Department is faced with huge challenges to protect CWS in face of the increasing pressures from the aquaculture industry and increased urbanization of the surrounding cities. The high dependence of the local communities on these forests for food, fuel wood and subsistence often lead to conflicting situation with the Forest Department. These problems are magnified by the severe shortage of protection and frontline staff, and lack of modernization in the department.

Figure 2.3. Glimpse of a mangrove patch within the Coringa Wildlife Sanctuary, Andhra Pradesh.

Figure 2.4. Local fishers practising small scale fishing within the mangrove-lined creeks of East Godavari River Estuarine Ecosystem (EGREE).

Figure 2.5. A traditional hut in a village adjoining the mangroves of Coringa Wildlife Sanctuary; *Myriostachya wightiana*, a mangrove associate species has been used as a thatching material for the roof.

Chapter 3

Spatial patterns in the fish community of sub-tidal creeks in a protected mangrove forest of Godavari River, India

3.1 Introduction

Mangroves are important habitats for fishes and play an important role in the fisheries of a particular region. They are often considered nursery habitats for several offshore and reef fish species (Laegdsgaard & Johnson, 2001; Mumby et al., 2004; Igulu et al., 2014). Fishes also use mangrove habitats for refugia (Robertson & Duke, 1990), feeding (Sheaves, 2005; Lugendo et al., 2006), as well as safe transitory passages during migration (Islam & Wahab, 2005). However, the relative importance of these unique coastal forests as fish habitats are still debated; while certain studies link the presence and extent of mangrove forests with fishery production (Kathiresan et al., 2001; Sukardjo, 2004; Anneboina & Kavi Kumar, 2017) but many other studies show mangroves are equally, if not more, important than other shallow-water coastal habitats (Laroche et al., 1997; Blaber, 2007). Regardless of these apprehensions, the role of mangroves and associated intertidal habitats in the subsistence of artisanal fishers cannot be ignored, especially in areas where they are the dominant coastal features.

India has a long coastline of around 7516 km, and 4740 km^2 is occupied by mangrove forests (Nayak, 2017; Kathiresan, 2018). Although they occupy a proportionally small area in the large coastal landscape of India, they provide innumerable ecosystem services, both locally and regionally. Mangroves in India, particularly those located on the eastern coast, are considered among the most diverse and speciose worldwide (Kathiresan, 2018). Since the tsunami in the Indian Ocean in 2004, their protective and mitigative role during events of a tsunami or cyclones have been well documented (Badola & Hussain, 2005; Dahdouh-Guebas et al., 2005; Kathiresan & Rajendran, 2005; Marois & Mitsch, 2015). Similarly, the contribution of mangroves to the local fishery resources has also been studied in different mangrove forests of India (Anneboina & Kavi Kumar, 2017; Kandasamy & Bingham, 2001; Kathiresan & Rajendran, 2005).

Studies on various estuaries point toward the immense diversity of fish fauna in Indian estuaries (Krishnamurthy and Jeyaseelan, 1981; Mukherjee et al., 2013; Ramanujam et al., 2014; Sreekanth et al., 2020; Roshni et al., 2021). However, only a few studies in India have focused on understanding the ecological patterns of fish community or factors that determine these patterns in estuaries or shallow coastal habitats (example- Nandan et al., 2012; Mukherjee et al., 2013; Sreekanth et al., 2020; Roshni et al., 2021). Most tropical estuaries experience a dry season when a well-defined salinity gradient develops in the estuary, with lower salinities in the upper zones and higher salinities towards the mouth. Usually, this gradient drives the spatial and seasonal structuring of the fish assemblage in an estuary (Barletta et al., 2005a). Other factors, including turbidity, water temperature, habitat heterogeneity, and tidal and diel regimes, have also been found to influence the estuarine fish community (Blaber, 2007). Nevertheless, identifying the assemblage patterns of fish community and the factors influencing those patterns, therefore, brings about a better understanding of the complex system of estuarine habitats such as mangroves.

Coringa Wildlife Sanctuary is a protected mangrove forest located at the confluence of the Godavari River with the Bay of Bengal on the eastern coast of India. The mangrove-lined creeks of this estuary are known to support an artisanal fishery based on different prawn species (Mohan et al., 1997), but not much information exists on the ichthyofaunal diversity of this mangrove forest. Therefore, in the present study, we aim to identify the species composition and variations in fish assemblage in the major sub-tidal creeks of the sanctuary. We ascertain if there exist any spatial and seasonal patterns in the species community variables and assemblage of fishes in these sub-tidal creeks. Subsequently, the role of different environmental factors (particularly salinity) in structuring the fish assemblages of the mangrove forest is also examined. Finally, the conservation status and threats to the fish community of the sanctuary are discussed.

3. 2 Methodology

3.2.1 Sampling design

3.2.1.1 Sampling for Phase 1

I divided this study into two parts – Phase 1 and Phase 2. In phase 1 of the study, I sampled 52 sites between 2014 and 2017 to create a checklist of finfish species occurring in the Gautami-Godavari Estuary of the East Godavari district or the EGREE region. Among these 52 sites, 28 were located within mangrove creeks of Coringa Wildlife Sanctuary (CWS; Figure 3.1), 16 were in the riverine part of the estuary, and eight were located in the Kakinada Bay. Additional surveys were carried out at the local fish markets and landing centres, including the Kakinada fish market, Yanam fish market, fish landing centres abutting Coringa Wildlife Sanctuary (CWS) and Kakinada Bay.

Within CWS, fish were collected using locally available trammel nets and gill nets, which were set perpendicular to the water flow, usually for 1 hour during low tides. In the case of intertidal creeks, block nets were placed at the creek entrance at the beginning of low tide. The fishes remaining within the blocked creek were collected before the onset of the next high tide. Since sampling was conducted inside a protected area, only unidentified specimens were collected for further identification in the laboratory. On a few occasions, specimens were collected opportunistically from fishers' catches from the mangrove creeks, Bay or the river mouth.

Identifications were made using the FAO fish catalogue (Fischer and Whitehead, 1974; Fischer and Bianchi, 1984) and other taxonomic keys available for the region (Day, 1888; Jayaram, 2010). The correct taxonomy of the species was updated in accordance with the California Academy of Sciences' online repository, the Catalog of Fishes (Eschmeyer et al., 2018). The threatened status of each species recorded during my study was identified based on the latest IUCN Red List of Threatened Species (IUCN 2021).

3.2.1.2 Sampling for Phase 2

The main objective of the phase 2 sampling was to study the community structure of fishes in the mangrove creeks of EGREE. For this, 27 sampling sites were identified located in four large sub-tidal creeks inside Coringa Wildlife Sanctuary (CWS) (Figure 3.1). Gaderu creek, the largest of the four creeks, is connected to the sea on the eastern side through numerous smaller sub-tidal and intertidal creeks. Coringa and Thulyabagha creeks are connected to the Godavari River through channels and canals in the south while draining into the Kakinada Bay in the north. The fourth creek – Giriyampeta, is directly connected to the Godavari River and is closely located near the confluence of the Gautami-Godavari River with the Bay of Bengal. The latter three creeks have no direct connections with the sea. The width of the four creeks ranged from 48 to 110 m in Thulyabhaga, 65 to 112 m in Coringa, 156 to 400 m in Gaderu, and 20 to 97 m in Giriyampeta.

In this phase 2 of the study, fish sampling was conducted at each of the 27 sampling sites between December 2014 to November 2015, accounting for three major seasons, *viz*. Winter (December to February), Summer (April to June), and Rainy (July to November). Fishes were sampled using a locally available trammel net, a passive fishing gear consisting of three layers of netting, with the middle net having a mesh size of 25.0 mm, whereas the outer two nets had a mesh size of 60.0 mm. Due to the entangling and pocketing effect, trammel nets can catch various species belonging to different size classes (Gabr & Mal, 2016). In Coringa Wildlife Sanctuary, artisanal fishers mainly use this type of a net in the mangrove-lined creeks and canals to target estuarine fishes.

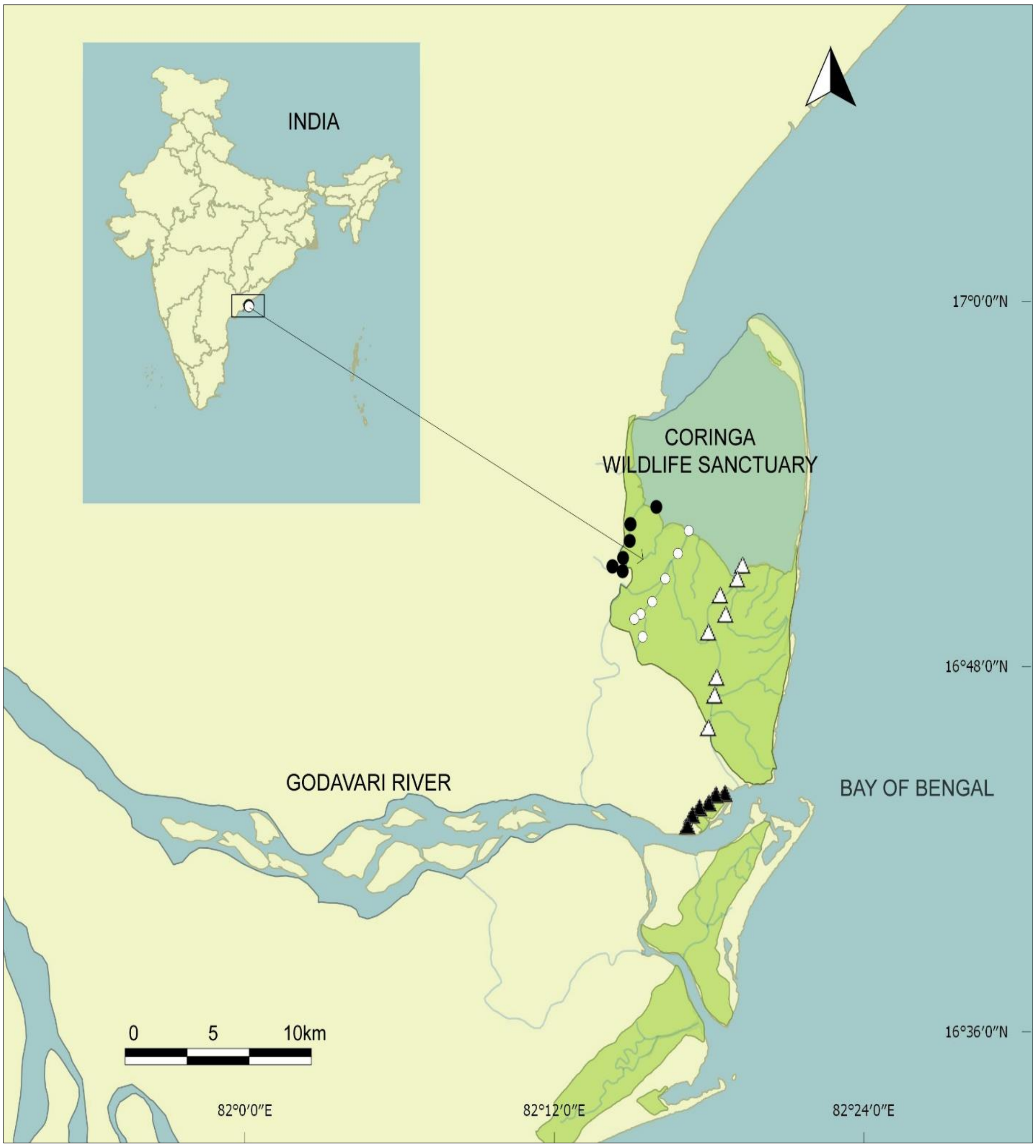


Figure 3.1. Map of the Godavari River delta showing Coringa Wildlife Sanctuary, along with sampling sites covering the four sub-tidal creeks. Black dots denote sampling sites at Thulyabhaga creek, white dots denote sampling sites at Coringa creek, white triangles denote sampling sites at Gaderu creek, and black triangles denote sampling sites at Giriyampeta creek. Greenish areas represent mangrove forests.

The net was set across the creek usually for a period of 1-hour during slack low tide periods. Sampling was conducted in the daytime, mostly during neap tides, to decrease the tidal regime's influence on this study and to prevent major damage to the net. It was ensured that the same fishing gear was used throughout the study period.

During each sampling occasion, the standard length, total length, and wet weight of every individual of the major species were recorded. In addition, environmental parameters- salinity, water temperature, and depth- were recorded during each sampling event. Since sampling was conducted inside a protected area, only unidentified specimens were collected for further identification in the laboratory.

3.2.2 Data analysis for Phase 2

The catch per unit effort (CPUE) for each species was used as a surrogate for fish abundances. Rarefaction curves based on abundances (or CPUE) were prepared for each creek to check for sampling completeness and to compare the species richness between the creeks. A non-parametric estimator of species richness, Chao 1 (S_{Chao1}), was used to estimate the asymptotic species richness for each creek. To prepare the curves and estimate S_{Chao1}, the iNEXT version 2.0.20 package in R (Hsieh et al., 2016). I used R version 4.1.1 (2021-08-10) (The R Foundation for Statistical Computing programme, 2021).

Variations in the environmental parameters (salinity, water temperature, and depth) were analysed using the non-parametric Kruskal-Wallis test. If any significant differences were found at $p < 0.05$, it was followed by non-parametric multiple pair-wise comparisons using Wilcoxon signed rank test with Bonferroni corrections on the significance levels. Differences in observed species number, species diversity index (H') and species evenness (J) were assessed using 2-way ANOVA with creeks and seasons as fixed factors. Abundance data for fish species were square root transformed before carrying out further analyses. All these analyses were conducted using different functions available in the vegan 2.4-3 package of R ver. 3.2.1 (J. Oksanen, 2015).

The fish assemblage patterns were analysed in PRIMER 7 complemented with the PERMANOVA+ software package (Clarke et al., 2015). For the multivariate analyses, a distance-based matrix of species' square root transformed abundance data was prepared using the Bray-Curtis similarity measure (Clarke, 1993). To test the null hypothesis of uniform species assemblage across temporal and spatial scales, a nested non-parametric Permutational Multivariate Analysis of Variance (PERMANOVA; (Anderson, 2001)) was conducted using the similarity matrix, where the season was considered as a fixed factor while creeks and sites (nested within the creeks) were considered as random factors. Since several species were singletons or doubletons, the species data was reduced to include the most abundant species (those having a relative abundance of more than 1% and occurring in more than 5% of sampling sites in each habitat). For this analysis, 9999 permutations of the data were carried out under a reduced model. Before conducting PERMANOVA, a multivariate test for measuring dispersion (PERMDISP) for each of the three factors (season, creek, and site) was also done to make sure high dispersion among the groups would not confound any differences detected between the groups (Anderson, 2006; Anderson et al., 2006). If the PERMANOVA analysis resulted in significant differences, further pair-wise comparisons were made to compare the three factors considered. Finally, the spatial patterns between the creeks were visualized using a constrained ordination technique – Canonical analysis of principal coordinates or CAP (Anderson & Willis, 2003). The

CAP plots were then overlaid with vectors to represent the species most strongly correlated to the coordinates (Pearson's correlation value > ±0.4). The important fish species contributing to the differences in fish assemblages were detected by the similarity of percentages (SIMPER).

I used distance-based linear model analysis (DistLM) to check for the role of the three environmental variables (salinity, depth and water temperature) in driving the assemblage patterns. For this, the best selection procedure and the lowest AICc value were used to select the most suitable model. Before this analysis, the environmental variables were first transformed (log(x+1)) and then normalized. Additionally, the three variables were tested before the analysis for any potential correlation using a draftsman plot; however, none correlated with each other (correlation values <0.2). The result of DistLM was then plotted using the distance-based Redundancy Analysis (dbRDA), with the dominant predictor variables (having Pearson's correlation > ±0.4) overlaid to visualize their effect on the fish assemblage.

3.3 Results

3.3.1 Environmental parameters

During the entire sampling period, water temperature in the sampling sites in creeks varied from 23°C to 34.2°C. Expectedly, seasonal differences were high where the summer temperatures were significantly higher than the winter temperatures (Figure 3.2c, Table 3.1). Among the four creeks, the mean water temperature was highest in Gaderu creek, but the statistical test did not reveal any significant spatial patterns in the water temperature. Similarly, the depth did not show any significant pattern between the three seasons. However, the average depth in Gaderu creek was lower than the other three creeks, differing significantly from Thulyabhaga creek (Figure 3.2a, Table 3.1).

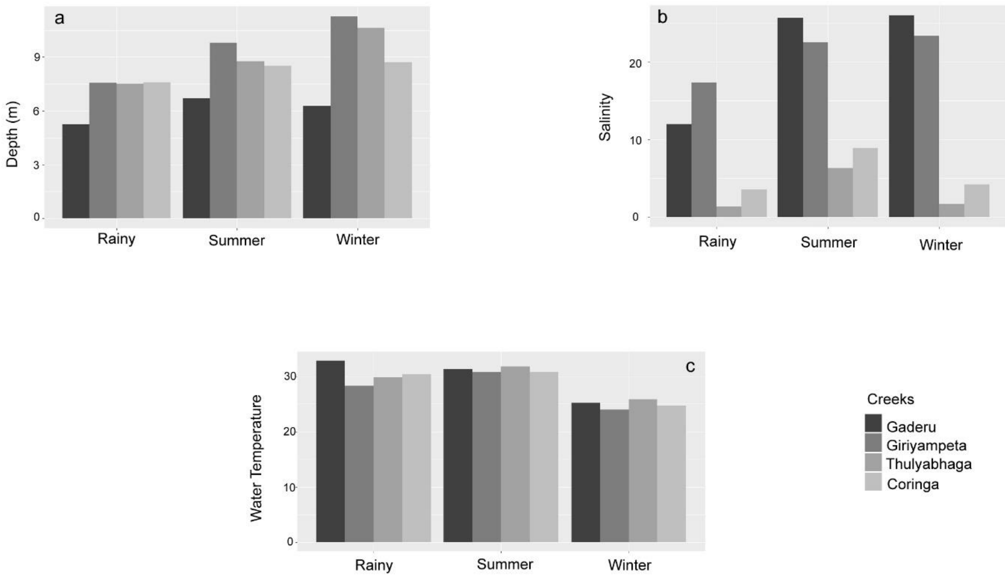


Figure 3.2. Mean values of *a)* Depth (m), *b)* Salinity, and *c)* Water temperature (°C), measured in the three seasons, viz. Rainy, Summer, and Winter in the four creeks.

Salinity significantly varied between seasons and creeks (Figure 3.2b, Table 3.1). The salinity values in Thulyabhaga and Coringa creeks during the rainy seasons did not rise beyond 5. The sites in Thulyabhaga creek showed nearly freshwater conditions in all three seasons, except in summer when the salinity of sites nearest to the Bay was recorded at 11. Giriyampeta and Gaderu consistently had higher salinity values than Thulyabhaga and Coringa. The overall salinity values were higher during summer than in the rainy season.

3.3.2 Species composition in the Gautami-Godavari estuary (EGREE)

3.3.2.1 Overall species composition in EGREE (Phase 1)

I recorded a total of 231 species of finfishes from the three habitat types in EGREE selected for this study. These species belonged to 30 orders, 81 families, and 167 genera (Appendix-I). The most speciose order was the Perciformes in this study with 41 species, 22 genera and 12 families, which was followed by Clupeiformes (25 species, 16 genera and five families), and then Carangiformes (18 species, 14 genera and three families).

Table 3.1. Results of the Kruskal-Wallis test and pair-wise Wilcox tests, showing the differences in the environmental variables between each season (Rainy, Summer and Winter) and between each sub-tidal creek (Thulyabhaga (Tu), Coringa (C), Gaderu (Ga) and Giriyampeta (Gi)). Only the pairs with significant p-values are included.

Environmental variables	**Season**		**Creek**	
	p-value	**significant pairs (adjusted p-value)**	**p-value**	**significant pairs (adjusted p-value)**
Depth (m)	0.19	NA	0.02	Ga x Tu (0.01)
Salinity	0.005	R x S (.002)	<.001	Ga x Gi (< .001) Ga x Tu (< .001) Ga x C (< .001) Gi x Tu (< .001) Gi x C (< .001)
Water temperature (°C)	< .001	R x S (< .001)	0.07	NA

R x W (<.001)
S x W(< .001)

Among the families, Carangidae was represented by the highest number of species (16 species), followed by Gobiidae and Sciaenidae (both represented by 12 species). I recorded 150 species in the Coringa Wildlife Sanctuary mangrove creeks, 151 species from the river mouth zone, and 149 species from the Kakinada Bay (images of few species can be seen from Figure 3.6 to Figure 3.9). Nearly 67% of the overall species occurred in at least two habitat types showing a high degree of overlap between the estuarine habitats of the EGREE. Sixty-four species were found in all three habitat types of the estuarine complex. Fishes recorded exclusively from the Bay and the river mouth respectively constituted nearly 16% and 11% of the total number of species recorded during this study. This high degree of overlap in species between the habitats indicates the importance of connectivity within this estuarine complex.

3.3.2.2 Threatened and non-native species recorded in EGREE

Four species recorded from this estuarine complex have been identified as threatened species by the IUCN. These include the Endangered *Silonia childreni,* the Vulnerable *Tenualosa toli, Cirrhinus cirrhosus* and *Wallago attu*. Additionally, three Near Threatened species- *Ompok bimaculatus, Harpadon nehereus* and *Protonibea diacanthus*, and 11 Data Deficient species were recorded during this study (Table 3.2).

Table 3.2. List of threatened, Near Threatened, and Data Deficient species as per the IUCN Red List of Threatened Species.

S. No.	**Species name**	**Main river**	**Mangroves**	**Bay**	**IUCN Status**
1	*Silonia childreni* (Sykes, 1839)	+	-	-	EN
2	*Tenualosa toli (*Valenciennes, 1847)	+	+	-	VU
3	*Cirrhinus cirrhosus (*Bloch, 1795)	+	+	-	VU
4	*Wallago attu (*Bloch & Schneider, 1801)	+	-	-	VU
5	*Ompok bimaculatus (*Bloch, 1794)	+	-	-	NT
6	*Harpadon nehereus (*Hamilton, 1822)	+	+	+	NT
7	*Protonibea diacanthus (*Lacepède, 1802)	-	+	+	NT
8	*Platycephalus indicus (*Linnaeus, 1758)	+	+	+	DD
9	*Epinephelus tauvina (*Fabricius, 1775)	-	-	+	DD
10	*Acanthopagrus datnia (*Hamilton, 1822)	-	-	+	DD
11	*Rastrelliger kanagurta* (Cuvier, 1816)	+	-	+	DD
12	*Scomberomorus guttatus* (Bloch & Schneider, 1801)	-	-	+	DD
13	*Parapocryptes rictuosus* (Valenciennes, 1837)	-	+	-	DD
14	*Taenioides cirratus (*Blyth, 1860)	+	+	-	DD
15	*Psettodes erumei (*Bloch & Schneider, 1801)	+	-	+	DD
16	*Cynoglossus arel (*Bloch &	+	+	+	DD

	Schneider, 1801)				
17	*Megalops cyprinoides (*Broussonet, 1782)	+	+	+	DD

**(“+” : Presence recorded; “—" : Presence not recorded; EN: Endangered; VU: Vulnerable; NT: Near Threatened; DD: Data Deficient)*

I also recorded five exotic species from the sampling locations across EGREE. These include *Oreochromis mossambicus, O. niloticus, Ctenopharyngodon idella, Cyprinus carpio and Piaractus brachypomus*. Alarmingly, my study showed that *O. mossambicus* has perhaps established a self-sustaining wild population within the Thulyabagha and Coringa creeks of CWS, where the salinities annually ranged from 2 ppt to 20 ppt (more details on this are in the subsequent sections of this chapter). The rest of the exotic species were recorded only from the riverine zone of the estuary complex, and the fish markets surveyed during this study. I, along with other researchers from the Wildlife Institute of India, also recorded the presence of another non-native species- *Pterygoplichthys* sp. (family Loricariidae) in local fishers' catch from the upstream freshwater zone of the river in the East Godavari district.

3.3.2.3 Species composition in the sub-tidal creeks of Coringa Wildlife Sanctuary (Phase 2)

From the sub-tidal creeks of the sanctuary (during the second phase of my study), I recorded 72 species that belonged to 35 families of finfishes. Out of the 35 families, Sciaenidae (6 species), Engraulidae (6 species) and Carangidae (5 species) were the three most speciose families in terms of abundance (or CPUE) and biomass, Bagridae, Ariidae, and Sciaenidae dominated in terms of abundance and biomass.

Among the species, *Mystus gulio* and *Arius* sp. dominated in terms of overall abundance during the study period. These two species, along with *Dichotomyctere fluviatilis, Dendrophysa russelii* and *Mugil cephalus* contributed little more than 50% to the overall catch of the fishes, reflecting a high dominance of few species in the sub-tidal creeks of these mangroves. On the other hand, *Mystus gulio* was among the most abundant species in the Thulyabhaga (42.7%) and Coringa (21%) creeks. In Gaderu, *Arius* sp. (33.5%) and *D. russelii* (18.8%) were the most abundant, with the latter mainly dominating the creek during the winter and rainy seasons. On the other hand, *D. fluviatilis* (13%) and *Ambassis gymnocephalus* (10.4%) together contributed nearly a quarter of the catch in Giriyampeta creek.

3.3.3 Community variables in the major sub-tidal creeks of CWS

The observed number of species at Giriyampeta (44 spp.) and Gaderu (33 spp.) were higher than Thulyabhaga (32 spp.) and Coringa (25 spp.). However, the rarefied species richness estimates (Chao1 species richness estimator, S_{Chao1}) indicated otherwise. The individual-based rarefaction curve (Figure 3.3) for Gaderu nearly stabilized at $S_{Chao}1$ value of 36.4. The $S_{Chao}1$ for Coringa was estimated at 37.4 and for Giriyampeta at 58, which was greater than the observed number of species in these two creeks. The curve for Thulyabhaga creek stabilized at a value of S_{Chao1} = 60.8, much higher than the number of species recorded during this study.

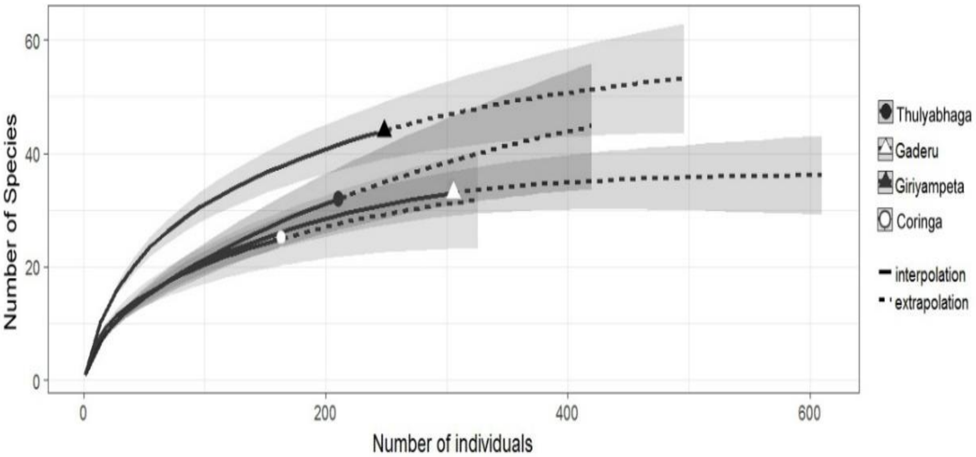


Figure 3.3. Graph showing individual-based rarefaction curves comparing species richness between the four sub-tidal creeks (Thulyabhaga, Coringa, Gaderu and Giriyampeta) and the shaded areas represent 95% CI. Symbols on the curves represent the observed number of species recorded in each creek.

The overall mean species diversity (Shannon index, H') was also highest for Giriyampeta creek (H'= 2.37), whereas Thulyabhaga (H'= 1.8) had the lowest mean diversity (Table 3.3). Giriyampeta recorded the highest diversity in the summer and Gaderu in the rainy seasons. On the contrary, species diversity in Thulyabhaga and Coringa creeks was highest in the winter season. The evenness (J) was higher for Gaderu in the rainy season and for Thulyabhaga in winter, but for Giriyampeta and Coringa the values did not differ much. The results of statistical analyses did not reveal any significant seasonal or spatial pattern in species diversity or evenness among the four creeks I selected in phase two of my study.

Table 3.3. Mean values of the Shannon diversity and evenness estimated for each of the four sub-tidal creeks of Coringa Wildlife Sanctuary, in different seasons. The table also includes the total number of sampling sites, and total number of species observed in each sampling season.

Seasons	Creeks	Total number of sampling sites	Total number of Species (Observed)	Mean Diversity (H')	Mean Evenness (J)
Summer	Gaderu	6	17	2.13	0.75
	Giriyampeta	6	34	3.07	0.87
	Thulyabhaga	6	12	1.52	0.61
	Coringa	6	9	1.84	0.84
Rainy	Gaderu	9	19	2.74	0.84
	Giriyampeta	6	21	2.47	0.81
	Thulyabhaga	6	14	1.83	0.69
	Coringa	7	11	1.92	0.8
Winter	Gaderu	9	17	1.73	0.61
	Giriyampeta	6	7	1.57	0.81
	Thulyabhaga	6	12	2.04	0.82
	Coringa	7	16	2.17	0.78

3.3.4 Patterns in fish assemblage in the major sub-tidal creeks of CWS

The results of the nested PERMANOVA analysis did not reveal any significant seasonal pattern for species assemblages, but significant spatial patterns between the four creeks and within the sites of the creeks were detected (Table 3.4). On further inspection through the pair-wise analyses, significant differences were recorded between the pairs of the creeks, except for the Thulyabagha and Coringa creeks. The CAP ordination (Figure 3.4) also reflected the same spatial differences that separated Thulyabagha and Coringa from the Gaderu and Giriyampeta creeks. The species vectors indicated the association of certain species with specific creeks (Figure 3.4).

For example, the non-native *O. mossambicus* showed a higher affinity for the Coringa and Thulyabagha creeks than the other two creeks.

In addition to the spatial differences in the fish assemblage, the interaction between the three seasons and four creeks was also highly significant. As a result, I further inspected the main differences between the seasons for each of the four creeks. In the case, of Thulyabagha, Coringa, and Gaderu, there were no significant seasonal differences. Contrarily, the summer and winter species assemblages of the Giriyampeta creek were significantly different (Table 3.4).

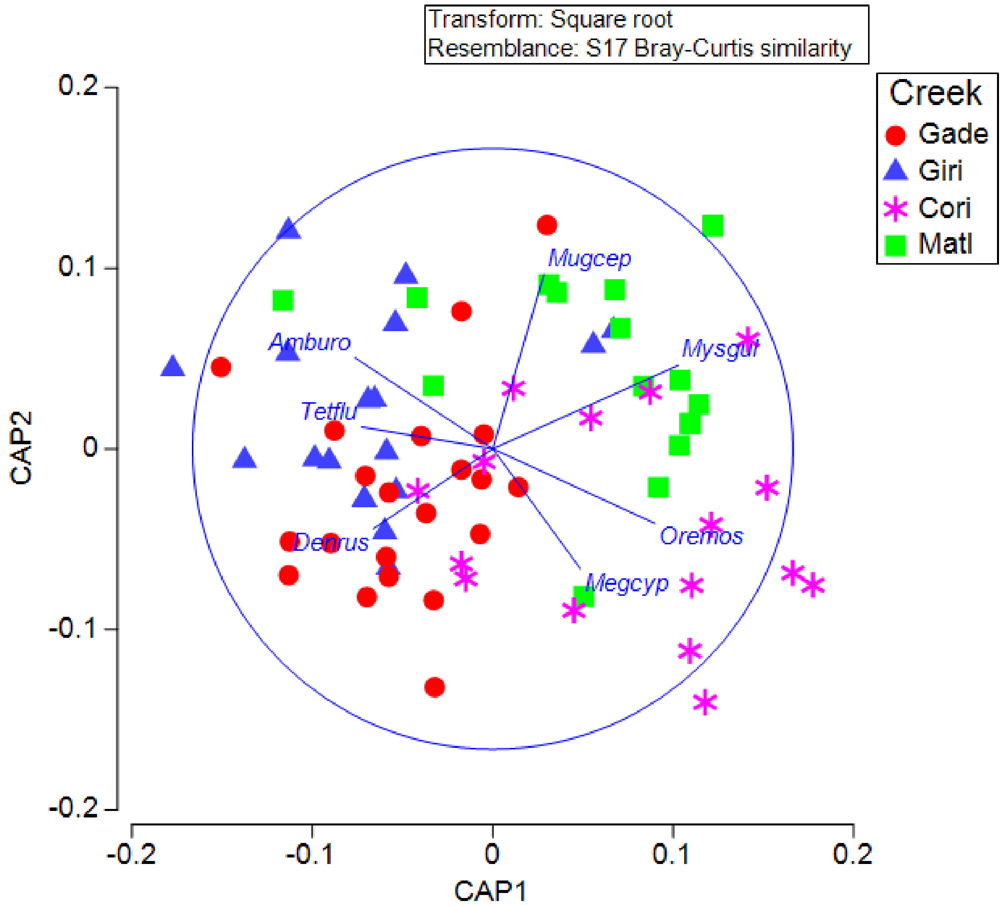


Figure 3.4. CAP ordination of fish assemblages in the four sub-tidal creeks of Coringa Wildlife Sanctuary. (Species names: Amburo: *Ambassis gymnocephalus*; *Mugcep: Mugil cephalus; Mysgul: Mystus gulio; Oremos: Oreochromis mossambicus; Megcyp: Megalops cyprinoides: Denrus: Dendrophysa russelii;* Creek names: Gade: Gaderu creek; Giri: Giriyampeta creek; Cori: Coringa creek; Matl: Thulyabagha creek)

Table 3.4. Results of the multivariate permutational analysis (PERMANOVA), and pair-wise tests showing differences in abundance of the most frequent species between the four sub-tidal creeks Thulyabhaga (Tu), Coringa (C), Gaderu (Ga) and Giriyampeta (Gi) for each of the three seasons. The results are based on a Bray-Curtis similarity matrix of square root transformed abundance data of the most frequent species. Only those pairs with significance are shown in the table.

Source	**Df**	**Sum sq.**	**Pseudo-F**	R^2	**p**
Winter					
creek	3	2.965	3.552	0.316	**0.001**
residuals	23	6.401		0.683	
total	26	9.367		1	
Significant pairs (adjusted p)	Ga x Tu (.**006**) Ga x C (.**006**)				
Summer					
creek	3	2.12	2.384	0.263	**0.004**
residuals	20	5.92		0.737	
total	23	8.04		1	
Significant pairs (adjusted p)	Ga x Tu (.**05**)				
Rainy					
creek	3	2.03	2.313	0.316	**0.004**
residuals	15	4.39		0.684	
total	18	6.42		1	
Significant pairs (adjusted p)	Ga x Tu (**0.01**) Gi x Tu (**0.02**)				

According to the SIMPER analysis, over 50% differences in the fish assemblages between the four creeks were contributed by a few species mainly *Dichotomyctere fluviatilis, Dendrophysa russelii, Mystus gulio, Ambassis gymnocephalus, Oreochromis mossambicus,* and *Mugil cephalus*. In the case of Gaderu and Giriyampeta creeks, over 50% differences were contributed by *Dichotomyctere fluviatilis, Dendrophysa russelii*, *Arius jella*, *Ambassis gymnocephalus, Arius arius*, and *Glossogobius giuris*. The average catch of *Dendrophysa russelii*, and *Arius* spp. was higher in Gaderu when compared to Giriyampeta. Nearly 55% of differences between Giriyampeta and Thulyabagha was contributed by *Mystus gulio*, *Dichotomyctere fluviatilis*, *Mugil cephalus*, *Ambassis gymnocephalus*, and *Dendrophysa russelii*, while major differences between Thulyabagha and Gaderu were due to *Mystus gulio*, *Dendrophysa russelii, Dichotomyctere fluviatilis* and *Mugil cephalus*. In case of major differences between Coringa and Giriyampeta, *Mystus gulio*, *Dichotomyctere fluviatilis*, *Oreochromis mossambicus, Megalops cyprinoides* and *Ambassis gymnocephalus* were the important species, whereas *Mystus gulio*, *Dichotomyctere fluviatilis*, *Oreochromis mossambicus*, *Dendrophysa russelii*, and *Arius arius* were driving over 54% differences in the fish assemblages between Coringa and Gaderu. Although no significant differences were found between the Coringa and Thulyabagha assemblages, notable species included *Mystus gulio*, *Oreochromis mossambicus*, *Mugil cephalus*, and *Dichotomyctere fluviatilis*.

3.3.5 Influence of environmental parameters on species distribution

The marginal distLM tests' results highlighted salinity's role in driving the fish assemblage patterns in the subtidal creeks of CWS. Salinity explained (8.3%) most of the variations in the fish community, while the other two variables- depth and water temperature did not significantly explain the variations in the fish community. Therefore, the best model based on the lowest AICc values included two variables – salinity and depth (Table 3.5). The sequential tests further confirmed the role of salinity, which explained ~85% of the fish composition; the second variable- depth, explained 15% of the variations (Figure 3.5).

Table 3.5. Results of the DistLM marginal test for each of the environmental variables along with an overview of the most parsimonious model selected

Variable	**SS**	**Pseudo-F**	**p value**	**Prop.**
Depth	4182	1.132	0.31	0.016
Salinity	22163	6.447	0.001	0.084
Water temperature	4751	1.289	0.223	0.018

Best solution: Depth and Salinity (R^2: 0.102, AICc: 589.15)

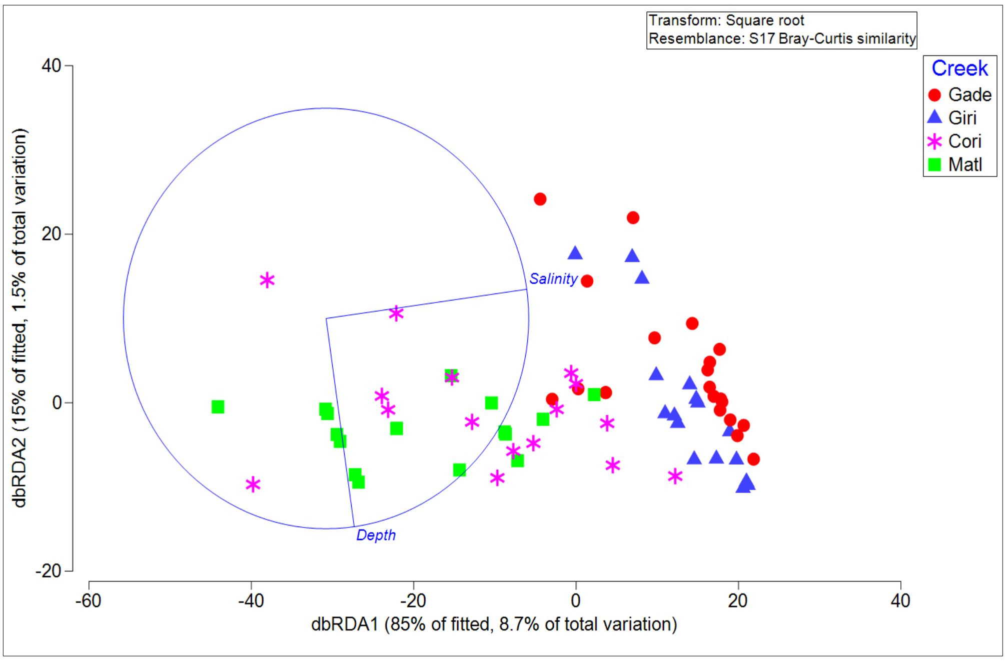


Figure 3.5. Graph of dbRDA showing the relation of salinity and depth with the fish community structure of CWS.

3.4 Discussion

3.4.1 Species richness and composition

Compared with the world's temperate regions, the tropical and subtropical estuaries of the Indo-West Pacific region show the highest diversity in aquatic fauna (Blaber, 2007). For instance, in the mangrove swamps of Selangor, Malaysia, 119 species of fish have been recorded (Chong et al., 1990), while 93 species have been recorded in the Sikao Creek in Thailand (Krumme et al., 2015). Likewise, many fish species have also been reported from the estuaries and mangroves on the Indian coast. Krishnamurthy & Jeyaseelan (1981) recorded 195 species from the Pichavaram mangroves in Tamil Nadu; 312 species have been reported from the Sundarbans mangroves in West Bengal (Mukherjee et al., 2013); Mohanty et al. (2015) reported

317 species in Chilika Lake in Odisha; 90 species have been recorded in Vembanad Lake in Kerala (Roshni et al. 2021); while Sreekanth et al. (2020) recently reported over 130 species each in four estuaries located in Goa (Zuari, Mandovi and Terekhol) and Karnataka (Kali).

Considering the above studies, the record of 231 species in EGREE is well within the comparable limits of the region. However, in an earlier study by Krishnan and Mishra (2001), 312 species belonging to 189 genera and 88 families were reported in the Godavari estuary. My list of 231 finfish species is slightly lower than what has been reported by Krishnan and Mishra (2001), but this cannot be only attributed to a decline in the overall number of species in the estuary. It is perhaps more reflective of the taxonomic changes and the smaller geographical scope of my study. Krishnan and Mishra (2001) selected a broader scope of the study, which included the other distributaries of the Godavari River; in my study, the focal point was the Gowthami-Godavari system in EGREE. While my overall checklist of fish species from EGREE is slightly lower, I recorded the first presence of species including *Plectorhinchus gibbosus* and *Diagramma pictum,* and non-native species such as *Oreochromis mossambicus* and *Piaractus brachypomus* from this estuary.

In the case of the mangrove-lined creeks of CWS, except Gaderu, the rarefaction curves estimated the presence of a slightly higher number of species than what I recorded during my surveys. The S_{Chao1} values in the four creeks ranged between 37.4 and 60.8 (Figure 3.4). When the observed numbers of species between the four creeks were compared at a base value of the lowest abundance, which was recorded in Thulyabhaga creek at 165 individuals, species richness in the Giriyampeta creek was found to be considerably higher than in the other three creeks. In the case of the other three creeks- Thulyabhaga, Coringa, and Gaderu, a certain degree of overlap was observed in their curves. This suggests that for the similar number of species richness, the abundance of individuals varied between the three creeks (Gotelli & Colwell, 2011). In fact, the curve for Gaderu stabilized at the highest number of individuals (n>600 individuals). The S_{Chao1} values for the other three creeks stabilized only at their respective final number of individuals. A considerable difference was recorded in the observed species richness and the estimated species richness (S_{Chao1}) in Thulyabhaga creek, which is connected to the Godavari River through a canal.

This discrepancy in the observed and estimated species richness can be attributed to an uneven species assemblage and a large number of singletons and doubletons (Gotelli & Colwell, 2011). In corollary, the fish community of the mangrove creeks in CWS is evidently dominated in terms of abundance (or CPUE) by a few species. *Mystus gulio*, *Arius* spp., *Dendrophysa russelii*, *Dichotomyctere fluviatilis*, and *Oreochromis mossambicus* combined with 11 other species contributed nearly 80% to the overall fish catch. Nevertheless, such a pattern of dominance by a few species is common in estuarine habitats across the world (Barletta et al., 2005; Chong et al., 1990; Day, 1989; Krumme et al., 2015). Moreover, the sampling carried out in the study's second phase was more focused and limited to using a single gear type – trammel nets. While these are the most commonly used gear by the local fishing communities, it is possible they might have missed several benthic and non-commercial species. In the first phase of sampling, which included market surveys and opportunistic recordings from fishers using different fishing gears, and surveys in mangrove habitats other than the sub-tidal creeks, I was able to record overall 150 species. This is far greater than the 70 species I recorded in the study's second phase, where I used only the trammel nets in the subtidal creeks.

In tropical and sub-tropical estuaries, commonly occurring fish families include Clupeidae (clupeids), Engraulidae, Ariidae (sea catfishes), Mugilidae (mugilids), Sciaenidae (drums), Gerreidae (gerreids), Haemulidae (grunts) and Tetraodontidae (pufferfishes) (Day et al., 1990). In my study, Sciaenidae, Gerreidae and Carangidae were the three most speciose families, but the two catfish families attributed the highest abundance and biomass -Bagridae and Ariidae, along with Sciaenidae and Tetraodontidae. While these families are often a dominant component of tropical and subtropical estuaries (except Bagridae) (Whitefield et al. 2022), they may have a certain degree of association with riverine influence. This was apparent in an Indo-pacific mangrove creek located in the Andaman Sea in Thailand, where species belonging to Ariidae and Sciaenidae were not recorded, potentially due to the lack of riverine influence in the estuary (Krumme et al., 2015).

The fish assemblages in my study also included freshwater species belonging to the orders Cypriniformes and Siluriformes. A few of them, such as *Mystus gulio* and *Etroplus* spp. are known to occur in other brackish water habitats of India (Bijukumar and Sushama 2000). *M. gulio* was recorded across the four creeks' entire salinity range but with the highest abundances in sites with salinity below 10. I also recorded the presence of gravid females during the summer season in the creeks, indicating that this species is successfully utilizing the creek habitats of these mangroves.

I also recorded the presence of carp species, including *Labeo rohita, Labeo calbasu, and Labeo fimbriatus*, in Coringa and Thulyabagha creeks, especially in the monsoon and post-monsoon seasons when the salinities reduced to 5 or less. Another freshwater species I recorded in this study was the *O. mossambicus* – a non-native species in India. This species can tolerate a wide range of salinity in estuaries (Whitfield, 2015). The occurrence of these commercially important freshwater species in the mangrove creeks can be explained by the stocking of these species in aquaculture ponds abutting the mangroves, creeks and canals across the East Godavari district. Although generally speaking, the representation of freshwater species is significantly less in estuarine habitats due to physiological stress induced by wide variations in salinity (Whitfield, 2015).

3.4.2 Spatial patterns in species composition

This study supported my hypothesis that salinity would play a fundamental role in driving the fish assemblage patterns in the mangrove creeks of CWS. The fish community of the subtidal creeks in the sanctuary is segregated into two main spatial assemblages- one in creeks with lower salinity values and the other in creeks with higher salinity values. Thulyabhaga and Coringa creeks are connected to the Godavari River, thus receiving freshwater directly through the canals and creeks; Gaderu, on the other hand, is also connected to the sea through several smaller sub-tidal and intertidal creeks making it more brackish. Giriyampeta is located at the river's confluence with the Bay of Bengal; therefore, this creek also has a relatively greater marine influence than Thulyabagha and Coringa. Due to the differences in connectivity with the sea, and variable degree of freshwater mixing with the marine water, a gradient of salinity has been established between the four creeks. Based on the average salinity values, Thulyabhaga creek can be classified as an oligohaline creek, Coringa as a mesohaline, and Giriyampeta and Gaderu creeks as polyhaline creeks.

Several studies have shown an important influence of salinity on fish assemblages of estuaries (Barletta et al., 2005a; G. Castellanos-Galindo & Krumme, 2013; Lin & Shao, 1999; Neves et al., 2011; Sheaves, 1998). The estuary reaches in lower salinity zones often have been found to possess lower species diversity, and lesser abundance than the lower estuary reaches. This was reflected in my study, too, where Thulyabhaga, the creek with the lowest salinity values, had the lowest species richness and diversity compared to Gaderu and Giriyampeta creeks, which were polyhaline. The abundance (CPUE) of the marine fish species was also lower in Thulyabagha than in the polyhaline creeks.

The presence or absence of a taxon is often a physiological response to the salinity regime existing in an estuary. The freshwater or marine species with lower tolerance to salinities (stenohaline species) are mainly limited to the upper or lower estuaries, respectively, while euryhaline species are best adapted to most estuarine habitats (Whitfield et al., 2022). Nevertheless, most estuaries are dominated by species of marine origin that are either temporary residents or migrate into estuaries for feeding or spawning purposes (Elliott et al., 2007).

A closer look at the SIMPER results shows that *Mystus gulio*- a euryhaline bagrid species, is perhaps among the most important species driving the differences in fish assemblages between the four creeks (except between Giriyampeta and Gaderu). This species occurred in all four creeks. However, higher average abundances (CPUE) were recorded in the Thulyabhaga and Coringa creeks (creeks with lower salinity values) than in Gaderu and Giriyampeta creeks (creeks with higher salinity values). Few other freshwater species were recorded in Thulyabagha creek, which had the most riverine influence, but not in the other three creeks. On the contrary, in the case of Gaderu and Giriyampeta creeks, *Dendrophysa russelii* and *Dichotomyctere fluviatilis* were the two important species driving the dissimilarities between the Thulyabagha and Coringa creeks. In the trawl fisheries off the Kakinada coast in EGREE, *Dendrophysa russelii* contributes over 7% of the total sciaenid catch (Sivakami & Ramalingam, 2003). This species usually occurs in the lower estuaries, closer to the confluence with the sea and higher salinities (Zhou et al., 2019). Therefore, it is expected to have a higher abundance in polyhaline creeks than in oligohaline or mesohaline creeks. *Dichotomyctere fluviatilis* followed a similar pattern; however, it was also the most important species contributing ~14% of the differences in the species assemblages between Giriyampeta and Gaderu. This possibly means the influence of other factors in the distribution of *Dichotomyctere fluviatilis* within the sanctuary.

The varying degree of freshwater run-off from the main channel of the Goutami-Godavari River coupled with higher precipitation in the rainy or monsoon season are the main drivers of the salinity differences between the four subtidal creeks. This is a general pattern in most estuaries in the Indian subcontinent, where higher precipitation during the monsoons is a prominent climatic feature (Kumbhar et al., 2020). In the case of the subtidal creeks of CWS, a salinity gradient also exists within each of the creeks. The sites closer to the river channel had expected lower mean salinity values while the sites closer to the Kakinada Bay or that directly influenced marine water had higher salinity values throughout the year.

High freshwater flow during the rainy season in the Caetè River estuary in Brazil lowers the salinity and makes it more conducive for freshwater species to enter the estuary leading to higher species numbers (Barletta et al., 2005a). At the same time, high freshwater run-off during the rainy season led to an overall decline in biomass and abundance in the Bahia Malaga mangrove estuary in Colombia (Castellanos-Galindo & Krumme, 2013) and the Malta estuary in India (Mukherjee et al., 2013). Despite the variable responses of species, these studies highlight the role of freshwater discharge in seasonally structuring the fish community by causing changes in the salinity. In our study, several sites in Thulyabhaga, Coringa, and Gaderu became depauperate during the rainy season, and the highest relative abundances were recorded at select few sites only. However, seasonal patterns in the species richness, species diversity or species assemblage were not of much significance. This can be likely attributed to the maintenance of salinity gradient between the creeks in rainy season with Coringa and Thulyabhaga showing nearly freshwater conditions while Gaderu and Giriyampeta remaining polyhaline similar to Paranaguá Estuary studied by Barletta et al. (2008). In addition to this, most of the estuarine residents and marine migrants did not show any significant seasonal changes in their abundance except for *O. mossambicus* and *D. russelii*.

Depth was the second important factor influencing the spatial distribution of species. While salinity followed by water depth explained most of the spatial variations in the fish community of CWS, several other factors may also drive the fish assemblages in an estuary (Blaber, 2007). Tidal, lunar, and diel regime affects the usage of intertidal and sub-tidal creeks by fishes in mangrove forests (Laroche et al., 1997; Castellanos-Galindo & Krumme, 2013; Krumme et al., 2015). Mwandya et al. (2010) found the availability of food and refuge as important factors structuring the fish community of non-estuarine mangrove-lined creeks in Tanzania. While my informal discussions with the local fishers did suggest the presence of a movement pattern of fishes, especially mugilids, within the subtidal creeks of CWS, the results of this study suggest salinity as the more important factor. Moreover, due to logistic challenges in surveying the subtidal creeks, I could not focus on the role of tidal factors. The potential role of tidal and lunar regimes has been discussed in another chapter of this thesis.

Figure 3.6. Images of fish species recorded in this study along with their standard lengths whenever available; a) *Lates calcarifer; b) Lutjanus johnii* (137 mm); c) *Opisthopterus tardoore* (98 mm); d) *Leiognathus ruconius* (48 mm); e) *Siganus javus* (78 mm); f) *Minous monodactylus* (72 mm).

Figure 3.7. Images of fish species recorded in this study along with their standard lengths whenever available; a) *Acanthurus mata* (56 mm); b) *Aulopareia cyanomos* (110 mm); c) *Lutjanus argentimaculatus* (153 mm); d) *Butis butis* (120 mm); e) *Elops machnata*.

Figure 3.8. Images of fish species recorded in this study along with their standard lengths whenever available; a) *Trachinotus mookalee* (86 mm); b) *Triacanthus biaculeatus* (129 mm); c) *Terapon jarbua* (37 mm); d) *Jaydia queketti* (88 mm); e) *Trypauchen vagina*.

Figure 3.9. Images of fish species recorded in this study along with their standard lengths whenever available; a) *Etroplus suratensis* (71 mm); b) *Oxyurichthys microlepis* (72 mm); c) *Allenbatrachus grunniens* d) *Kurtus indicus* (62 mm).

Figure 3.10. Thulyabhaga/Matlapalem creek, one of the subtidal creeks of Coringa Wildlife Sanctuary, during high tide.

Figure 3.11. Coringa/Korangi creek, one of the subtidal creeks of Coringa Wildlife Sanctuary, during high tide.

Figure 3.12. Gaderu creek, one of the subtidal creeks of Coringa Wildlife Sanctuary, during high tide.

Chapter 4

Trophic ecology of ichthyofauna in East Godavari Riverine Estuary Ecosystem (EGREE)

4. 1 Introduction

Mangroves are important habitats for fishes and play an important role in the fisheries of a particular region. They are often considered nursery habitats for several offshore and reef fish species (Laegdsgaard & Johnson, 2001; Mumby et al., 2004; Igulu et al., 2014). Fishes also use mangrove habitats for refugia (Robertson & Duke, 1990), feeding (Sheaves, 2005; Lugendo et al., 2006), as well as safe transitory passages during migration (Islam & Wahab, 2005). Moreover, mangrove forests are important for the marine-coastal food webs because of the generally higher productivity and provisioning of food (via detritus) to both estuarine and ocean consumers. They also serve as habitat for early life history stages, juveniles and adults of estuarine and marine species, and play an important role in the regulation of estuarine biogeochemical cycles (Vega-Cendejas & Arreguín-Sánchez, 2001). To understand mangrove food webs better, a study of multispecies interactions is needed, which includes trophic fluxes and efficiencies of energy assimilation as well as energy transfer (Vega-Cendejas 2003). These are then reflected in the diversity, structure, and persistence of its biological components, which are ultimately regulated by primary productivity (Oksanen et al., 1981; Oksanen, 1983), environmental variability (Pimm & Kitching, 1987), and a combination of both (Persson et al. 1992). Due to their temporal and biological complexity, it is difficult to understand the structure of food web and trophic interactions by direct observation (Schoenly & Cohen, 1991; Niquil et al., 1999) and ecosystem-level experiments are difficult to replicate (Carpenter, 1990), so a modelling approach is adopted.

Ecosystem models are popular tools in fisheries management to understand the direct and indirect relationships among the various trophic levels or components of an ecosystem, as well as to predict the impacts of fisheries or other external factors. Ecopath with Ecosim (EwE), mainly developed by the University of British Columbia, has emerged as a widely used suite of software to build snapshot models of exploited ecosystems. The Ecopath approach was first developed by Polovina (1984), which has since 1990 continually being developed to incorporate additional features in the software. The Ecosim later emerged in 1995 (Walters et al., 1997, 2000) while Ecospace was developed in 1998. The Ecopath program helps in building a mass balanced trophic model by grouping different species and taxa into functional groups, and using various input parameters including diet composition, fishing catch rates, etc. While Ecopath provides a snapshot basic view of an ecosystem, the Ecosim extends the model by incorporating temporal dynamics, while the Ecospace feature allows to explore the trophic dynamics in a spatial explicit manner over a spatial map grid (Walters et al., 1999).

In this chapter, I explore the trophic dynamics present within the various functional groups occurring in the mangrove-lined creeks of Coringa by using the Ecopath approach with Ecosim (EwE) model. The main aim in this chapter was to assess the trophic ecology of the ichthyofauna in the East Godavari River Estuarine Ecosystem (EGREE), Andhra Pradesh. For this, the scope of the study is the mangrove-lined creek system of Coringa Wildlife Sanctuary (CWS) that is home to a diverse biological community as well as supports small-scale fisheries targeting different taxa.

The research questions that I had set out before initiating this study are:

Question 1. What are the feeding habits and patterns of resource (food) utilization in the fish community?

Question 2. Is there any resource partitioning or resource overlap between closely linked fish species in the estuary?

As I carried out my surveys and made observations on the linkages between the local communities and the small-scale fisheries practiced by them within the mangrove-lined creeks of CWS, I realized the importance of the concept of ecosystem-based fisheries management. As a result, I set out additional research questions during my study, which include:

Question 3: What is the current status of the resource exploitation within the mangrove-lined creeks of Coringa?

Question 4: What are the keystone species or functional groups that have crucial role within the food web of the mangrove-lined subtidal creeks of Coringa?

4. 2 Methodology

The ecosystem-based approach was used to assess the trophic linkages and relationships between different functional groups and taxa in the Coringa mangroves. An ecosystem model for the mangrove system of Coringa Wildlife Sanctuary (CWS) was constructed using the Ecopath with Ecosim program (EwE). The EwE is a freely available suite of ecological modelling software that is based on the Ecopath approach, through which static, mass-balanced models of an ecosystem is created (Christensen et al. 2005). This mass-balanced model represents the interactions and organic matter flow between species or group of species.

An Ecopath model is broadly based on two equations:

1) The first equation defines the production for each of the group/species as:

Production = catch + predation + net migration + biomass accumulation + other mortality

2) The second equation derives from the principle of conservation of matter within a group, and defining the mass-balance approach of Ecopath:

Consumption = production + respiration + unassimilated food

The trophic mass-balanced relationships can be generally expressed as:

$$B_i\,(P/B_i)\,EE_i - y_i - B_j\,(Q/B)_j\,DC_{ji} = 0$$

where B_i and B_j are biomass of functional groups *i* and *j* respectively, $(P/B)_i$ is the ratio of production to biomass of functional group *i*; EE_i is the Ecotrophic Efficiency of *i* and is described as the proportion of the production that is utilized in the system; Y_i is the fisheries yield of *i*; $(Q/B)_j$ is the ratio of consumption per unit biomass of functional group *j*; and DC_{ji} is the proportion of prey *i* in the diet of predator *j*.

The Ecopath model requires at least 3 of the 4 parameters B_i, $(P/B)_i$, $(Q/B)_j$, and EE_i for each of the functional group along with DC_{ji} and Y_i.

4.2.1 Creation of functional groups

Based on the observations made during the fishing surveys in 2015-2017, a total of 21 functional groups (single species or groups of species) were defined (Table 4.1). These functional groups used in the model were selected based on the data availability. The primary producers were represented by phytoplankton, mangroves and benthic algae. The finfish species recorded in the mangrove-lined creeks during the fishing surveys were categorized into five broad groups including planktivorous fishes, detritivore fishes, zoobenthivore fishes, piscivore fishes and mudskippers. In addition to these five groups, the species *Mystus gulio* (most abundant fish species in the estuary), and *Oreochromis mossambicus* (non-native species occurring in the sanctuary) were included as separate groups due to an interest to understand their potential role or impact within the system. A functional group representing detritus was also included in the model.

The other important mangrove-associated species considered in the model included mud crabs, oysters, blood cockles, penaeid shrimps, subtidal benthic macrofauna, intertidal macrofauna, and zooplanktons. We also included aquatic birds occurring or feeding in the mangroves, and higher mammals including otters and fishing cats. The otters are wetland-dependent mammal species that feed on fishes and other aquatic species while fishing cats are unique, small cat species that are known to feed on fishes along with rodents and birds.

4.2.2 Model construction, data collection and input

For each of the functional groups, five input parameters were used that included biomass (B), diet composition (DC), annual production per unit of biomass (P/B), annual consumption per unit of biomass (Q/B), and annual fisheries yield (Y). For most of the functional groups, the data was collected from published literature. Adjustments were made in their biomasses and percentage of diet composition and other parameters until a mass balanced model was stumbled upon and run with 1000 iterations.

The biomass and fisheries information for the fish groups were used from my own surveys (please see the detailed methodology at Chapter 3). The average fish biomass was estimated from the equation B=Y/F (Gulland, 1971) wherein Y is the annual coverage catch rate of each functional group and F is the fishing mortality coefficient.

The biomass for mangroves was calculated on the basis of primary data of the density and DBH of mangroves collected from CWS by Sivakumar et al., 2017. Likewise for fishing cats and birds, the density estimates and abundances respectively in CWS were used from Sivakumar et al., 2017. Diet composition for fishing cats and smooth-coated otters in CWS was also used from primary studies carried out by other authors (Malla & Sivakumar 2014, Malla et al. 2018)

For other functional groups, information on their biomass, diet, and fisheries in CWS were collated from published sources. Diet data for the most common fish species in each functional groups were taken from published literature.

Table 4.1. Components of the functional groups (apart from detritus) used to develop the preliminary Ecopath model of Coringa Wildlife Sanctuary

S. No.	Functional group	Species/subgroups
1	Fishing cat (Figure 4.7)	Top predator
2	Smooth coated otter	Secondary predator
3	Birds	Fish consuming birds including Asian openbill, Painted stork, egrets, herons, and other aquatic birds
4	Piscivore or Carnivore fishes	Fullbeak, Halfbeak, Seabass, etc.
5	Zoobenthic fishes	Silver sillago, snappers, silverbiddies, grunts, croakers, etc.
6	*Mystus gulio*	-
7	*Oreochromis mossambicus*	-
8	Planktivore fishes	Glass perchlets, silverbellies
9	Detritivore fishes	Mullets
10	Mudskippers	Omnivores
11	Oysters	Window pane oysters and other bivalves apart from blood cockles
12	Blood cockles	-
13	Crabs (Figure 4.8)	Mud crabs, tree climbing crabs, etc.
14	Intertidal macrofauna	Gastropods, polychaetes, etc.
15	Subtidal benthic macrofauna	Polychaetes, nematodes, etc.
16	Shrimps	Penaeid brackish water shrimps
17	Zooplankton	Primary consumer - Copepods, bivalve larvae, amphipods, fish larvae, etc.
18	Mangroves (Figure 4.6)	Primary producer – *Avicennia* sp., *Rhizophora* sp., *Excoecaria agallocha*, etc.
19	Benthic producers	Primary producer - Benthic algae
20	Phytoplankton	Primary producer - Diatoms, algae, etc.

Values for other input parameters were collected from published literature or sourced from FishBase. When the information on an input parameter for a specific functional group was not available for CWS, data available from other mangrove systems or estuaries located in the Bay of Bengal region or the Indo- West Pacific region was used. Following Winberg (1956), a value of 0.2 or 20% was assigned to the unassimilated food. In a few instances, guestimates were also provided based on the observations made during the field surveys or on the general understanding of the ecological and social context of the ecosystem.

The Ecotrophic Efficiency (EE), which is essentially the proportion of a group's yield that is consumed within a system or caught by a fishery, was estimated by the software once the input parameters were entered into the model. An EE value over 1 is practically not possible, indicating imbalance in the input parameters. To balance the model, it was ensured to maintain the EE values between 0 and 1 as per the definition (Christensen et al. 2005).

4.2.3 Model output and indices

EwE creates a series of indices to explain energy flow within the food web and examine the important relationships between the different functional groups. Two of the important indices that were used to examine the system were multiple trophic impact (MTI) and index of keystoneness (KSi). The MTI examines the impact of a unit change in a functional group's biomass on the biomass of other groups (Ulanowicz and Puccia, 1990). The keystoneness index (KSi) helps in identifying groups that are relatively less abundant or low in biomass but exert disproportionately higher impact on the food web (Libralato et al., 2006). KSi does not evaluates the functional group of detritus. The functional groups with KSi close to 0 or higher than 0 were considered to be important. Other indices used in the study were represented in Table 4.2**.**

Finally, the model generated for CWS was compared with previous models generated for estuaries in India and other countries using the different indices that explain trophic structure, energy flows between the functional groups, and exploitation levels in terms of fisheries.

Table 4.2. List of the indices used to describe the ecological status of Coringa Wildlife Sanctuary.

Performance indicator	**Definition**
Mean trophic level of the catch (MTL)	Weighted mean value of all trophic levels in the catch
Gross efficiency of the fishery (GE)	Ratio of the total fish catch and NPP
Net system production (t km^{-2} year^{-}^{1}) (NSP)	Difference of total respiration from the total primary production
Total catch (t km^{-2} year^{-1}) (C)	Summation of catch of all fish groups
Total biomass (exc. detritus) (t km^{-2} year^{-1}) (B)	Total biomass of all functional groups except detritus
Total primary production/respiration (PPR/R)	Total primary production/Total respiration
Total primary production/B (PPR/B)	Total primary production/total biomass
Total biomass/TST (B/TST)	Total biomass/total throughput
Sum of all consumption (t km^{-2} year^{-1}) (SC)	Total consumption within the ecosystem
Sum of all exports (t km^{-2} year^{-1}) (SE)	Total exports from the ecosystem
Sum of all respiratory flows (t km^{-2} year^{-1}) (SR)	Total respiratory flows within the ecosystem
Sum of all flows into detritus (t km^{-2} year^{-1}) (SD)	Total flows to detritus within the ecosystem

Sum of all production (t km^{-2} year^{-1}) (SP)	Summation of all production
Total system throughput (t km^{-2} year^{-1}) (TS)	Summation of total consumption, total export, total respiration, total flows to detritus in an ecosystem
Mean path length (MPL)	Average ecological distance between various pathways
Finn's cycling index (FCI)	The fraction of flows of TST recycled
System omnivory index	Average omnivory indices of all consumers weighed by the logarithm of each consumer's food intake
Ascendancy (%) (AS)	This measures the extent of balance of food web in an ecosystem.
System overhead (%) (SO)	Energy in balance for an ecosystem. It corresponds to Ascendency value.

4.3 Results

A preliminary mass-balanced model for Coringa Wildlife Sanctuary (CWS) was created using the Ecopath function of EwE software. Though the model is a preliminary version, it still provided a broad overview of CWS' ecosystem status. Values of the different indices estimated by the model have been included in Table 4.3**.**

The total throughput of CWS, which is the aggregate of all the flow components of the system (total consumption + total export + total respiration + total flow to detritus), was estimated at 5,135 t/km^2/year. Of this, the total export (1934 t/km^2/year) was the highest contributor closely followed by the total flow to detritus (1918 t/km^2/year). The overall transfer efficiency between trophic levels was 19.8%

while the transfer efficiency from primary producers is 20.1% and from detritus is 18.1% (Table 4.3). As per the Lindeman spine representation (Figure 4.1), most of the total system throughput (~84%) is generated by the first trophic level (TL 1) followed by TL 2 (14%).

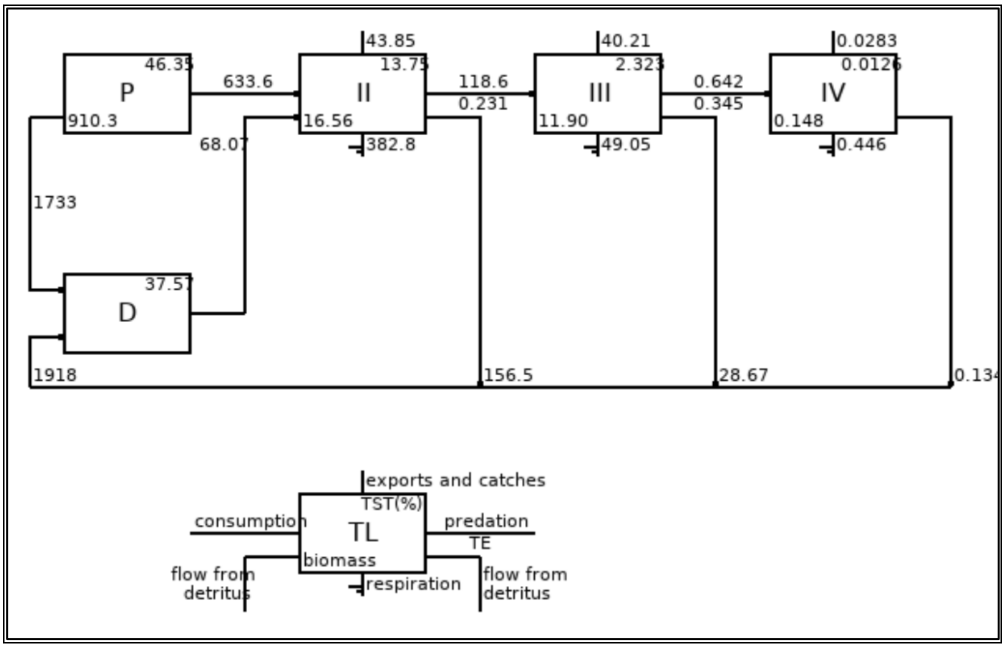
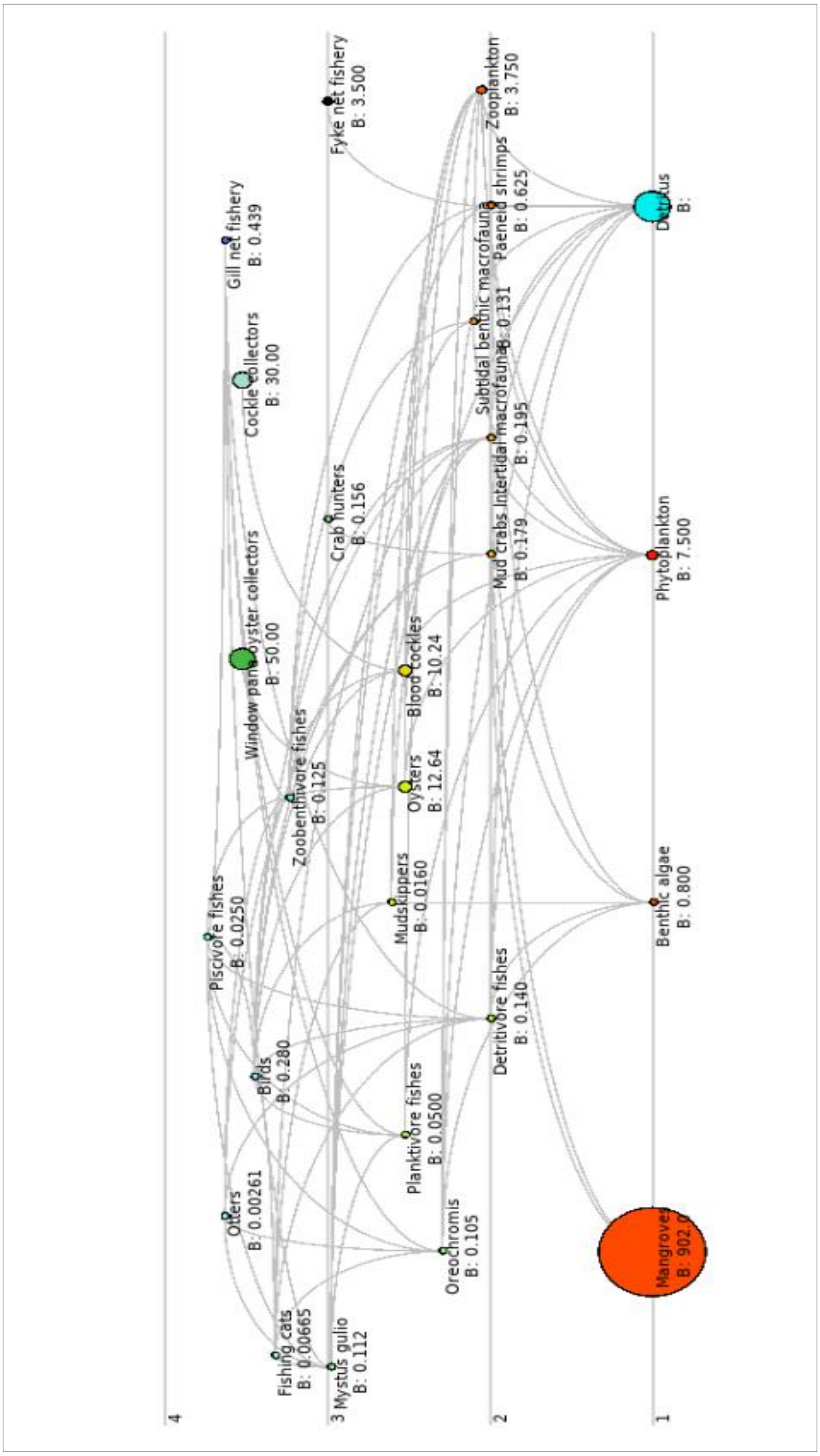


Figure 4.1. Lindeman spine representation of the mass-balanced trophic model of CWS



4
3
2
1
Fyke net fishery
B: 3.500
Zooplankton
B: 3.750
Gill net fishery
B: 0.439
Paeneid shrimps
B: 0.625
Detritus
B:
Cockle collectors
B: 30.00
Subtidal benthic macrofauna
B: 0.131
Intertidal macrofauna
B: 0.195
Crab hunters
B: 0.156
Mud crabs
B: 0.179
Phytoplankton
B: 7.500
Window pane oyster collectors
B: 50.00
Blood cockles
B: 10.24
Zoobenthivore fishes
B: 0.125
Oysters
B: 12.64
Mudskippers
B: 0.0160
Benthic algae
B: 0.800
Piscivore fishes
B: 0.0250
Detritivore fishes
B: 0.140
Birds
B: 0.280
Planktivore fishes
B: 0.0500
Otters
B: 0.00261
Oreochromis
B: 0.105
Mangroves
Fishing cats
B: 0.00665
Mystus gulio
B: 0.112

Figure 4.2. A representation of the mass-balanced trophic model of Coringa Wildlife Sanctuary using the Ecopath approach

The ratio of total primary production to total respiration, considered as an indicator of the maturity of an ecosystem, was 5.47. A similar indicator, net system production was estimated at 1934 t/km^2/year. Indicators for energy use and material recycling in the system – Finn's cycling index and Finn's mean pathway, were estimated as 1.04% and 2.2 respectively.

The trophic levels in the system varied from 1.0 for primary producers and detritus to 3.7 for the piscivorous fishes. The total biomass of the system (excluding detritus) was calculated as 939 t/km^2, of which 96% was due to the mangroves while ~1% each of the total biomass was contributed by window-pane oysters and blood cockles (Figure 4.2). Biomass of the other consumers was extremely low. The total catch for the sampling year was 84.1 t/km^2/year, and the mean trophic level for the catch was 2.5.

Significant degree of niche overlap was found among a number of functional groups, especially among the blood cockles and the window-pane oysters, both in terms of their prey and their potential predators. These two groups also shared similar prey resources with planktivorous fishes, and thus had high prey overlap as well as occupied the same trophic level within the food web. *Oreochromis mossambicus* showed a high degree of prey overlap with penaeid shrimps and benthic macrofauna. The other finfish groups did not show any prey overlap among each other, suggesting certain degree of niche segregation between each other. The niche overlap in terms of similar predators has been represented in Figure 4.3.

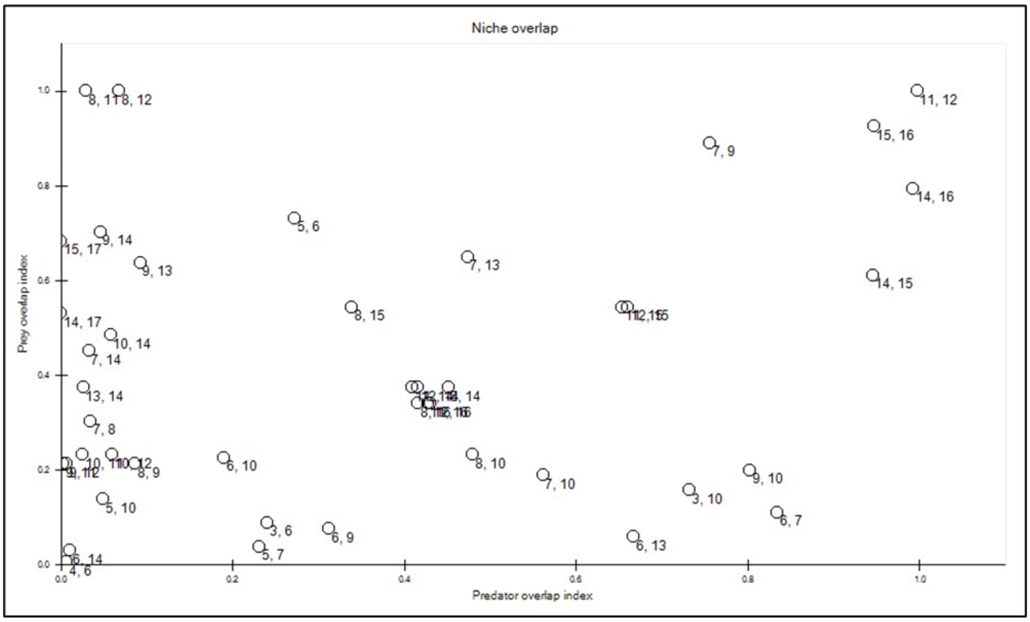


Figure 4.3. Niche overlap between the functional groups. Overlap between the predators is represented on the right portion of the graph and overlap between the prey groups is represented on the left portion. **(**1 denote Fishing cats; 2 denotes Smooth-coated otters; 3 denotes Fish-eating birds; 4 is Piscivore and carnivore fishes; 5 is Zoobenthivore fishes; 6 is *Mystus gulio;* 7 is *Oreochromis* spp.; 8 is Planktivore fishes; 9 is Detritivore fishes; 10 is Mudskippers; 11 is Oysters; 12 is Blood cockles; 13 is Crabs; 14 is Intertidal macrofauna; 15 is Subtidal benthic macrofauna; 16 is Shrimps; 17 is Zooplanktons)

Results of the mixed trophic impact (MTI) analysis are provided at Figure 4.4. The MTI analysis indicated a positive role of phytoplanktons on several functional groups including zooplanktons, blood cockles, window-pane oysters and planktivorous fishes, while a relatively negative role of benthic algae on intertidal macrofauna and mudskippers. Mangroves had a positive impact on crabs as well as played an important part in sustaining the crab hunter’s community of Coringa.

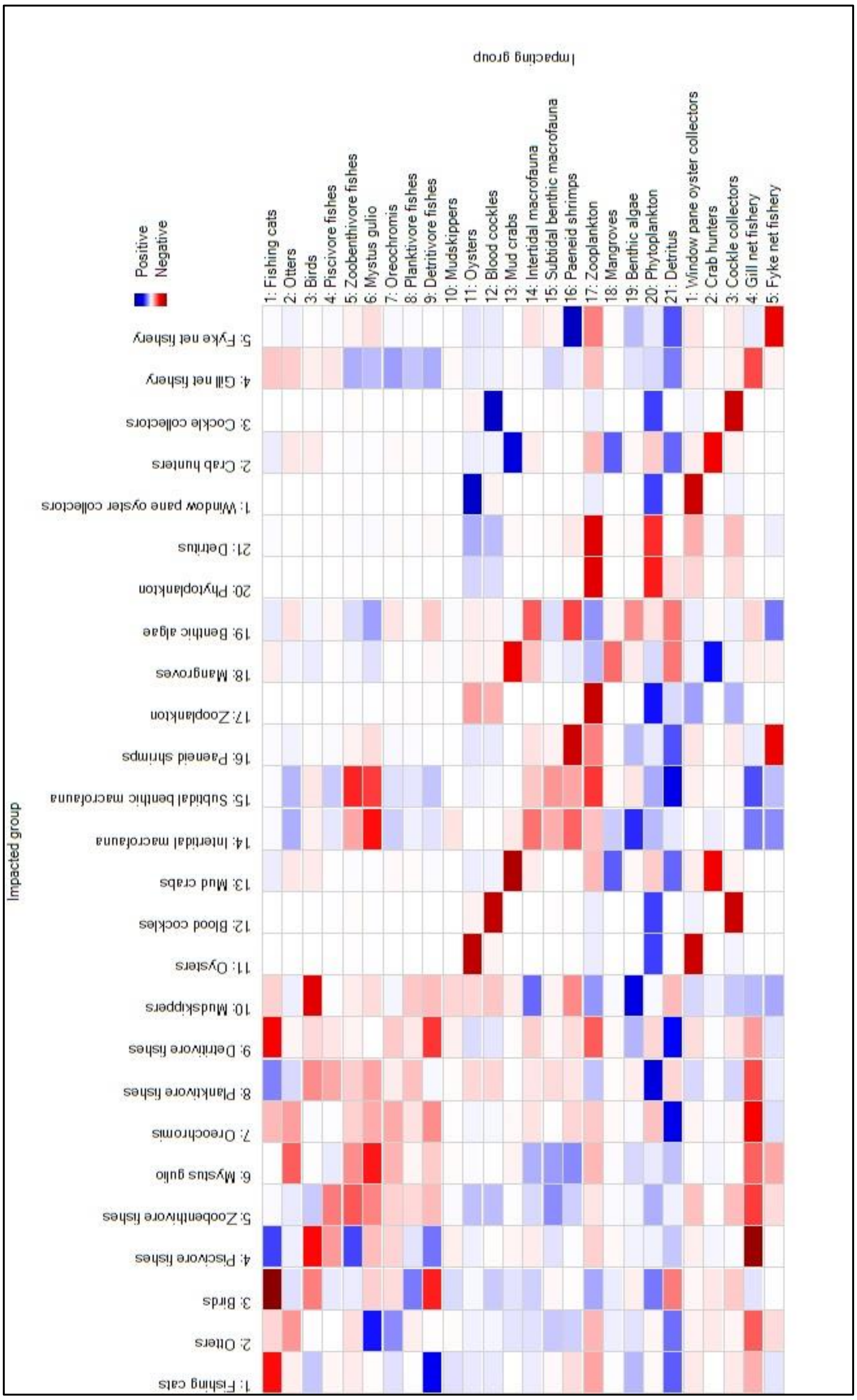


Figure 4.4. Graphical representation of the Mixed Trophic Impact analysis.

Table 4.3. The details of each functional group after running the (preliminary) mass-balanced Ecopath model

	Group name	**Trophic level**	**Hab. area (proportion)**	**Biomass in habitat area (t/kmÂ²)**	**Biomass (t/kmÂ²)**	**Production / biomass (/year)**	**Consumption / biomass (/year)**	**Ecotrophic Efficiency**	**Production / consumption (/year)**
1	Fishing cats	3.327127	0.95	0.007	0.00665	0.16	50	0	0.0032
2	Otters	3.636368	0.87	0.003	0.00261	0.15	50	0	0.003
3	Birds	3.451898	1	0.28	0.28	0.18	0.484	0.989583	0.371901
4	Piscivore fishes	3.743221	0.25	0.1	0.025	0.86	3	0.768651	0.286667
5	Zoobenthivore fishes	3.236842	0.25	0.5	0.125	1.1	12.9	0.976658	0.085271
6	*Mystus gulio*	2.981579	0.25	0.449	0.11225	2	14.9	0.826837	0.134228
7	*Oreochromis mossambicus*	2.297369	0.25	0.422	0.1055	1.7	6.2	0.882743	0.274194
8	Planktivore fishes	2.526316	0.25	0.2	0.05	2.57	26.2	0.84692	0.098092
9	Detritivore fishes	2	0.25	0.56	0.14	2.5	8.2	0.983149	0.304878
10	Mudskippers	2.610526	0.4	0.04	0.016	2.1	3.37	0.898125	0.623145
11	Oysters	2.526316	0.07	180.5	12.635	4	10	0.995965	0.4
12	Blood cockles	2.526316	0.1	102.37	10.237	3.9	10	0.760281	0.39
13	Crabs	2	0.95	0.188	0.1786	3.36	16.8	0.304288	0.2
14	Intertidal macrofauna	2	0.92	0.212	0.19504	3	11	0.935706	0.272727
15	Subtidal benthic macrofauna	2.105263	0.5	0.26192	0.13096	7	11.14	0.93154	0.628366
16	Shrimps	2	0.25	2.5	0.625	7.621	13.6	0.991505	0.560368
17	Zooplankton	2.052632	0.25	15	3.75	40	160	0.968814	0.25

18	Mangroves	1	0.82	1100	902	0.517	-	0.003677	-
19	Benthic algae	1	0.08	10	0.8	10.5	-	0.339897	-
20	Phytoplankton	1	0.25	30	7.5	252.2	-	0.332569	-
21	Detritus	1	1	-	-	-	-	0.035494	-

The penaeid shrimps, which sustain large parts of the local fisheries of Coringa, had a negative impact on benthic algae but a positive impact on *Mystus gulio*. On the other hand, *Mystus gulio* had a negative impact on subtidal and intertidal faunal communities but a positive impact on the Smooth-coated otter population. The non-native *Oreochromis mossambicus* did not have any major impact on other functional groups. Fishing cats, which were also the topmost keystone group (Keystonness index KSi = -0.0841), were found to be positively regulating the piscivore fish group. The other two keystone groups (Figure 4.5) were phytoplankton (KSi = -0.155) and zooplankton (KSi = -0.179).

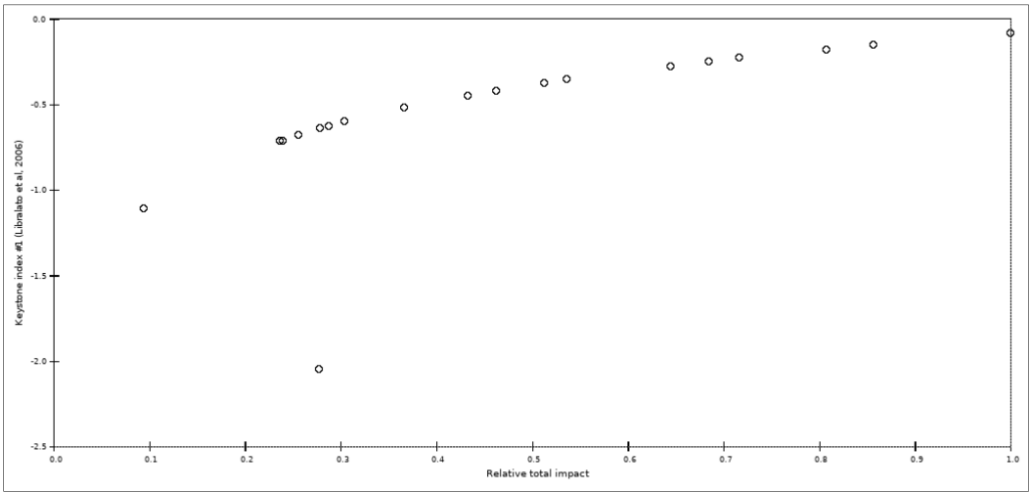


Figure 4.5. Representation of the functional groups in CWS based on their keystonness index (KSi); the fishing cat has the highest keystonness index, and is represented by a circle at the right-uppermost corner of the graph)

4.4 Discussion

This is perhaps the first attempt to devise a model of the food web of Coringa Wildlife Sanctuary (CWS). The Coringa system is a low productive system but has high gross efficiency (GE = 0.03) when compared with other estuaries of India as well as in other countries. A very high catch rate of the fisheries (84.1 t/km^2/year) was estimated by the model for Coringa. In contrast to Coringa, the total catch rate estimated in case of Sundarbans was 1.69 t/km^2/year with a gross efficiency of 0.001 (Dutta et al., 2017) while Bahı´a Ma´laga estuary, a mangrove-lined estuary in Brazil, had a total catch of 0.2774 t/km^2/year and a gross efficiency of 0.0001 (Castellanos-Galindo et al., 2017). The catch rates observed in this study are perhaps among the highest for any estuarine model of the world.

The trophic level (TL) is considered as a fundamental part of any ecosystem model (Pauly and Christensen, 2000), and the mean trophic level of fisheries catch provides insight into the extent of fishing pressures (Dutta et al. 2017). It is calculated on the basis of an organism's preys and predators, and their abundances in the system. In Coringa, the 21 functional groups ranged from TL 1 (corresponding to primary producers and detritus) to TL 3.7 (corresponding to piscivore fishes). Terrestrial species including Fishing cats, Smooth-coated otters, and the birds occupied TL 3.3, TL 3.6, and 3.5 respectively. The diet of Fishing cat in this sanctuary mainly consists of fishes but it also consumes rodents, aquatic birds, etc. (pers comm. Giridhar Malla). In case of fishes, it potentially consumed higher proportion of Mugilidae followed by catfishes, cichlids, etc. Majority of the fish species belonged to TL 2, ranging from 2 for detritivores to 3.7. Most of them are commercially important except for the mudskippers. Additionally, other groups including oysters, blood cockles, shrimps and mudcrabs, which are also commercially important in the region, also belonged to TL 2. Since most of the commercially important species in this system belong to TL 2, the mean trophic level of fisheries catch was estimated as 2.5. A similar pattern has been detected from other ecosystems of India including the Sundarbans estuary (Dutta et al., 2017) and southwest coast (Vivekanandan et al. 2001). Dependence of fisheries on the lower trophic levels may be explained by the composition of the fish community of CWS where detritivores such as mullets, and zoobenthivores such as catfishes (*Mystus gulio, Arius* spp., etc.) are dominant, and also tend to occupy lower trophic levels in a system. At the same time, role of high fishing pressures cannot be neglected since other indicators including the high gross efficiency value. This is particularly significant for the window-pane oysters, blood cockles, and shrimps, which recorded greater proportions of fishing mortality than natural mortality.

Mangroves, part of the primary producer group, contributed nearly 95% to the system biomass (excluding detritus). Window-pane oysters, blood cockles, phytoplanktons, and zooplanktons are the other taxa with higher biomass relative to the other taxa. The dominance of mangroves in terms of the overall system's biomass has also been observed in the Bahia Malaga mangrove, Colombia (Castellanos-Galindo et al., 2017). In this study, the author found that the inclusion of mangroves as a discreet taxon led to higher values of the different indices when compared to the model wherein the mangroves were included as part of the detritus. Since, in CWS, the mangroves constitute a major and dominant part of the landscape, it was important to consider it separately than detritus (Castellanos-Galindo et al., 2017). Despite this, utilisation of mangroves by consumers was poor in comparison to the other primary producers, which was also evident by the extremely low EE values for the former. Phytoplanktons and benthic algae, though having lower biomass, made greater contributions to the higher trophic levels. The transfer efficiency (TE) was, therefore, high for CWS. Similar higher values for TE were recorded for Zuari estuary (Sreekanth et al., 2021) and Hooghly-Matla estuary.

On the contrary, the total system throughput (TST) was nearly comparable to Sundarbans estuary (Dutta et al., 2017) but was relatively lower than other coastal systems of India (Sreekanth et al., 2021). TST is a measure of all the flows in a system and is an indicator of the overall size of an ecosystem. Therefore, the CWS is still a smaller system ecologically. The lower values of PP/R, PP/B, Finn's cycling index

(FCI), System Omnivory Index (SOI) also suggest that CWS is still an immature and a developing system. A relatively higher relative ascendancy than the other Indian models is indicative of a system having higher stability, helping it to resist any perturbations from within the system. This may be explained by the protected nature of CWS, allowing for proliferation of a number of primary producers in the ecosystem that can help maintain the ecosystem flows, if anything was supposed to happen. At the same time, the top-down control due to the presence of terrestrial species possessing aquatic habits may also play an important role in contributing to the complexity and stability of the system. It should be noted that Fishing cat has been identified as a keystone species by the model. On the other hand, a lower relative overhead value signifies higher vulnerability to external disturbances, which is confirmed by a lower FCI value. This is an important outcome considering the very high fishing pressures on fishes and a number of other functional groups of CWS.

CWS being a protected area and having a large contiguous patch of mangrove forests, it provided with a good opportunity to examine the trophic interactions and fluxes within a protected mangrove forest. Although, these mangroves are not completely isolated from anthropogenic perturbations; they are subjected to high fishing pressures, as evident from these results, and subjected to threats that translate to this sanctuary from the upstream reaches. This Ecopath model of CWS, however, can be further strengthened. The biomass for detritus needs to be estimated through published literature, along with rechecking the sources for other functional groups. I also could not include a few taxa in this model due to their extremely low biomasses or because of absence of any data. Additionally, this model can be utilized to examine the changes in the trophic relationships or on other ecological processes driven by external perturbations including increasing fishing pressure, major pollution events, and sea level rise.

Figure 4.6. Mangrove floor showing leaf litter of mangrove species including *Xylocarpus granatum* in Coringa Wildlife Sanctuary, Andhra Pradesh

Figure 4.7. Fishing cat camera trap image from the mangroves of Coringa Wildlife Sanctuary, Andhra Pradesh. This species has been identified as a keystone species in the Ecopath model of CWS.

Figure 4.8. Catch comprising of orange mud crab *Scylla olivacea*, in a crab collector's basket seen inside the Coringa Wildlife Sanctuary.

Chapter 5

Role of mangroves in structuring the ichthyofauna in Coringa Wildlife Sanctuary

5.1 Introduction

Situated at the interface of coastal land and marine habitats in the tropical and subtropical regions, mangrove forests are recognized for their important role as habitats for fishes. Several studies have indicated higher species richness and abundance within the mangrove-lined estuaries than in adjacent unvegetated habitats such as mudflats (Henderson et al., 2019). These coastal forests constitute an integral part of the seascape, contributing significantly to the fisheries of a region (Aburto-Oropeza et al., 2008; Anneboina & Kavi Kumar, 2017). This role is more noteworthy for areas such as the coastal zones of Andhra Pradesh, which lack other highly productive marine habitats, including seagrasses and coral reefs. In certain places such as the Caribbean, the proximity of mangroves has been found to positively influence the density and diversity of fishes in adjacent coral reef habitats.

Two main reasons have been propounded to explain the attractiveness of mangroves for fish:

a) The structural complexity within a mangrove forest makes it difficult for the larger carnivorous and predatory species to enter and navigate easily. Thus, providing safer refuges to the juveniles and smaller-sized fishes (Robertson & Blaber, 1992; Igulu et al., 2014).

b) The higher abundance of food resources, due to the higher productivity of the mangroves, coupled with a detritus-based food web, attract many fishes and other invertebrates (Robertson and Blaber 1992).

The structural complexity of habitat is one of the fundamental factors shaping a biological community and driving habitat usage by taxa (Downes et al., 1998; Kovalenko et al., 2011). The unique features of a mangrove forest, including its unique root systems (pneumatophores, prop roots, etc.), tree density, canopy cover, overhanging vegetation, the understory composed of mangrove-associated shrubs, elevation, and the reticulating network of inter-tidal creeks, give rise to several microhabitats. The structural complexity, thus created in the mangrove forests, provides excellent refuge and feeding habitats for fishes.

When talking about the physical architecture of mangroves, their unique root systems, which are adaptations for surviving in saline, hypoxic environments, deserve a special mention. The prop roots of *Rhizophora* spp. that branch out from its trunk create a complex, constricted microhabitat – perhaps allowing the usage by fishes of a particular size class. In contrast, the pencil-like and peg-like pneumatophores of *Avicennia* spp. and *Sonneratia* spp., respectively, lead to the creation of microhabitats different from those of the prop roots. Pneumatophores emerge only a few centimetres above the substratum, therefore largely getting submerged by the tidal waters during high tide. This leaves a few meters of water column for the fishes to move freely into the intertidal zone and the forest, thus allowing them to use a larger area of the mangrove forest. Likewise, other features such as overhanging vegetation, canopy cover, etc., add to the physical complexity within a fish habitat, leading to spatial differences at a very small scale.

While a heterogeneous habitat may include an array of suitable microhabitats, habitat usage will depend mainly on its accessibility to the animal (Igulu et al., 2014). The Indo-Pacific region's coastal habitats, including the Bay of Bengal, mainly experience semidiurnal tides. As a result, the intertidal zones are accessible to the fish for use only when they are inundated during the high tides. Accessibility to specific elevated mangrove patches is further restricted to periods of spring high tides or during the monsoon floods. Therefore, along with the structural complexity, these short-term changes are driven by diel and tidal cycles (as well as their interactions) and affect the intertidal fish assemblages in mangroves (Castellanos-Galindo and Krumme, 2013).

An overwhelming number of studies have been carried out to study the relationships between abiotic factors and fish assemblages in the main, sub-tidal channels of mangroves (Blaber et al., 1989; Laroche et al., 1997; Rönnbäck et al., 1999; Barletta et al., 2005, 2008; Huxham et al., 2008; Ramos et al., 2011; Koochaknejad et al., 2020) including a number of recent publications from India such as Sreekanth et al. 2020, Roshni et al. 2021, etc. However, many of such studies examining the microhabitat uses of fishes in mangroves are from the neotropics, where the coastal habitats are microtidal, and the mangroves are permanently inundated. On the contrary, most of the mangroves of the Indo-Pacific are riverine in nature with a more extensive tidal regime and are inundated (or available) only during the high tides. Therefore, in this chapter, I examine the potential role of microhabitat features in the structuring of the fish assemblages within the small, intertidal creeks of CWS. The influence of other factors, including the diel, tidal cycles, and seasons are also studied. The intertidal creeks considered in this study differ in the management treatment but also possess distinct microhabitat variations, making them structurally different from each other. This allowed me to incorporate management types as another factor and to examine their potential effect on habitat usage of fishes.

In this chapter, therefore, I intend to address the following research questions:

3.1 Is there a role played by the root systems or the different microhabitat features in shaping the fish community in Coringa Wildlife Sanctuary?

3.2 Do the management strategies within the Coringa Wildlife Sanctuary influence the fish assemblage structure of the intertidal creeks of Coringa mangroves?

5.2 Methodology

5.2.1 Sampling design

Four mangrove-lined intertidal creeks were selected to assess the differences in the fish assemblage structure within intertidal creeks with differing management types and microhabitat features (Figure 5.1). The width of the intertidal creeks ranged from 1.5 to 2.5 m in the subtidal creeks of CWS. All the four creeks that were selected for this study were located within the Coringa subtidal creek system. This was done to minimize the influence of small-scale differences in environmental factors between the selected intertidal creeks. Other reasons the Coringa creek system was selected included the presence of differing management types, ease of accessibility, safety, and easier logistics.

Figure 5.1. Map representing the Coringa subtidal creek system, showing the four intertidal creeks selected for this objective. The blue-coloured creeks are natural creeks while the red coloured ones are the artificial creeks dug out to carry out mangrove plantations within the sanctuary. (The longer blue marked creeks represent natural creeks; the shorter red-marked creeks represent artificial creeks for this study)

Two of the four creeks included intertidal creeks draining natural patches of mangroves with no known history of plantation or degradation (see Figure 5.6 at end of this chapter). The rest of the two creeks were artificially created by the Forest Department to facilitate the regeneration of newly planted mangrove saplings within the blank spaces inside Coringa Wildlife Sanctuary (CWS) (see Figure 5.7 at the end of this chapter). Therefore, the two types of management regimes included creeks lined by naturally growing mangroves and creeks created artificially for mangrove plantations. These sites were identified and selected based on the preliminary observations that indicated differences in the microhabitat structure of the two types of creeks, wherein the artificially created creeks were dominated by the *Avicennia marina* that was planted along the creek for regeneration. On the other hand, the creek lined by naturally growing mangroves visibly exhibited higher structural complexity and mangrove species diversity than the artificial creeks, with species like *Avicennia officinalis, Sonneratia apetala, Avicennia alba, Excoecaria agallocha, Acanthus ilicifolius.*

This study was carried out from 2016 to 2017, accounting for three major seasons, *viz*. Winter (December to February), Summer (April to June) and Rainy (July to November). An equal number of sampling surveys were carried out in the spring tides and neap tides to account for the influence of tidal regimes. Smaller block nets of mesh sizes 20mm were set across the mouth of the intertidal creeks just before the onset of low tide to block the further movement of fishes in or out of the creeks (Castellanos-Galindo and Krumme, 2013). Wooden poles were used to tie the net at the creek entrance and set it upright, while the top line of the net was pushed deep into the mud by hands and feet (see Figure 5.6 and Figure 5.7).

During the neap tide periods, the creeks, except for one of the natural creeks, would entirely become empty during the ebbing tides. In such instances, the stranded fishes upstream of the blocked mouth were intensively searched and collected by hand for further identification. The fishes that were sampled during the surveys were identified to the species level or collected in 10% formalin for further identification in the laboratory. Identifications were made using taxonomic keys available for the region (Day, 1958; Fischer and Whitehead, 1974). At each sampling occasion, the standard length, total length, and wet weight of every individual of each species were recorded.

5.2.2 Data analysis

A checklist was created for the species recorded within the intertidal creeks during this study. The species were then categorized into various trophic guilds to identify the main functional groups using the creeks. Next, rarefaction curves based on abundances were prepared for each creek to check for sampling completeness and compare the species richness between the creeks. Finally, a non-parametric estimator of species richness, Chao 1 (S_{Chao1}), was used to estimate the asymptotic species richness for each creek. To prepare the curves and estimate S_{Chao1}, the iNEXT version 2.0.20 package in R (Hsieh et al 2016). I used R version 4.1.1 (2021-08-10) (The R Foundation for Statistical Computing programme, 2021).

Differences in observed species number, species diversity index (H') and species evenness (J) were assessed using 2-way ANOVA and were analyzed using the non-parametric Kruskal-Wallis test. If any significant differences were found at $p < 0.05$, it was followed by non-parametric multiple pairwise comparisons using Wilcoxon signed-rank test with Bonferroni corrections on the significance levels, with seasons, creek type, lunar, and diel patterns as fixed factors, while creeks as a random factor. Abundance data were transformed using square root ($\sqrt{(x+1)}$) before carrying out the analyses.

For the multivariate analyses, a distance-based matrix of the square root ($\sqrt{(x+1)}$) transformed abundance data of species was prepared using the Bray-Curtis similarity measure (CLARKE, 1993). To test the null hypothesis of uniform species assemblage across the four sub-tidal creeks, a non-parametric Permutational multivariate analysis of variance (PERMANOVA; (Anderson, 2001) was conducted using the similarity matrix to compare between the creeks as well as between the seasons. Several species were singletons or doubletons, so the species data was reduced to include only the most abundant species (those having a relative abundance of more than 1% and occurring in more than 5% of sampling sites in each habitat). Before conducting PERMANOVA, a multivariate test for measuring dispersion within each creek was done to ensure high dispersion among the groups and did not confound the significant differences between the groups (Anderson, 2006; Anderson et al., 2006). Whenever PERMANOVA resulted in significant differences, a pairwise test was carried out to determine the most differing pair. Finally, the spatial patterns between creeks in each season were visualized using CAP analysis, and the important fish species contributing to the differences were detected by the similarity of percentages (SIMPER).

In addition to the above analyses, the species were also grouped into ecological guilds based on their usage of estuaries. Based on Elliot *et al.* (2007), five guilds were identified: Marine migrants (MM), Marine straggler (MS), Estuarine (ES), C (Catadromous), and FM (Freshwater migrant). Marine migrants are species that spawn at sea but have often been found to use estuaries in large numbers; marine stragglers are marine species that enter the estuaries in low numbers and mainly restrict themselves to the lower reaches; ES are estuarine residents that may or may not be represented by distinct marine or freshwater populations; catadromous species are those who spend their entire trophic life in freshwater habitats but migrate to the sea for spawning, and the freshwater migrants are freshwater species that regularly enter estuaries in moderate numbers, often extending beyond the upper estuarine reaches.

5. 3 Results

5.3.1 Species composition

A total of 18 species belonging to 16 families were recorded in this study (Table 5.1). Polynemidae (2 species) and Cichlidae (2 species) were the two most speciose families, though the contribution of these two families in terms of the number of individuals was low. Among the species, *Mugil cephalus*, *Mystus gulio* and *Dichotomyctere fluviatilis* dominated in terms of overall abundance during the study period (Figure 5.2). These three species, along with *Oreochromis mossambicus and*

Scatophagus argus contributed a little more than 50% to the overall abundance of fishes, reflecting the high dominance of few species in the intertidal creeks.

The fish assemblage in terms of the number of species was dominated by estuarine species (ES)- represented by seven species, followed by marine migrants (MM), comprised of six species. The marine migrants (MM) and the estuarine species contributed equally to the overall number of individuals (39.6% each).

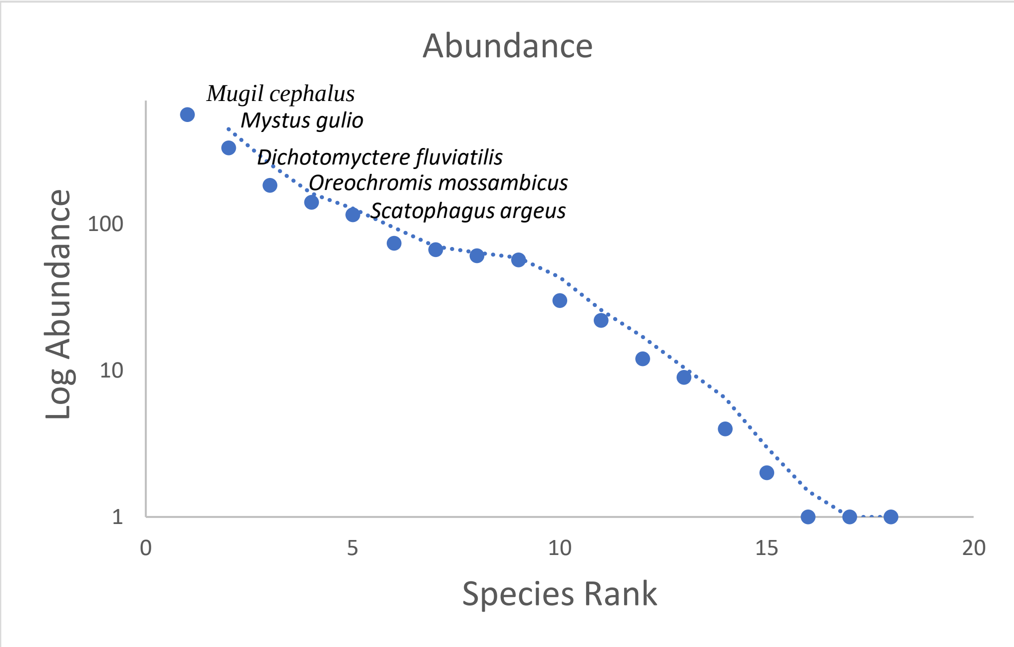


Figure 5.2. Plot showing rank-abundance of the intertidal mangrove fishes recorded during the study period.

The freshwater migrant (FM) was the third most important guild, which comprised of three species and contributed 19.3% to the total number of individuals in the intertidal creeks. The marine straggler (MS) and catadromous (C) guilds were represented by only one species each. These two guilds also made a negligible contribution (<1% and 1.3%, respectively) to the overall abundance of fish.

Table 5.1. List of species recorded from the four intertidal creeks of Coringa in CWS with corresponding number of individuals, where Creek A and B are natural, and Creek C and D are man-made or artificial.

Species recorded	**Total number of individuals**	**Creek A** (Natural)	**Creek B** (Artificial)	**Creek C** (Artificial)	**Creek D** (Natural)
Oreochromis mossambicus	141	52	25	46	18
Glossogobius giuris	67	36	2	17	12
Mugil cephalus	561	191	119	114	137
Mystus gulio	332	161	22	80	69
Lates calcarifer	22	3	5	12	2
Dichotomyctere fluviatilis	184	63	40	31	50
Hyporhamphus limbatus	57	4	22	2	29
Etroplus suratensis	74	2	21	12	39
Lutjanus argentimaculatus	61	5	31	7	18
Ambassis gymnocephalus	12	0	4	1	7
Scatophagus argus	116	56	9	35	16
Butis butis	1	1	0	0	0
Gerres filamentosus	30	9	4	2	15
Acanthurus mata	1	1	0	0	0
Eleutheronema tetradactylum	1	0	0	0	1
Dendrophysa russelii	9	5	0	3	1
Polydactylus sp.	2	0	0	1	1
Plotosus sp.	4	4	0	0	0

5.3.2 Community variables

The observed number of species in the natural creeks (Creek A: 15 spp., and Creek D: 15 spp.) was marginally higher than in the artificial creeks (Creek C: 14 spp., and Creek B: 12 spp.). The individual-based rarefaction curve (Figure 5.3) for Creek A nearly stabilized at $S_{Chao}1$ value of 17 (SE ± 3.7). The $S_{Chao}1$ for Creek B was estimated at 12 (SE ± 0.4) and for Creek C at 15 (SE ± 1.9). The curve for Creek D stabilized at a value of S_{Chao1} = 19.5 (SE ± 7.2), relatively higher than the actual number of species recorded during this study.

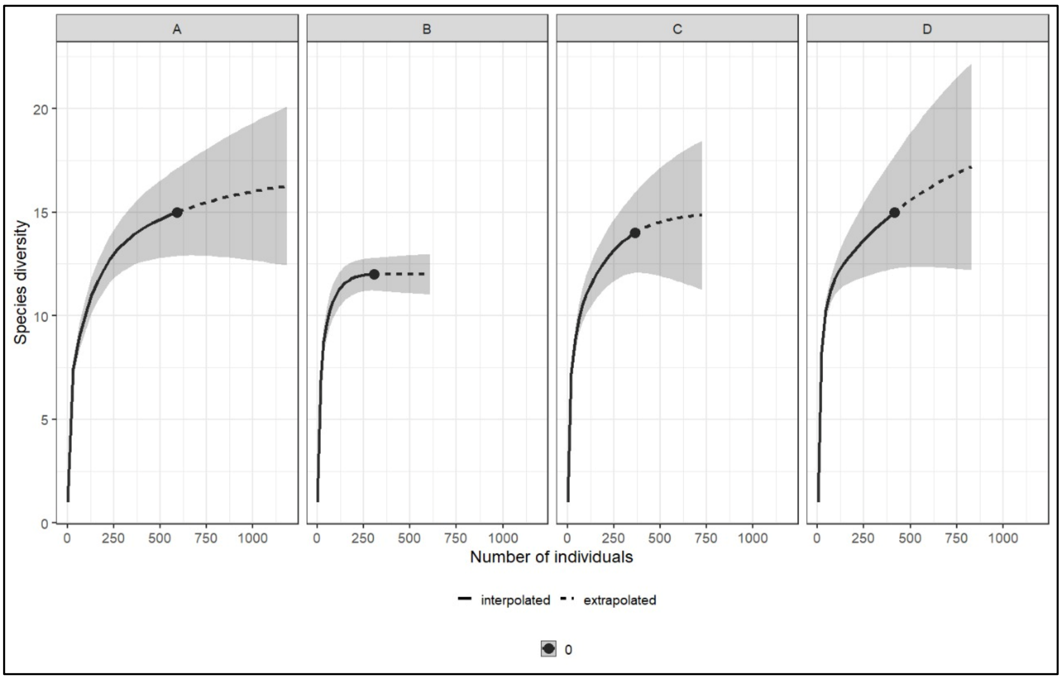


Figure 5.3. Graph showing individual-based rarefaction curves comparing species richness between the four intertidal creeks (A: Creek A, B: Creek B, C: Creek C and D: Creek D) and the shaded areas represent 95% CI. Symbols on the curves represent the observed number of species recorded in each creek.

Therefore, based on the rarefaction carried out, the Chao1 species richness estimator (S_{Chao1}) also suggested that the intertidal Creeks A and D had higher potentially higher species richness than the other two creeks. Likewise, statistical analysis showed the overall abundances to be significantly higher in the natural creeks when compared to the artificial creeks (Figure 5.4).

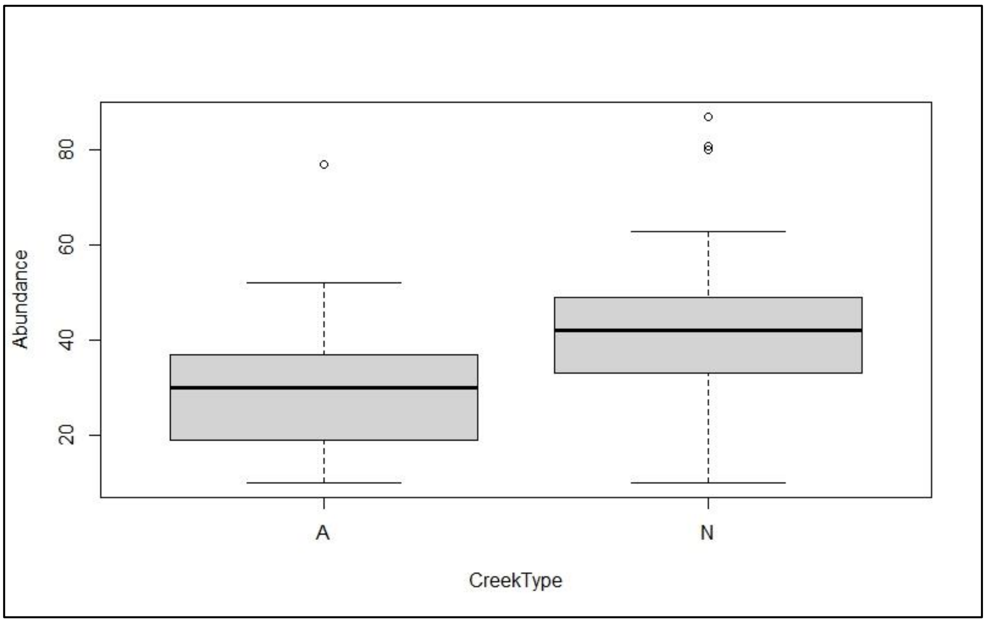


Figure 5.4. Overall abundance of fishes in Artificial (A) and Natural (N) creeks

The mean species diversity (Shannon index, H') was nearly similar for Creek A (H'= 1.18), Creek D (H' = 1.15) and Creek C (H' = 1.02), whereas Creek B (H'= 0.87) had the lowest mean diversity (Table 5.2). The species diversity values in the winter season were highest for all the four creeks; between the creeks, Creek B had the lowest overall diversity in comparison to the other three creeks. However, statistical analyses did not reveal any significant seasonal or spatial patterns in the species diversity or evenness.

Table 5.2. Mean values of the different community variables (Shannon diversity, evenness, number of species) for each of the four intertidal creeks of Coringa subtidal creek system

Creeks	Management type	Mean of Shannon diversity	Mean evenness	Mean no. of species
Creek A	Natural	1.180	0.738	5.0
Creek B	Artificial	0.871	0.631	3.6
Creek C	Artificial	1.018	0.789	4.2
Creek D	Natural	1.154	0.738	4.5

5.3.3 Patterns in intertidal fish assemblage

Temporal differences

The results of two-factorial PERMANOVA, with seasons and lunar diel as the factors (Table 5.3), showed only a significant influence of seasons on the fish assemblage structure (Pseudo F = 2.83, p-value = 0.002). The pairwise test suggested the Rainy season fish assemblage to be different from the Summer and Winter season assemblages, but there was no difference between the latter. The CAP ordination also depicted the same seasonal pattern (Figure 5.5). No effects of lunar diel or effects of the interaction between seasons and lunar diel were found.

Spatial patterns

No significant spatial patterns were detected in the fish assemblage structure between the creeks or the creek types. Although the creeks differed in structural and management types, these factors did not appear to influence the fish community of Coringa's intertidal creeks.

Table 5.3. Results from the multivariate permutational analysis (PERMANOVA) and pairwise tests showing differences in the abundance of the most frequent species between the four inter-tidal creeks, in three seasons, lunar and diel cycles. The results are based on a Bray-Curtis similarity matrix of the fish species square root transformed CPUE data.

Source	**Df**	**Mean Sum sq.**	**Pseudo-F**	**p**	
Seasons**	2	5647	2.83	**0.001**	Winter x Rainy (.002) Summer x Rainy (.041)
Lunar-Diel	3	2086	1.05	0.425	
Seasons x Lunar-Diel	4	2081	1.04	0.419	
Residuals	35	1995			

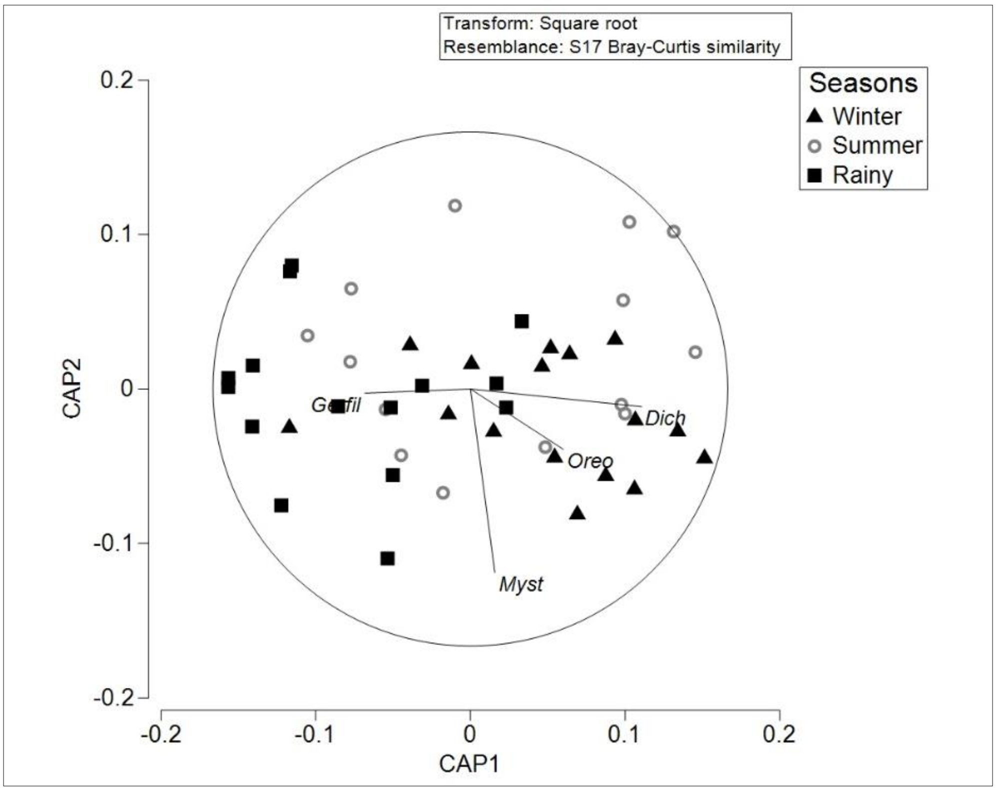


Figure 5.5. CAP ordination of fish assemblages in the four intertidal creeks of Coringa sub-tidal creek.

5. 4. Discussion

5.4.1 Species diversity and composition

In this study, I examined the possible role of habitat structure and accessibility in shaping the fish assemblages of intertidal creeks of a protected mangrove forest- CWS. Based on the results of this study, the fish assemblage of the intertidal creeks of Coringa include 16 species, which is seemingly low when compared with other estuaries in India and the Indo-West Pacific zone. Kumbhar et al. (2021) recorded 26 species in the Kali estuary; 90 species were recorded in Vembanad lake (Roshni et al., 2021) – both located on the western coast of India. Over 290 species have been enlisted on the eastern coast in Chilika lake (Mohanty et al. 2015) while 312 species have been recorded in the Sundarbans mangrove forests by Bhattacharya et al. (2018). Likewise, a higher number of taxa have been recorded from Embley estuary in Australia (Blaber et al., 1989), mangroves in the Philippines (Honda et al., 2013), and Pattani Bay in Thailand (Soe et al., 2021). The low species diversity recorded in my study possibly could be a result of differences in the sampling technique and sampling gear, as a result of which I may have missed a few species. The rarefaction curves for the creeks also suggested the same.

In fact, the species composition of the four intertidal creeks of Coringa appears to be a small subset of the overall fish community of Coringa creek (please see the results of Chapter 3). The species, including *Mystus gulio* and *Dichotomyctere fluviatilis* were among the most important species in the Coringa creek and the four intertidal creeks. *Oreochromis mossambicus*- a non-native, was another species that made important contributions to both the subtidal and intertidal creeks of Coringa. The main difference between the Coringa creek and the intertidal creek assemblages was the dominance of *Mugil cephalus* in the intertidal creeks. I recorded juveniles of this cosmopolitan marine species on multiple occasions during this study. This lends credence to the possible role of shallow estuarine habitats and mangroves being safe refuges for fish juveniles (Igulu et al., 2014). *M. cephalus* and *M. gulio* also contribute significantly to the local fisheries for communities fishing in the Coringa creek.

Several fishing families also engage in the smoking of these two species for further sale in the markets.

In the four intertidal creeks, the fish fauna was equally dominated by estuarine residents (ES) and marine migrants (MM) regarding species richness. This is a slight deviation from the general pattern in tropical estuaries, where a higher number of marine species are reported than in estuarine or freshwater (Barletta et al., 2008; Nicolas et al., 2010; Sreekanth et al., 2020). Using estuaries by different ecological guilds often vary over a marine-estuarine gradient, where the diversity of marine fishes may decline from the lower estuary or the polyhaline zones to the upper reaches or the oligohaline zones (Whitfield 2015). Species belonging to the estuarine guild tend to be euryhaline and tolerant to more comprehensive and variable salinity regimes. In this study, the intertidal creeks are connected to the subtidal Coringa creek, which has a direct connection with the Godavari River but not the sea- thereby, higher freshwater influence than marine and the salinity regime ranges from mainly oligohaline in the rainy season to mesohaline in other seasons. As a result, fewer marine species manage to penetrate deeper into these creeks. In the absence of the larger marine predators, these conditions perhaps proved to be favourable for the estuarine species, leading to greater numbers when compared with other estuaries. Notably, the top five species contributing over 50% to the fish abundance included two estuarine species (*Mystus gulio, Dichotomyctere fluviatilis*), and two freshwater migrants (*Oreochromis mossambicus* and *Scatophagus argus).*

5.4.2 Fish assemblage structure of the intertidal creeks

This study identified two distinct fish assemblages that were structured along the temporal scale of seasons. The first group of fish is specific for the rainy season and the second for the summer and winter seasons. Rainfall significantly influences estuaries' biological communities in India, particularly on the eastern coast, where large river deltas give rise to extensive estuarine and other coastal habitats. The south-west monsoon brings in a heavy downpour and high freshwater discharge, flooding large parts of the mangroves in CWS and drastically reducing the water salinity in the creeks.

Several studies have shown the negative influence of freshwater flow on the marine fishes in tropical estuaries (Igulu et al., 2014). For example, in Caete´ River estuary in Brazil, most of the marine and estuarine species were restricted to the lower estuary during the rainy season due to salinity decline (Barletta et al., 2005). Likewise, in Indian estuaries on the western coast, a similar response of the marine species to decreasing salinities in the rainy season has been recorded (Sreekanth et al., 2020). In the summer and winter seasons, more estuarine and marine species were present in the intertidal creeks. During the rainy season, overall salinity in the Coringa creek is reduced below 5, thus creating an oligohaline system more conducive for freshwater and euryhaline species like *Mystus gulio*, etc., to enter the creeks for feeding or seeking shelter.

On the contrary, the tides and diurnal cycle did not significantly affect the fish assemblages. This is different from other studies that found these two factors play an essential role in structuring the fish community of mangroves and intertidal habitats; for example- the fish composition of a mangrove forest in Madagascar (Laroche et al., 1997) or an intertidal creek in Colombia (Castellanos-Galindo and Krumme, 2013) was found to depend on the tidal-diel cycle, besides other factors. In addition to the tide-diel cycle, no spatial influence of the four creeks or the two types of management types was found on the fish assemblage structure. These results suggest that the seasonal forcing masks any potential spatial or temporal effect acting on a shorter scale (tidal or diel cycles).

The natural creeks had higher species diversity and evenness than the artificial creeks, indicating the possible influence of habitat. However, these results could not be corroborated by the multivariate analyses. Despite this, the potential influence of habitat heterogeneity cannot be discounted when a significant difference in the species abundance was recorded between the natural and artificial creeks. Furthermore, the natural creeks had a higher density of mangrove trees (mainly *Avicennia* spp.), higher canopy cover, and ground coverage, indicative of a heterogeneous habitat. Contrarily, the artificial creeks were created in open *Suaeda* spp., patches for replanting mangrove trees, and had lower canopy cover and ground cover. Differences in these habitat-related factors have been reported to be essential drivers of fish assemblage (Henderson et al., 2019; Zhang et al., 2019), but in this study, the influence of these varying habitats (microhabitat) features could not be established.

Figure 5.6. Sampling in one of the natural inter-tidal creeks selected for this objective.

Figure 5.7. Sampling in one of the artificial inter-tidal creeks selected for this objective.

Chapter 6

Perceptions of local fishers towards mangrove conservation in East Godavari River Estuarine Ecosystem (EGREE)

6.1 Introduction

Mangroves are one of most productive ecosystems of the world (Tomlinson, 1986), which provide many services like protecting coastlines from tidal waves, sea erosion and hurricanes, providing nutrients, sheltering many commercially important aquatic organisms, etc. (Deegan et al., 1986; Mitsch & Gosselink, 1993; WCMC, 1994). Since the last two decades, nearly 20 to 35% of global mangrove cover has been lost (Valiela et al 2001) due to aquaculture expansion, overexploitation for fuelwood and timber, agriculture, and urbanization. Mangrove forests are being lost at a rate (~1% per year) higher than inland tropical forests and coral reefs and if the present rate of loss continues, mangroves would disappear globally in the next 100 years (Duke et al., 2007). India also lost up to 40% of its historical mangrove cover by 1987 (Kathiresan, 2018). As per the latest report published in India's State of Forest Report (2021), mangroves cover an area of 4992 km^2 in India, most of which are concentrated in the eastern coast. The concerted efforts of plantation across the Indian coast by the government and non-governmental agencies have led to a net gain in mangrove cover in the country for the past few years. However, these plantation drives are limited to few species including *Avicennia* and *Rhizophora,* which in turn may lead to simplification of the floral diversity in these coastal forests.

Mangroves provide ecosystem services worth at least US$ 1.6 billion each year and support coastal livelihoods worldwide. The sustenance and well-being of human society is intricately linked to the full range of services and goods provided by Earth's natural ecosystems and rich biodiversity. Most often these services are hard to quantify since they do not have any actual market value or apparent economic significance. Economic valuation, therefore, helps to express these hidden values by unravelling the various socioecological linkages affecting them.

Typically, willingness to pay (WTP) is related to the concept of total economic value (TEV) and comprises of two main categories, use value and non-use value (Born et al., 2005). Use values is the value derived from an actual use of a service or good which involve direct and indirect consumption that is essential for health, human well-being, survival, and livelihood, while non-use value consist of altruism non-use value, bequest non-use value and existence non-use value (de Groot et al., 2012).

The non-use values of an ecosystem are more challenging to estimate. Non-use values are different from the direct or indirect use-values, in that they most often relate to the Intangible emotions of humans. Just the knowledge of maintenance of or access to a service, in the present as well as for future, can evoke strong emotional responses in people. Therefore, non-use values provide more significant challenges in estimating their values. Contingent Valuation Method (CVM) is a popular method for valuation of both use and non-use values, though it is most commonly used for the latter. In this method people are directly asked to state their willingness to pay or accept (WTP or WTA) to maintain or compensate for an ecosystem service. In case of non-use values, the economic estimates cannot be revealed through purchases or behaviour of the people. Thus, people are directly asked to state their values for that service.

Despite growing intolerance among people towards conservation, there are many examples from India where local villagers go out of their way to protect biodiversity. The primary objective of this chapter is to measure the value attached by the local communities and household willingness to pay towards mangroves of Coringa Wildlife Sanctuary by using the Contingent Valuation Method. Specifically, I wanted to study if Willingness to Pay (WTP) has an impact on people's behaviour towards mangrove conservation. After a detailed survey, questionnaire-based surveys were conducted to sample mangrove dependent villages around the sanctuary. An attempt was also made to understand whether awareness of climate change makes any difference in the stated preferences of the people.

6.2 Methodology

6.2.1 Sampling

A total of 417 households were surveyed during the period from September 2016 to January 2017. This study was conducted in 14 mangrove dependent villages surrounding the sanctuary in the district of East Godavari, Andhra Pradesh viz. Chollangipeta, Pagadalapeta, Matlapalem, Kotturu, Ramannapalem, Chinna Boddu Venkataypalem, Chinnavalasala, Peddavalasala, Lakshmipatipuram, Gadimoga, Dariyalatippa, Savitrinagar and Bhairavapalem (Figure 6.1). Most of the respondents in these villages were fishers by occupation. Shrimp fishery is a major source of livelihood for these fishers but other fish species such as grey mullets, eels, and catfishes also are important in the mangroves (Figure 6.2). The local communities are closely dependent on the mangrove forests for livelihood as well as for fuelwood and timber (Figure 6.3). A small proportion also worked in aquaculture ponds or agricultural lands as daily workers.

6.2.2 Surveys

The questionnaire had three parts to it; in the first part, general information related to the household, respondent and the village was asked. Other questions on timber collection or damage by cyclone or natural disasters were also asked. In the second part, the respondents were first asked about the importance of the mangrove and fishery services that it provides. Thereafter they were asked the extant status of the mangrove forests around their village, whether the forests are degrading or increasing. In this part, we also asked about awareness level about issues related to climate change and sea level rise.

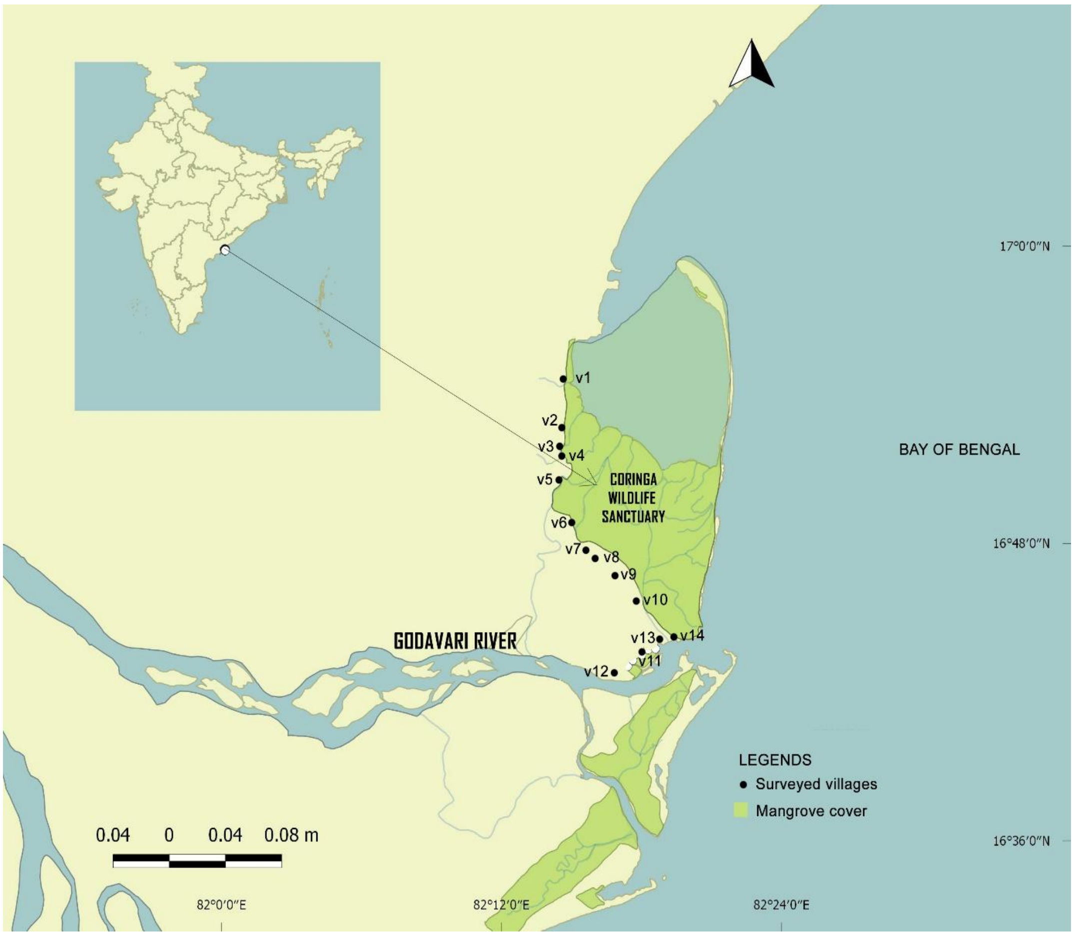


Figure 6.1. Location of Godavari mangroves including Coringa Wildlife Sanctuary with 14 mangrove dependent villages surveyed.

In the third part, the respondents were explained about the vulnerability of mangroves around their villages to sea level rise, and the continuing efforts of the government and local NGOs to protect them. They were given a hypothetical situation where they might have to pay a certain amount of money monthly to the forest department to protect the mangroves. The contribution would be voluntary and depending on their economic ability. If the respondent answered ‘No’ or was not willing to pay for the same, the value was recorded as ‘0’. If they replied in positive, they were then asked the amount they would be willing to pay monthly Among the explanatory variables AGE, HI, EDU, FM are quantitative variables; TIM, MGST and CCAW are binary variables; and OCCU is the categorical variable. Gender was not taken as a variable since all our respondents were males. Males were the head in most of the households surveyed, so females were not comfortable responding to our questions. Based on these variables, the probability of a person to pay for the non-use values of mangroves was calculated.

Using stepwise regression, the most important factors influencing the WTP were identified. The mean value of WTP was estimated through non-parametric methods.

Table 6.1. Different variables used for the regression analysis

Variable name	**Description**
Dependent variable	
WTP	Stated Willingness to pay to protect Coringa mangroves from climate change (Yes=1, No=0)
Explanatory variables	
AGE	Age of the respondent (number of years)
EDU	Years of education (number of years)
HI	Household annual income (in Rupees)
FM	Number of members in the household
OCCU	Type of Occupation (Categories:
TIM	Does the respondent collect timber from the mangrove or not? (Yes=1, No=0)
MGST	Whether the mangrove is decreasing (=0) or increasing (=1) near village as per respondent's

	observation?
CCAW	Is the respondent aware or not about Climate Change and its impacts? (Yes=1, No=0)

6.3 Results

6.3.1 Collection of Timber

Based on the survey it was found that majority of the respondents (66%) did not collect fuelwood or timber from the sanctuary. Interestingly, those who collected timber or wood were not ready to abandon doing that since they use them as an alternate fuel for cooking or for construction purposes. Both *Avicennia marina* and *Avicennia officinalis* mangroves were collected mostly by them for construction and firewood purpose.

6.3.2 Importance and perceived status of mangroves in Coringa Wildlife Sanctuary

Respondents unanimously agreed that the mangrove forests are especially important for the sustenance and protection of their villages. They said that the mangrove forests around their villages provide protection during cyclones or storms. Around 88% of the respondents observed that the mangrove forest near their villages was increasing while only 11% observed that they were decreasing. Interestingly, in several villages almost everybody noticed an increase in mangrove cover, but relatively higher proportions of respondents from the villages of Peddavalasala (40%) and Gadimoga (31%) noticed a decrease.

6.3.3 Awareness on Climate Change and Its Impacts

The survey results reveal that although everybody noticed a rise in temperatures in the past ten years but only 41.7% of the respondents were aware of the concept of Climate Change and their impacts on coastal areas. In contrast to the overall result, all the respondents from the villages of Dariyalatippa, Gadimoga, and Savitrinagar were aware of the concept, but it was not so in the other villages. In Cholangipeta and Ramannapalem none of the respondents were aware of Climate Change and its impacts.

Table 6.2. Summary of socio-economic characteristics of survey respondents

Attribute	**Category**	**Frequency (no of respondents)**	**Percent age**
Age	18-25	4	0.01
	26-35	96	0.23
	36-45	155	0.37
	46-55	126	0.30
	56-65	32	0.08
	>65	4	0.01
Education	Illiterate	142	0.34
	Pre-Primary School	0	0.00
	Primary School	105	0.25
	Secondary School	116	0.28
	Senior School	20	0.05
	Graduation	8	0.02
	Post-Graduation	0	0.00
	unknown	26	0.06
Occupation	Fisherman	344	0.82
	Fish seller	2	0.00
	Aquaculture owner	13	0.03
	Daily wage worker	31	0.07

	Government servant	3	0.01
	Private sector job	3	0.01
	business	2	0.00
	Home maker	1	0.00
	Farmer	13	0.03
	others	5	0.01
Household size	1	0	0.00
	2	7	0.02
	3	18	0.04
	4	86	0.21
	5	95	0.23
	6	93	0.22
	7	52	0.12
	8	28	0.07
	9	23	0.06
	10	4	0.01
	>10	11	0.03
Income (INR/month)	1000	0	0.00
	2000	7	0.02
	3000	353	0.85
	4000	44	0.11
	5000	7	0.02
	>5000	4	0.01
Dependence on mangroves for timber and fuelwood	Yes	140	0.34
	No	275	0.66

6.3.4 Willingness to Pay

Around 92.7% of the respondents agreed to pay a yearly amount for protecting and restoring the mangroves. The mean annual WTP was estimated as Rs. 637/- per household. As per the probit modelling three factors were identified that influenced an individual's willingness to pay. The three variables are Education level of the respondent, annual household income and awareness of climate change. None of the other variables show any significant impact on the WTP. Respondent's education level had a positive influence; with every increase in the year of education the willingness to pay an individual increased. On the other hand, with every increase in household income the willingness decreased. A final model was run with just these three variables which resulted in a lower AIC value as well as a better fit (McFadden's $R_2 = 0.208$). Therefore, the analysis revealed that the probability of a person with higher education level, lower household income and awareness of climate change is more than others to pay for mangrove protection.

6.4 Discussion

The findings of this study reveal that despite the low incomes of the local communities, they are ready to pay for protection of the mangroves around them. The results show that the mangroves here have high significance in the lives of the local 387 communities. However, the value of contribution varied depending on the personal situation of the respondent. Most of the local people engage in fisheries and live a life of subsistence. Therefore, they are highly dependent on the mangroves around them. On asking the respondents some reasons for their willingness to pay, everybody pointed out that mangrove play a very important role in their lives by giving them livelihood as well as providing protection during cyclones and storms. This service is an important aspect since one of the major impacts of climate change in the region will be increase in intensity and frequency of cyclones.

The results show that education level, household income and awareness of climate change are important factors that determine the willingness to pay of an individual. The mean number of years of education in the study was calculated to be just 4.5 years, which is not even beyond primary level of schooling. In few villages, it was less than 3 years. However, WTP increases with the number of years of education. Education has the potential to provide more information to the people about the various services of the mangrove forests around them. Many of the regulating or supporting services might not be obvious to the local communities but higher level of education might give them more perspective and knowledge.

On the other hand, a higher household income meant lower WTP of the respondents. This is surprising since common experience suggest a higher income increases the capacity of people to spend more on goods and services. This result can be interpreted in this way that a lower household income might mean a higher dependence of the family on the mangroves. A higher dependence would make protection of these forests more significant for such families. In other words, families with lower household incomes value the mangrove forests more due to their higher dependence. It is important to note that there were some respondents who were collecting timber or fuelwood from the sanctuary despite availability of alternate sources. At the same time, majority of the respondents said that the mangroves around their villages were increasing in area. This perception could also be due to the successful restoration program by the local forest authorities. These two results possibly indicate a lack of awareness or proper knowledge available to them.

My observations suggested that mangroves in the region are decreasing on the sea-ward side and are migrating towards the land. This landscape here is experiencing a spurt in aquaculture ponds particularly around the mangrove forests and many local fishers are opting for it; therefore, this perception might have a negative influence on a longer term. There also exists a lack of awareness on issues related to climate change and its impacts among the local communities. A little more than half of the respondents did not know about it despite the increase in temperatures that they have experienced. This lack of awareness also had an influence on their willingness to pay. In other words, people who did not have awareness about climate change are more likely to attach less value to the mangroves or their protection.

Therefore, this study shows that the local communities attach high value to the mangroves and are even willing to pay for intangible services and goods. If people know about the benefits provided to them by a project, they will extend their support in ways they can (Chen & Jim, 2010). Mangroves are often considered to be natural defence against natural disasters as well as the impacts of climate change. This landscape has a large coastal area under the mangrove cover and much of it is protected. However, the mangroves are still highly vulnerable to degradation, encroachment, and reclamation by aquaculture ponds. To successfully restore and conserve these coastal forests, the local forest authorities and the state government need the support of local communities. The locals are ready to support the mangrove conservation activities, but education and level of awareness are very important in shaping their perspective. Therefore, it is recommended that the authorities engage more with the local communities and create more awareness about the mangroves and services they provide.

Figure 6.2. Local fishers sorting through the daily catch collected the creeks of Coringa Wildlife Sanctuary, Andhra Pradesh.

Figure 6.3. Ongoing fishing activity seen inside the Gaderu subtidal creek of Coringa Wildlife Sanctuary, Andhra Pradesh.

Chapter 7

Conclusion and Recommendations

This thesis work documented the rich finfish diversity of the dynamic Godavari River estuarine complex as well as attempted to examine its current ecological status. Among the species that were recorded in the mangrove-lined creeks of Coringa Wildlife Sanctuary (CWS), one freshwater straggler *Cirrhinus cirrhosus* is listed as Vulnerable while *Wallago attu* are listed as 'Near Threatened' in IUCN Red List due to unsustainable exploitation. Another ten fish species including *Taenioides cirratus, Megalops cyprinoides,* and *Platycephalus indicus* are listed as Data Deficient._My study is perhaps one of the first to holistically document the coastal ecosystem, its processes, and associated biodiversity in EGREE.

CWS is located close to Kakinada city, which is an important marine fishery centre on the east coast of India. The mangroves of Godavari River (EGREE region) act as an important connecting link between the freshwater and marine ecosystems. Yet the mangroves possess a relatively distinct fish assemblage comprising mainly of euryhaline species. Although these mangrove forests are particularly known to support a productive prawn fishery in the region (Mohan et al., 1997), several finfishes (except the pufferfishes) recorded during our study also have high commercial value and contribute to the artisanal fishery practiced by the locals.

As the results of this thesis suggests, salinity has been identified as a major factor structuring the fish community of CWS mangroves. A clear spatial pattern exists between the major sub-tidal creeks that were studied, with polyhaline conditions in 2 creeks and low salinity values in the other two. The low salinity in certain creeks has allowed freshwater and euryhaline species such as *M. gulio* and *O. mossambicus* (a non-native species) to not just establish themselves as residents in the estuary but also dominate the overall fish abundances. Further studies are required to ascertain the role of tides and diel regime on the movement of fishes in these mangrove forests.

Additionally, the freshwater discharge during the monsoon season is responsible for changes in the fish assemblage not only in the subtidal creeks of the sanctuary but also in the smaller intertidal creeks, which are mainly utilized by juveniles and small-sized fishes. Another crucial feature identified through these studies is the ecological connectivity present between the estuary, river and the seascape. Maintenance of this continuum between the three ecosystems is equally important for the fish community and the artisanal fishery in the region.

Connectivity between the three ecosystems is also crucial for the migratory species present in the region. The flagship migratory species is *Tenualosa ilisha*, which undertakes large-scale migration from the sea into the Godavari River during the monsoon season. It is popularly known as 'Pulusa' in Andhra Pradesh (or 'Hilsa' throughout the Indian sub-continent), and has high commercial value. It constitutes an important fishery in the river during the monsoon season when it undertakes large-scale migration from the sea into the river. Other important migratory species occurring in the estuary (EGREE) include *Tenualosa toli, Anodontostoma chacunda,* *Lates calcarifer*, and a number of eel species. Several other species such as mullets (Mugilidae) undertake migrations in the creeks on shorter temporal scales, mainly driven by the food availability.

7.1 Threats to the fish community

This estuary complex, formed by India's largest peninsular river, is undergoing rapid changes driven by a number of anthropogenic factors coupled with sea-level rise, coastal erosion and natural disasters including cyclones. Construction of dams and barrages coupled with increased extraction of water lead to disturbance in the natural flow regime of a river, thereby negatively affecting the biodiversity and ecosystem functioning of not just the river but downstream ecosystems such as estuaries. Catches of certain species such as sardines declined by nearly 36% after the construction of Aswan Dam in Egypt in 1965 (Aleem, 1972). Compared to other rivers in India, Godavari River has among the highest number of dams, and still more are at planning or construction stages. A three times reduction in the sediment load has already been observed in the Godavari delta, from 150.2 million tons during 1970–1979 to 57.2 million tons by 2000–2006, due to increased sediment retention in the reservoirs of dams on the upstream stretches of the river (Rao et al., 2010). Gupta et al. (2012) have also estimated a 74% decline in the historic sediment load of the Godavari after the construction of additional dams in the Godavari. Polavaram Dam, which is one of the largest dams under construction in India lies about 200 km upstream of Coringa Wildlife Sanctuary. It is being feared that this dam would bring about changes in the downstream fish community of the Godavari River estuary and its mangrove forests, where a well-established salinity gradient and the seasonal freshwater flow is an important determining factor for the fish community.

Alongside this, it is also important to recognize the negative impacts of stocking and introduction of non-native fish species on the native aquatic community of the region. Alarmingly one of the most dominant species in these mangroves- *O. mossambicus* has been listed among the worst invasive species of the world (Lowe et al., 2000). This species has been able to establish a population in the low salinity waters of Thulyabhaga and Coringa creeks. Another species that has rung alarm bells is the *Piaractus brachypomus* (Red-bellied pacu), which perhaps got accidentally introduced in Godavari River a few years ago, and since then has become very common in the local fish markets in the district.

Pollution from the untreated effluents of aquaculture ponds as well as from industries located along the upstream parts of the creeks is another threat. On two different occasions during my study period, I recorded mass mortality of fishes in the Coringa creek near Coringa village, which was attributed to release of effluents by industries by the locals. However, as pointed out by (Dahdouh-Guebas et al., 2006), despite the pollution and habitat degradation caused by aquaculture ponds, the fishers in this region do not attribute this industry as a reason for the potential decline in their catches.

The preliminary Ecopath model of CWS suggested the fragility of the ecosystem to external factors, most importantly being the high fishing pressure existing within the creeks. Interestingly, an informal system of site-based fishing is practiced inside the protected area by the local fishers. Each village has pre-determined spots for fishing in the creeks, and different groups of fishermen from each village fish at the respective spots on a turn-wise basis. In such a situation, the spatial pattern of fishes driven by salinity differences can become an important aspect for these subsistence fishers. Since Gaderu and Giriyampeta creeks have more marine influence and greater biomass of marine species, fishers practicing in these creeks might fetch higher prices for their catch.

While the local fishermen have access to the protected creeks but there exists no regulation on fishing or fishing gears inside these mangroves. Although certain guidelines exist in the coastal zones including usage of fishing gears with appropriate mesh sizes and an annual fishing ban of around 60 days in the pre-monsoon season, they are rarely followed by the fishers nor properly implemented by the authorities. A study showed that the fishers in this region identified over-exploitation and unsustainable fishing practices as reasons for a decline in fish catches (Dahdouh-Guebas et al., 2006). However, it is also important to recognize that despite the poverty, the local fishers entail high value towards protection of the mangroves. Increased awareness about the various issues and threats posed by overfishing would be a valid initial step towards sustainable fishing.

Climate change is also an imminent threat to this highly vulnerable ecosystem. Not only the ecosystem is threatened by mangrove squeeze and habitat loss, but sea-level rise would also increase the salinity within the creeks of CWS. Moreover, in a subsiding delta like Godavari delta, the relative rise in sea levels can lead to coastal erosion (Peltier & Tushingham, 1989). I was also able to observe multiple evidence of coastal erosion on the seaward side of the Godavari delta. EGREE is also prone to cyclonic storms, an annual phenomenon in this region (Gray, 1968). Cyclonic storms have increased in the Bay of Bengal from 1877 to 1977, and the state of Andhra Pradesh has experienced the maximum number of post-monsoon cyclones on the East coast (Sahoo & Bhaskaran, 2016). The cyclones usually last for 2-4 days, and may inundate the low-lying areas depending upon their severity. Godavari and Krishna deltas are the second-highest cyclone-prone stretch on the East Coast. In fact, the CWS, which was once an important trade port for the East India Company, was nearly decimated by a major cyclone in November, 1839 (Winchester, 2014).

7.2 Recommendations

It is believed that nearly 40% of mangrove-dependent species worldwide are at high risk of extinction due to habitat degradation (Luther & Greenberg, 2009). In order to better manage the threats, and to protect the aquatic ecosystems of the East Godavari district, it is crucial to understand and acknowledge the importance of the ecological connectivity between the different coastal habitats, which is responsible for a number of processes and flows in the region. While the protected mangroves of the CWS do provide a crucial refuge for estuarine and juvenile marine fishes, it is important to adopt a holistic and prescient approach for sustainable usage of the coastal resources in EGREE.

The district authorities and the fisheries department need to take immediate steps to address the issue of proliferating aquaculture ponds in the region without proper regulations. Stocking of non-native fishes in the reservoir, canals or aquaculture ponds in the district should also be prohibited. Instead, the fisheries department may encourage protection of the carp and catfish species that are native to the Godavari River basin. Additionally, a minimum buffer should be allowed around the mangrove forests and the creeks, to allow them to maintain their structural integrity and landward shift driven by sea-level rise. It is recommended that the aquaculture ponds should be located at a minimum distance away from the mangrove forests and the creeks. Strict monitoring of the ponds, as per the guidelines prescribed by the Coastal Aquaculture Authority of India, should be carried out to prevent untreated effluent discharge and release of non-native species into the natural habitats. A scientific study is also recommended that would assess the ecological capacity of this estuarine region to support the aquaculture industry along with assessing the extant negative ecological and socio-economic impacts of the same.

While the Polavaram Dam is already under construction, it is still important to focus on mitigating the negative impacts on the riverine and coastal habitats. The minimum freshwater flows to the downstream habitats must be ensured by the dam authorities, taking in consideration the river's natural pattern of seasonal variation in freshwater discharge. Based on the results of this thesis, it is also recommended to map the unprotected and degraded patches of mangroves and coastal water bodies in EGREE. This would help in identifying and prioritizing the most vulnerable stretches for focused conservation efforts. Declaring the most degraded and vulnerable habitats as 'eco-sensitive zones' or 'community reserves' would provide them with a basic protection from future conversions and losses.

The district authorities should also enhance monitoring of destructive activities in the delta such as sandmining, deforestation of the riparian zones, conversion of riverbanks to other land-uses, etc. The government should proactively monitor the pollution levels in the river, mangroves, and the associated creeks and canals, and initiate action against the industries and aquaculture ponds found releasing untreated effluents into the estuary, as prescribed by law. Garnering the support of local communities and other stakeholders is crucial for the long-term conservation and management of this estuarine complex.

For generating local support, district and village-level organizations such as the panchayat, self-help groups, fishers' collectives, aquaculture collectives, etc. can be leveraged. Regular and focused campaigns would be helpful to improve awareness as well as generating local stewardship for sustainable fisheries, climate change, and biodiversity conservation. Such awareness programs should also be developed for the policy makers, planners, and stakeholders from the agricultural and industrial sectors since their actions may also have serious impacts on the aquatic ecosystems of EGREE.

Along with this, further inter-disciplinary studies are important to understand the different features of this estuarine complex including biological, ecological, social, cultural and economic complexities. Utilization of advanced tools including the Ecosim approach of the EwE software would be beneficial. The information collected during the course of this thesis along with the other studies carried out by Wildlife Institute of India (WII) will serve as a baseline to monitor future changes in the estuarine community of this region.

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Appendix-I

Habitat-wise list of finfish species recorded during this study from the East Godavari River Estuarine Ecosystem (EGREE)

S.No.	Order	Family	Species	Main River	Mangroves	Kakinada Bay
1	Elopiformes	Elopidae	*Elops machnata* (Fabricius, 1775) (Image 5e)	0	1	0
2		Megalopidae	*Megalops cyprinoides* (Broussonet, 1782)	1	1	1
3	Anguilliformes	Muraenidae	*Strophidon sathete* (Hamilton, 1822)	1	1	0
4		Ophichthidae	*Bascanichthys deraniyagalai* Menon, 1961	1	1	1
5			*Cirrhimuraena playfairii* (Günther, 1870)	1	1	0
6			*Pisodonophis boro* (Hamilton, 1822)	1	1	0
7			*Pisodonophis cancrivorus* (Richardson, 1848)	1	1	0
8		Muraenescocidae	*Congresox talabonoides* (Bleeker, 1852)	1	1	0
9			*Congresox talabon* (Cuvier, 1829)	1	1	0
10			*Muraenesox cinereus* (Forsskål, 1775)	1	1	0

11			*Muraenesox bagio* (Hamilton, 1822)	1	1	0
12		Congridae	*Uroconger lepturus* (Richardson, 1845)	1	0	0
13		Moringuidae	*Moringua raitaborua* (Hamilton, 1822)	1	1	1
14	Osteoglossiformes	Notopteridae	*Notopterus notopterus* (Pallas, 1769)	1	0	0
15	Clupeiformes	Clupeidae	*Anodontostoma chacunda* (Hamilton, 1822)	1	1	0
16			*Escualosa thoracata* (Valenciennes, 1847)	1	1	1
17			*Hilsa kelee* (Cuvier, 1829)	1	1	1
18			*Nematalosa nasus* (Bloch, 1795)	1	0	0
19			*Sardinella longiceps* Valenciennes, 1847	1	1	1
20			*Sardinella fimbriata* (Valenciennes, 1847)	1	1	1
21			*Tenualosa ilisha* (Hamilton, 1822)	1	0	0
22			*Tenualosa toli* (Valenciennes, 1847)	1	1	0
23		Dussumieriidae	*Dussumieria acuta* Valenciennes, 1847	0	1	1
24			*Dussumieria elopsoides* Bleeker, 1849	0	1	1
25		Engraulidae	*Coilia dussumieri* Valenciennes, 1848	1	1	1
26			*Coilia reynaldi* Valenciennes, 1848	1	1	1

27			*Setipinna taty* (Valenciennes, 1848)	1	1	1
28			*Setipinna tenuifilis (*Valenciennes, 1848)	1	1	1
29			*Stolephorus commersonnii* Lacepède, 1803	1	1	1
30			*Stolephorus indicus* (van Hasselt, 1823)	0	0	1
31			*Thryssa mystax* (Bloch & Schneider, 1801)	1	1	1
32			*Thryssa malabarica* (Bloch, 1795)	1	1	1
33			*Thryssa baelama* (Fabricius, 1775)	1	1	1
34		Chirocentridae	*Chirocentrus dorab* (Fabricius, 1775)	1	0	1
35		Pristigasteridae	*Ilisha melastoma* (Bloch & Schneider, 1801)	1	1	1
36			*Ilisha megaloptera* (Swainson, 1838)	1	1	1
37			*Opisthopterus tardoore* (Cuvier, 1829) (Image 4c)	1	1	1
38			*Pellona ditchela* Valenciennes, 1847	1	1	1
39			*Raconda russeliana* Gray, 1831	1	0	1
40	Gonorynchiformes	Chanidae	*Chanos chanos* (Fabricius, 1775)	1	0	1

41	Cypriniformes	Cyprinidae	*Cirrhinus cirrhosus* (Bloch, 1795)	1	1	0
42			*Cirrhinus mrigala* (Hamilton, 1822)	1	0	0
43			*Cyprinus carpio* Linnaeus, 1758	1	0	0
44			*Labeo catla* (Hamilton, 1822)	1	0	0
45			*Labeo calbasu* (Hamilton, 1822)	1	1	0
46			*Labeo fimbriatus* (Bloch, 1795)	1	1	0
47			*Labeo rohita* (Hamilton, 1822)	1	1	0
48			*Puntius sophore* (Hamilton, 1822)	1	1	0
49			*Pethia ticto* (Hamilton, 1822)	1	0	0
50		Xenocypridida e	*Ctenopharyngodon idella* (Valenciennes, 1844)	1	0	0
51	Characiforme s	Serrasalmidae	*Piaractus brachypomus* (Cuvier, 1818)	1	0	0
52	Siluriformes	Plotosidae	*Plotosus canius* Hamilton, 1822	1	1	0
53			*Plotosus lineatus* (Thunberg, 1787)	0	0	1
54		Ailiidae	*Silonia childreni* (Sykes, 1839)	1	0	0
55		Bagridae	*Mystus gulio* (Hamilton, 1822)	1	1	0
56			*Mystus vittatus* (Bloch,	1	1	0

			1794)			
57		Pangasiidae	*Pangasius pangasius* (Hamilton, 1822)	1	1	0
58		Siluridae	*Wallago attu* (Bloch & Schneider, 1801)	1	0	0
59			*Ompok bimaculatus* (Bloch, 1794)	1	0	0
60		Heteropneustidae	*Heteropneustes fossilis* (Bloch, 1794)	1	1	0
61		Ariidae	*Arius arius* (Hamilton, 1822)	1	1	1
62			*Arius gagora* (Hamilton 1822)	1	1	1
63			*Arius maculatus* (Thunberg, 1792)	1	1	1
64			*Plicofollis dussumieri* (Valenciennes, 1840)	0	0	1
65	Aulopiformes	Synodontidae	*Saurida tumbil* (Bloch, 1795)	0	0	1
66			*Synodus indicus* (Day, 1873)	0	0	1
67			*Harpadon nehereus* (Hamilton, 1822)	1	1	1
68	Batrachoidiformes	Batrachoididae	*Allenbatrachus grunniens* (Linnaeus, 1758) (Image 7c)	1	1	0
69	Scombriformes	Scombridae	*Katsuwonus pelamis* (Linnaeus, 1758)	0	0	1
70			*Rastrelliger kanagurta* (Cuvier, 1816)	1	0	1
71			*Scomberomorus*	0	0	1

			guttatus (Bloch & Schneider, 1801)			
72		Trichiuridae	*Eupleurogrammus muticus* (Gray, 1831)	1	1	0
73			*Lepturacanthus savala* (Cuvier, 1829)	1	0	1
74			*Trichiurus lepturus* Linnaeus, 1758	1	0	1
75	Syngnathiformes	Mullidae	*Upeneus sulphureus* Cuvier, 1829	1	1	1
76			*Upeneus vittatus* (Forsskål, 1775)	1	0	0
77			*Upeneus moluccensis* (Bleeker, 1855)	0	0	1
78			*Upeneus taeniopterus* Cuvier, 1829	1	1	1
79		Callionymidae	*Callionymus carebares* Alcock, 1890	0	1	0
80	Kurtiformes	Kurtidae	*Kurtus indicus* Bloch, 1786 (Image 7d)	0	1	1
81		Apogonidae	*Jaydia queketti* (Gilchrist 1903) (Image 6d)	0	0	1
82	Gobiiformes	Eleotridae	*Eleotris fusca* (Bloch & Schneider, 1801)	1	1	0
83			*Butis butis* (Hamilton, 1822) (Image 5d)	0	1	0
84			*Butis humeralis* (Valenciennes, 1837)	0	1	0
85		Gobiidae	*Aulopareia cyanomos*	0	1	1

			(Bleeker, 1849) (Image 5b)			
86			*Apocryptes bato* (Hamilton, 1822)	0	1	0
87			*Boleophthalmus boddarti* (Pallas, 1770)	0	1	1
88			*Glossogobius giuris* (Hamilton, 1822)	1	1	0
89			*Oxyurichthys microlepis* (Bleeker, 1849) (Image 7b)	0	1	0
90			*Parapocryptes rictuosus* (Valenciennes, 1837)	0	1	0
91			*Periophthalmus chrysospilos* Bleeker, 1853	0	1	0
92			*Taenioides anguillaris* (Linnaeus, 1758)	1	1	0
93			*Taenioides cirratus* (Blyth, 1860)	1	1	0
94			*Trypauchen vagina* (Bloch & Schneider, 1801) (Image 6e)	1	1	0
95			*Yongeichthys nebulosus* (Forsskål, 1775)	1	0	0
96			*Stigmatogobius sadanundio* (Hamilton, 1822)	1	0	0
97	Synbranchiformes	Mastacembelidae	*Macrognathus pancalus* Hamilton 1822	1	0	0

98		Synbranchidae	*Ophisternon bengalense* McClelland, 1844	1	0	0
99	Anabantiformes	Anabantidae	*Anabas testudineus* (Bloch, 1792)	1	1	0
100		Osphronemidae	*Trichogaster fasciata* Bloch & Schneider, 1801	1	0	0
101		Channidae	*Channa punctata* (Bloch, 1793)	1	0	0
102			*Channa striata* (Bloch, 1793)	1	0	0
103		Nandidae	*Nandus nandus* (Hamilton, 1822)	0	1	0
104	Carangiformes	Latidae	*Lates calcarifer* (Bloch, 1790) (Image 4a)	1	1	0
105		Lactariidae	*Lactarius lactarius* (Bloch & Schneider, 1801)	1	0	1
106		Sphyraenidae	*Sphyraena obtusata* Cuvier, 1829	0	0	1
107			*Sphyraena jello* Cuvier, 1829	0	0	1
108		Polynemidae	*Eleutheronema tetradactylum* (Shaw, 1804)	1	1	1
109			*Polydactylus sextarius* (Bloch & Schneider, 1801)	1	1	1
110			*Leptomelanosoma indicum* (Shaw, 1804)	1	1	1
111		Psettodidae	*Psettodes erumei* (Bloch & Schneider, 1801)	1	0	1

112		Bothidae	*Bothus myriaster* (Temminck & Schlegel, 1846)	0	1	1
113		Paralichthyidae	*Pseudorhombus arsius* (Hamilton, 1822)	0	1	1
114			*Pseudorhombus triocellatus* (Bloch & Schneider, 1801)	0	1	1
115			*Pseudorhombus elevatus* Ogilby, 1912	1	1	1
116		Soleidae	*Aesopia cornuta* Kaup, 1858	0	0	1
117			*Solea ovata* Richardson, 1846	0	1	1
118			*Dagetichthys albomaculatus* (Kaup, 1858)	1	1	1
119			*Zebrias synapturoides* (Jenkins, 1910)	1	1	1
120		Cynoglossidae	*Cynoglossus arel* (Bloch & Schneider, 1801)	1	1	1
121			*Cynoglossus bilineatus* (Lacepède, 1802)	1	1	1
122			*Cynoglossus puncticeps* (Richardson, 1846)	1	1	1
123			*Cynoglossus lingua* Hamilton, 1822	1	1	0
124			*Cynoglossus cynoglossus* (Hamilton, 1822)	1	1	1
125			*Paraplagusia bilineata* (Bloch, 1787)	1	1	1

126		Menidae	*Mene maculata* (Bloch & Schneider, 1801)	0	1	0
127		Carangidae	*Megalaspis cordyla* (Linnaeus, 1758)	0	0	1
128			*Scyris indica* (Rüppell, 1830)	1	0	1
129			*Alepes djedaba* (Fabricius, 1775)	1	0	1
130			*Alepes kleinii* (Bloch, 1793)	1	0	1
131			*Atropus atropos* (Bloch & Schneider, 1801)	0	0	1
132			*Atule mate* (Cuvier, 1833)	1	0	1
133			*Platycaranx malabaricus* (Bloch & Schneider, 1801)	0	0	1
134			*Caranx ignobilis* (Forsskål, 1775)	0	1	1
135			*Caranx sexfasciatus* Quoy & Gaimard, 1825	0	1	1
136			*Caranx heberi* (Bennett, 1830)	0	0	1
137			*Decapterus russelli* (Rüppell, 1830)	0	0	1
138			*Parastromateus niger* (Bloch, 1795)	0	1	1
139			*Scomberoides commersonnianus* Lacepède, 1801	0	0	1

140			*Scomberoides tol* (Cuvier, 1832)	0	0	1
141			*Selar crumenophthalmus* (Bloch, 1793)	0	0	1
142			*Trachinotus mookalee* Cuvier, 1832. (Image 6a)	0	1	1
143		Rachycentridae	*Rachycentron canadum* (Linnaeus, 1766)	0	0	1
144	Cichliformes	Ambassidae	*Ambassis gymnocephalus* (Lacepède, 1802)	1	1	0
145			*Chanda nama* Hamilton, 1822	1	1	0
146		Cichlidae	*Etroplus suratensis* (Bloch, 1790) (Image 7a)	1	1	0
147			*Pseudetroplus maculatus* (Bloch, 1795)	1	0	0
148			*Oreochromis mossambicus* (Peters, 1852)	1	1	0
149			*Oreochromis niloticus* (Linnaeus, 1758)	1	0	0
150	Cyprinodontiformes	Aplocheilidae	*Aplocheilus blockii* Arnold, 1911	1	1	0
151	Beloniformes	Belonidae	*Strongylura strongylura* (van Hasselt, 1823)	1	0	1
152			*Xenentodon cancila* (Hamilton, 1822)	1	1	0
153		Hemiramphida	*Hyporhamphus*	1	1	1

		e	*limbatus* (Valenciennes, 1847)			
154		Adrianichthyidae	*Oryzias dancena* (Hamilton 1822)	0	1	0
155	Mugiliformes	Mugilidae	*Mugil cephalus* Linnaeus, 1758	1	1	1
156			*Chelon parsia* (Hamilton, 1822)	1	1	1
157			*Planiliza subviridis* (Valenciennes, 1836)	1	1	1
158			*Planiliza planiceps* (Valenciennes, 1836)	1	0	0
159			*Planiliza tade* (Fabricius, 1775)	1	1	0
160			*Rhinomugil corsula* (Hamilton, 1822)	1	1	0
161			*Crenimugil seheli* (Fabricius, 1775)	1	1	1
162	Blenniiformes	Blenniidae	*Omobranchus ferox* (Herre, 1927)	1	1	0
163	Perciformes *sedis mutabilis*	Sillaginidae	*Sillaginopsis domina* (Cuvier, 1816)	0	0	1
164			*Sillago sihama* (Fabricius, 1775)	1	1	1
165		Lutjanidae	*Lutjanus johnii* (Bloch, 1792) (Image 4b)	1	1	1
166			*Lutjanus russellii* (Bleeker, 1849)	0	1	1
167			*Lutjanus argentimaculatus* (Forsskål, 1775) (Image 5c)	0	1	1

168			*Lutjanus fulviflamma* (Forsskål, 1775)	0	1	1
169		Gerreidae	*Gerres filamentosus* Cuvier, 1829	1	1	1
170			*Gerres limbatus* Cuvier, 1830	1	1	1
171			*Gerres setifer* (Hamilton, 1822)	1	1	1
172			*Gerres oyena* (Fabricius, 1775)	1	1	1
173			*Gerres longirostris* (Lacepède , 1801)	0	0	1
174		Haemulidae	*Pomadasys kaakan* (Cuvier, 1830)	1	1	1
175			*Pomadasys argenteus* (Forsskål, 1775)	1	1	1
176			*Pomadasys maculatus* (Bloch, 1793)	1	1	1
177			*Plectorhinchus gibbosus* (Lacepède, 1802)	0	0	1
178			*Diagramma pictum* (Thunberg, 1792)	0	0	1
179		Sparidae	*Acanthopagrus berda* (Fabricius, 1775)	0	0	1
180			A*canthopagrus datnia* (Hamilton, 1822)	0	0	1
181			*Rhabdosargus sarba* (Gmelin, 1789)	0	0	1
182		Sciaenidae	*Chrysochir aurea* (Richardson, 1846)	0	1	1

183			*Daysciaena albida* (Cuvier, 1830)	0	1	1
184			*Dendrophysa russelii* (Cuvier, 1829)	1	1	1
185			*Johnius belangerii* (Cuvier, 1830)	0	1	1
186			*Johnius coitor* (Hamilton, 1822)	1	1	1
187			*Johnius dussumieri* (Cuvier, 1830)	0	1	1
188			*Kathala axillaris* (Cuvier, 1830)	0	1	1
189			*Nibea maculata* (Bloch & Schneider, 1801)	0	1	1
190			*Nibea soldado* (Lacepède, 1802)	0	1	1
191			*Otolithes ruber* (Bloch & Schneider, 1801)	1	1	0
192			*Panna microdon* (Bleeker, 1849)	0	1	1
193			*Protonibea diacanthus* (Lacepède, 1802)	0	1	1
194	Perciformes	Epinephelidae	*Epinephelus coioides* (Hamilton, 1822)	0	1	1
195			*Epinephelus malabaricus* (Bloch & Schneider, 1801)	0	1	1
196			*Epinephelus melanostigma* Schultz, 1953	0	0	1
197			*Epinephelus tauvina* (Fabricius, 1775)	0	0	1
198		Platycephalida	*Grammoplites scaber*	1	1	0

		e	(Linnaeus, 1758)			
199			*Cociella crocodilus* (Cuvier, 1829)	1	0	0
200			*Platycephalus indicus* (Linnaeus, 1758)	1	1	1
201		Triglidae	Lepidotrigla sp.	0	0	1
202		Synanceiidae	*Minous monodactylus* (Bloch & Schneider, 1801) (Image 4f)	0	1	1
203			*Minous inermis* Alcock 1889	0	0	1
204	Centrarchiformes	Terapontidae	*Terapon jarbua* (Fabricius, 1775) (Image 6c)	1	1	0
205			*Terapon puta* Cuvier, 1829	1	1	0
206			*Pelates quadrilineatus* (Bloch, 1790)	1	0	1
207	Acanthuriformes	Lobotidae	*Lobotes surinamensis* (Bloch, 1790)	1	0	1
208		Drepaneidae	*Drepane longimana* (Bloch & Schneider, 1801)	1	1	0
209			*Drepane punctata* (Linnaeus, 1758)	0	1	0
210		Ephippidae	*Ephippus orbis* (Bloch, 1787)	0	0	1
211			Platax sps.	0	0	1
212		Leiognathidae	*Leiognathus equula* (Forsskål, 1775)	1	1	1
213			*Eubleekeria splendens* (Cuvier, 1829)	1	1	1

214			*Leiognathus berbis* (Valenciennes, 1835)	0	1	1
215			*Photopectoralis bindus* (Valenciennes, 1835)	1	1	1
216			*Gazza minuta* (Bloch, 1795)	0	0	1
217			*Deveximentum insidiator* (Bloch, 1787)	1	1	1
218			*Nuchequula blochii* (Valenciennes, 1835)	0	1	1
219			*Leiognathus ruconius* (Hamilton, 1822) (Image 4d)	1	1	1
220		Scatophagidae	*Scatophagus argus* (Linnaeus, 1766)	1	1	1
221		Siganidae	*Siganus canaliculatus* (Park, 1797)	1	1	1
222			*Siganus javus* (Linnaeus, 1766) (Image 4e)	1	1	1
223		Acanthuridae	*Acanthurus mata* (Cuvier, 1829) (Image 5a)	1	0	0
224			*Acanthurus xanthopterus* Valenciennes, 1835	1	1	1
225	Tetraodontiformes	Triacanthidae	*Triacanthus biaculeatus* (Bloch, 1786) (Image 6b)	0	0	1
226		Tetraodontidae	*Takifugu oblongus* (Bloch, 1786)	0	0	1

227			*Chelonodontops patoca* (Hamilton, 1822)	1	1	1
228			*Dichotomyctere fluviatilis* (Hamilton, 1822)	1	1	1
229			*Lagocephalus lunaris* (Bloch & Schneider, 1801)	1	0	1
230			*Lagocephalus inermis* (Temminck & Schlegel, 1850)	1	0	1
231		Monacanthida e	*Aluterus monoceros* (Linnaeus, 1758)	0	0	1
			Total	**15 1**	**15 0**	**14 9**

(“1” : Presence recorded; “0” : Presence not recorded)

Appendix-II. Questionnaire Survey Data Sheet.

Economic Valuation of Aquatic Resources in East Godavari district

Investigator(s):____________________________Date:______________Time:____________

Name of Village / Town:___________________GPS coordinates:________________________

Number of household______________________ Distance from mangroves________________

Altitude_________

1. What are the income-generating activities practised by the inhabitants in this village? *(Please tick against the ones listed by respondent)*

Fishermen
Aquaculture pond
Crab Hunting
Shell collectors
Agriculture
Cattle herders
Port
Forest Department
Laborers
Business
Crafts
Other (Specify)? ....

2. Since, how long does this village exists?

<1year______, >25 years_______, >50 years______, >100 years_______

3. Primary source of water:_______________________________________

4. Are there any community services in this village? Yes / No, …………

a. Primary school: .... b. Secondary school: ....c. Hospital: ....d. Health center / health post: ......e. Other (specify): ....

Part A

DEPENDENCE ON MANGROVES

1. Livestock:

Do you own livestock? Yes/No______

a) If yes, then details:

Species	No.	Main purpose	Av. daily Income	Source of fodder (Place of grazing)	Expenditure on Feed/Fodder
Buffalo (Feral)					
Buffalo (Domestic)					
Cow					
Goat					
Others					

Main purpose: 1) Self consumption 2) Cow 3) Meat 4) Leather 5) Any other purpose.

Source of fodder (Place of grazing): 1) Mangrove forests 2) Village fallow lands 3) Any other site.

b) If source of fodder is mangroves then:

Which mangrove plants do they mainly feed on? Trees ________________________

Grasses______________________

How many months does village livestock grazes in forests?____________________

c) Feral Cattle:

Who owns them? Individual_____Group____Village_____

Do you keep them permanently in mangroves? Yes/No______

If yes, then why____

Are there any killings of feral cattle by the wild animals inside mangroves? Yes/No/Don't know____

2. **Timber**

a) Do you collect timber from mangroves (including grasses for roof thatching)? Yes/No_____,

If yes, then:

Species	**Purpose**					**Av. Collection/ day**	**Selling Price (/kg)**
	Cooking	**House construction/ repair**	**Boat construction/ repair**	**Selling in markets**	**Fish Smoking**		
Tella Mada							
Nella Mada							
Tilla							
Ponna							
Kalingi							
Thanduga							
Togaru							
Ulleti karra							
Dabba gaddi							
Others____________							

b) Effort needed to gather timber from the mangroves (Weekly/daily/monthly)………Kms…………Hrs.

c) For cooking and fish smoking what do you use?

Type of fuel	Qty/month	Unit Price
Kerosene		
LPG		
Timber (from mangroves)		

Timber (from market)

Any other source

d) If Govt. provides further subsidy on LPG or provides cleaner and cheaper sources of cooking fuel such as solar '*chullahs'*, will you stop extracting timber from mangroves? Yes/No____________If no, then please provide reasons:

____

____

____

e) Do you collect any other item such as medicines or honey from the mangrove forests?

3. **Storm protection/ cyclone protection**

a) Which year did the most destruction and loss of life happened due to a cyclone/storm in your village? ____

b) Did anyone in your family died or got seriously injured? ___________________________

c) How much loss you suffered during that time? ____________________________________

(*Mainly money-wise, or else in terms of damage to house or boat or any other belongings and properties*)

c) Did you get any compensation from the Government? Yes/No_______________________

If yes, how much Rs.______________________________________

d) Do you think mangroves protect you from direct impact of storms and cyclones every year? Yes/No/Don't Know____

If yes, then please give details______________________________

e) Any other major calamities your village suffered in recent past? _____________________

Part B

General level of Awareness on ecological issues

1. Do you think if these mangroves were not there your lives would have been:

Better____ Worse_______?

2. Are there any problems which you have to face as you live near the mangroves? Yes/No

If yes, then please state them: ________________________________ (e.g. Mosquitoes).

3. Do you think the mangrove forests near your village are: Increasing/Decreasing?

If decreasing, then what do you think are the two most important reasons? Please tick:

Cause	**Most Important**	**Second Most Important**
Aquaculture ponds		
Timber extraction		
Dredging, Oil exploration and extraction activities		
Growth of cities and industries, expansion of Kakinada Port		
Global Warming		
Cyclone/Tsunami		
Decrease in flow of freshwater from Godavari (due to Dowlaiswaram barrage and other dams which control flow of river)		

4. Do you think the fish catch over the years is: Increasing/Decreasing?

If decreasing, then what do you think are the two most important reasons? Please tick:

Cause	**Most Important**	**Second Most Important**
Pollution from nearby habitations, industries and		

aquaculture ponds		
Overfishing or overexploitation of aquatic resources		
Decline in mangrove forests		
Dredging, Oil exploration and extraction activities		
Uncontrolled benthic and shell collection in the Bay		

5. What do you think is more important of the following for your grandchildren and future generations (Please tick the appropriate answer):
    a) Protecting these mangrove forests and the fishery resource ______________________
    b) Proliferation of industries and more economic development ______________________.
6. I am going to read out a few statements. Please indicate your opinion as agree, disagree or don't know. There is no right or wrong answer; I only need your frank opinion.

S.No.	Statements	Agree	Disagree	No opinion
1	We have a duty to protect our environment and natural resources from destruction regardless of the cost.			
2	We should reduce our use of the mangroves and decrease fishing intensity now so that our grandchildren may benefit from it.			
3	We should protect rare animals and birds found in the mangroves such as fishing cat, otters, open billed storks etc. regardless of the cost.			
4	Andhra Pradesh needs to develop its forests, seas, and land to increase jobs and incomes, regardless of the environmental damage.			
5	Economic development is more important than protecting these mangroves.			

6 It is worth spending money to protect the mangroves because they provide fishery resources and protect us from cyclones.

Part C

Awareness on Climate Change

1. Do you notice any changes in the climate of your region compared to 10 years before? Yes/No/ Don't know__________

   If yes, then what changes: temperatures have raised /declined/ no change?

2. Do you notice any changes in sea shore compared to 10 years ago?

   Yes/No/Don't know__________

   If yes, then what changes: Erosion/No erosion /No change?

3. Are you aware of the phenomenon of Global Warming and Climate Change? Yes/No.
4. If yes, are you aware that coastal regions including your village are most vulnerable to sea level rise, increased cyclones and other associated impacts? Yes/No.

Part D

Willingness to Pay

Management and protection of the mangrove forests is important for your livelihood and daily source of food as well as to protect the unique animals and birds. Also mangrove forests are very important to protect your family and village from the cyclones and tsunami. Also, in near future when the sea levels will rise further these mangrove forests might protect your village from drowning. But industrial development, natural gas sector and proliferation of aquaculture ponds are negatively affecting these forests. Therefore, the Government wants to initiate a new project to increase protection and minimize the negative impacts of development but it is obviously a costly project. So, people would have to pay their share of the costs on a continuing basis if they want to enjoy the benefits protection of the mangroves will offer.

As such, suppose that in order to protect the mangroves, your household would be asked to pay a monthly fee to **A BIODIVERSITY FUND**, which will be established and managed by the government to help protect the Coringa mangroves. Please think for a second about how much this would be worth to you and your family.

Please keep in mind:

1. Your own personal income is limited and has important alternative uses.
2. There is no right or wrong answers and you should answer for your household.

1. Are you willing to pay towards the fund? Yes/No/Don't Know ____________

If yes, then how much:

Amount in rupees	Tick the amount
5/-	
10/-	
20/-	
30/-	
40/-	
50/-	
60/-	
70/-	
80/-	
90/-	
100/-	
Specify amount if more than 100:________________	

So this means that you are sure that you would pay (last amount ticked), not sure (amounts with blanks) and would not pay (first amount crossed) for sure. Is that correct? Do you want to revise your answer?

IF RESPONDENT WANTS TO REVISE, PLEASE DO SO. OTHERWISE, MOVE TO QUESTION.

2. If willing to pay, then what are the reasons?

Reasons	Tick the appropriate one.
I am concerned about the existence of these mangroves.	
I feel such project is important.	
I feel this is a reasonable amount to pay.	
I am not sure I can pay what I said but I wish I could.	

3. If zero willingness to pay, then ask the reasons for it as following:

Reasons	Tick the appropriate one.
I have no spare income but would otherwise contribute.	

I don't believe there would be any changes brought by the project.
It is the Government's or Forest Department's responsibility.
Conservation of these mangroves is not important.
I am happy with the current situation than pay more.
I feel without my contribution also these mangroves can be conserved.
I could not understand the question

4. Instead of contributing money to the fund, would you volunteer some of your time in helping with this project? (The tasks could be participating in awareness programmes, conducting guided tours for tourists, helping the forest department. in protection of the sanctuary). Please remember that your time is precious and you may have other important tasks. Yes/No.
5. If yes, then how many hours per month can you spare? __________hrs.

Part F

<u>Household Details</u>

1. Personal information about the respondent:

Sex	Caste	Age (years)				Education Level	Occupation	
		<18	18-30	30-60	>60		Primary	Secondary

a) Education level:
b) Occupation:

2. How many members are there in your household apart from you?
3. How many are above 18 and earning?
4. Is this house your own_______ or rented_________?
5. For how many years your family has been living in this village?

1) Less than a year___ 2) 1-5 years___ 3) 5-10 years___ 4) 10 years or more____

6. Assets / property if any: ______________________ Location________________.

7. What is your monthly household income?

Appendix-III. List of publications and Conference Presentations

Publications:

1. **Paromita Ray,** Giridhar Malla, J. A. Johnson, K. Sivakumar (2022). An overview of the fish diversity and their threats in the Gowthami-Godavari Estuary in Andhra Pradesh, India. *Journal of Threatened Taxa 14(8),* 21588-21604. https://doi.org/10.11609/jott.7842.14.8.21588-21604

2. **Paromita Ray,** Giridhar Malla, Upma Manral, J. A. Johnson, K. Sivakumar (2020). Avifaunal diversity along the riverine habitats of Papikonda National Park, Andhra Pradesh, India. *Journal of Threatened Taxa, 12(14),* 16993-16999. https://doi.org/10.11609/jott.5513.12.14.16993-16999

Conference presentations:

1. **Paromita Ray**. *Examining the perceptions and attitudes of fishers on conservation of ichthyofauna in the largest river basin in southern India*. 29th International Conference for Conservation Biology (ICCB), Kuala Lumpur, Malaysia. 2019. Oral presentation

2. **Paromita Ray**. *Towards conservation of mahseers and their habitats in Eastern Ghats, India.* The International Mahseer Conference, Paro, Bhutan. 2018. Oral presentation

3. **Paromita Ray**. *Conserving the threatened fishes of a 'biodiversity coldspot' in India.* 55th Annual Meeting of Association for Tropical Biology and Conservation (ATBC 2018), Kuching, Malaysia. 2018. Oral presentation

4. **Paromita Ray**, Giridhar Malla, K. Sivakumar, and J.A. Johnson. *Assemblage Patterns of Fishes in Mangrove and Non-Mangrove Habitats of an Estuary in Eastern Coast of India.* Third International Symposium on Mangroves as Fish Habitat, Kuala Lumpur, Malaysia. 2018. Oral presentation

5. **Paromita Ray**, Giridhar Malla, J.A. Johnson, and K. Sivakumar. *Distribution and biogeography of fish fauna in Godavari Estuary, Andhra Pradesh: a preliminary assessment*. International Biogeography Society Meeting 2017, Bengaluru, India. 2017. Poster presentation

6. **Paromita Ray**, J.A. Johnson, K. Sivakumar and Giridhar Malla. *Spatio-temporal distribution of catfishes in Coringa Wildlife Sanctuary, India.* IUCN Mangrove Symposium 2017, Bremen, Germany. 2017. Poster presentation

7. **Paromita Ray**, Giridhar Malla, K. Sivakumar, J.A. Johnson. *Diversity patterns of mollusks in the natural and restored mangroves of Coringa Wildlife Sanctuary, Andhra Pradesh.* Student Conference on Conservation Science, Bengaluru. 2016. Poster presentation

8. **Paromita Ray**, K. Sivakumar, J.A. Johnson, Gopi G.V. and Panna Lal. *Patterns and processes of estuarine fish diversity in the upper Godavari Estuary, Andhra Pradesh*. Annual Research Seminar XXIX, Wildlife Institute of India, Dehradun, India. 2015. Poster presentation

Published paper

Building evidence for conservation globally

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continued on the back inside cover

Cover: Fish species recorded in the Gowthami-Godavari Estuary, Andhra Pradesh: *Lutjanus johnii* (top left), *Triacanthus biaculeatus* (top right), *Acentrogobius cyanomos*, *Elops machnata*, *Trypauchen vagina*, *Oxyurichthys microlepis*. © Paromita Ray.

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COMMUNICATION

An overview of the fish diversity and their threats in the Gowthami-Godavari Estuary in Andhra Pradesh, India

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Abstract: The fish diversity of different estuarine habitats of the Gowthami-Godavari River was studied from 2014 to 2017. We recorded 231 species of finfishes belonging to 27 orders, 81 families, and 167 genera. Perciformes was the most speciose order, followed by Carangiformes and Clupeiformes. Of the 231 species, one is an Endangered species (*Silonia childreni*), three are Vulnerable (*Tenualosa toli*, *Cirrhinus cirrhosis*, and *Wallago attu*), three are Near Threatened, and 11 are Data Deficient species. We also recorded five exotic species from the study area, of which *Oreochromis mossambicus* was the most dominant. The major threats, including potential impacts of river regulation and climate change on the estuarine habitats of Gowthami-Godavari, are also discussed.

Keywords: Coringa, dam, eastern coast, ichthyofauna, mangroves.

సారాంశం: 2014 నుండి 2017 మధ్య కాలంలో, గౌతమి-గోదావరి నదికి చెందిన వివిధ నదీముఖ ఆవాసాలలో ఉండే చేపల వైవిధ్యం మీద అధ్యయనం చేయబడింది. మా అధ్యయనంలో 231 ఫిన్‌ఫిష్ జాతులను నమోదు చేసాము, ఇవి 27 ఆర్డర్‌లు, 81 ఫామిలీస్ మరియు 167 జెనెరేలకు చెందినవి. నమోదు చెయ్యబడిన ఈ 231 ఫిన్‌ఫిష్‌లలో, అత్యధికంగా పెర్సిఫార్మ్స్ జాతులు ఉన్నాయి, వాటి తర్వాత కారంగిఫార్మ్స్ మరియు క్లూపీఫార్మ్స్ జాతులు ఉన్నాయి. ఈ 231 జాతులలో, ఒకటి అంతరించిపోతున్న జాతి (సిలోనియా చిల్డ్రెని), మూడు వాల్నెరబుల్ (టెనువాలోసా టోలి, సిర్రినస్ సిర్రోసిస్, మరియు వల్లగో అట్టు), మూడు ముప్పు పొంచి ఉన్నవి మరియు 11 డేటా లోపం ఉన్న జాతులు. మా అధ్యయనంలో ఐదు అన్యదేశ జాతులను కూడా నమోదు చేసాము, వాటిలో ఒరియోక్రోమిస్ మొసాంబికస్ ఎక్కువుగా కనిపించాయి. అంతే కాకుండా గౌతమి-గోదావరి నదీముఖ ఆవాసాలపై నియంత్రణ మరియు వాతావరణ మార్పుల గురించి కూడా మా అధ్యయనంలో చర్చించబడ్డాయి.

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Competing interests: The authors declare no competing interests.

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Author contributions: PR—collection of field data, analysis, preparation of manuscript. GM—collection of field data and preparation of manuscript. JAJ—guidance on the study, manuscript reviewing and editing. KS—guidance on the study, manuscript editing and reviewing,

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INTRODUCTION

Among the large monsoonal rivers of the Indian peninsula, the Godavari River is the largest, with a drainage basin of 312,812 km^2 (Rao et al. 2015). The river originates at Triambakeshwar in the Western Ghats and travels eastward for ~1,460 km flowing through eight states and various landscapes such as the Western Ghats, Deccan traps of central India, and the Eastern Ghats along the eastern coast. It finally drains into the Bay of Bengal through a number of distributaries before creating a large, fertile delta in Andhra Pradesh. The Godavari river basin accounts for nearly 10% of India's geographical area, thereby playing a major role in accruing socio-ecological, economic, and cultural benefits to the country.

At its confluence with Bay of Bengal, numerous distributaries of the Godavari River form an estuarine complex constituting a diverse array of coastal habitats that include the estuaries formed at the river mouths, mangrove forests, and a large bay partially enclosed by a natural sand spit known as Hope Island. The mangroves created at the confluence of Gowthami River, a major distributary of the Godavari River, are among the largest mangrove forests in India. These habitats support rich and unique biodiversity, including rare mangrove species such as *Ceriops decandra* and *Xylocarpus granatum*, and threatened mammals such as the Fishing Cat *Prionailurus viverrinus* and Smooth-coated Otter *Lutrogale perspicillata* (Malla 2014; Malla et al. 2019). The estuarine complex and the mangrove-lined creeks of the estuary located at the interface of freshwater and salt water also contributes immensely to the region's fisheries particularly supporting the sustenance of the local small-scale fisheries.

Many studies, including those by Krishnamurthy & Jeyaseelan (1981), Mukherjee et al. (2013), Ramachandra et al. (2013), and Ramanujam et al. (2014), have documented the diversity of fish fauna present in Indian estuaries. In the case of the lower basin of the Godavari River, earlier ichthyological studies provide substantial information on the distribution and taxonomy of fish species (Day 1888; Chacko & Ganapati 1949; Rao 1965, 1976; Rajyalakshmi 1973; Rao 1976; Talwar & Jhingran 1991). Species including *Awaous fluviatilis* Rao, 1971 and *Incara multisquamatus* Rao, 1961 were first described from the Godavari delta. Nearly two decades ago, Krishnan & Mishra (2001) provided a comprehensive summary of the fish diversity of the Godavari River estuary, accounting for 312 species belonging to 189 genera and 88 families.

In this paper, we provide an overview of the fish diversity and distribution in different habitats of the Godavari River estuarine complex, and specifically focusing on the fish diversity in the mangrove-lined creeks. We also discuss various threats to these mangrove forests, and their fish communities. This study is important in the context of the vulnerability of this estuary, and its biological communities to potential large-scale changes triggered by rising sea levels and freshwater regulation by an under-construction large dam.

METHODS

Study area

This study was conducted in the Godavari River Estuary located in the southeastern state of Andhra Pradesh in peninsular India. Before its confluence with the sea, the river branches out into two major distributaries, namely the Gowthami-Godavari and Vasistha-Godavari. The present study focuses on the Gowthami distributary of the river (16.98 °N, 82.30 °E and 16.58 °N, 82.31 °E).

With an area of 316 km^2, a substantial part of the mangroves formed at the northern confluence of Gowthami-Godavari with the sea are protected inside the Coringa Wildlife Sanctuary (CWS) (Bagaria et al. 2021). Here, the mangroves are drained by three major sub-tidal creeks, namely Thulyabhaga, Coringa, and Gaderu; these creeks flow south to north, dividing the sanctuary into different zones. Another smaller sub-tidal creek, namely Giriyampeta is located outside the southern border of the sanctuary. In addition to these major creeks, the sanctuary is drained by several smaller sub-tidal and intertidal creeks.

The subtidal creeks drain into the Kakinada Bay, a naturally formed semi-enclosed bay formed at the northern edge of the sanctuary. The main branch of the Gowthami-Godavari creates a riverine estuary at the southern edge of the sanctuary, where the tidal influence can extend up to 50 km upstream.

Sampling sites

Fish sampling was carried out across 52 sites between 2014 and 2017 (Figure 1). Of these, 28 sites were located within mangrove creeks of the CWS (Image 1), 16 sites were in the riverine part of the estuary, and eight sites were located in the Kakinada Bay. Additional surveys were carried out in the local fish markets and landing centers located adjacent to the mangroves, and the river

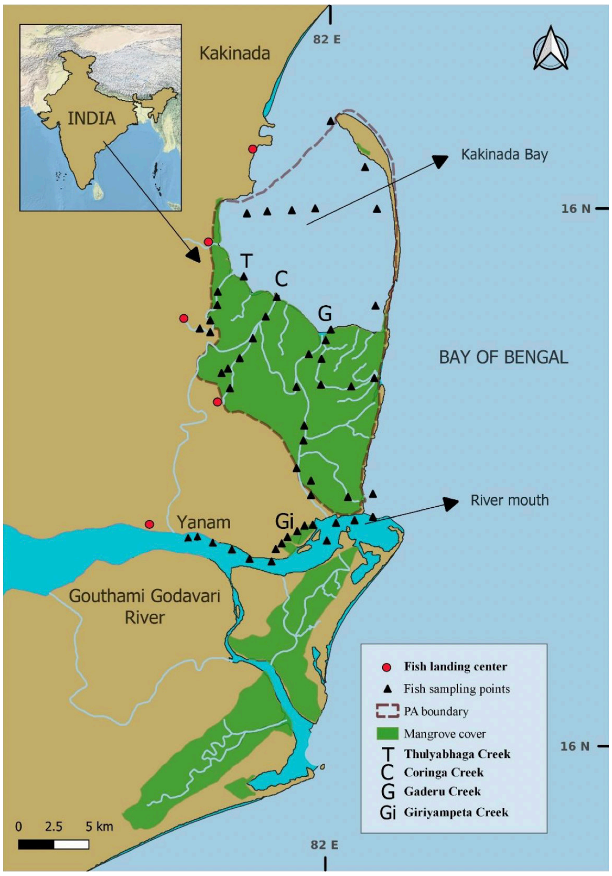

Figure 1. Map showing the location of Coringa Wildlife Sanctuary along with all the fish sampling sites, including landing centers in East Godavari district, Andhra Pradesh.

Image 1. One of the sampling sites during spring high tide. This site was located within the mangrove creeks surveyed inside the Coringa Wildlife Sanctuary, Andhra Pradesh. © Giridhar Malla.

Image 2. An aquaculture pond adjoining the mangrove forests of the Coringa Wildlife Sanctuary, Andhra Pradesh. © Paromita Ray.

mouth.

In the main river within the sanctuary, fishes were collected using locally available trammel nets and gill nets, which were set perpendicular to the water flow for a period of one hour during low tides. In the case of intertidal creeks, block nets were placed at the creek entrance at the beginning of low tide. The fishes that remained within the blocked creek were collected before the onset of the next high tide. Since sampling was conducted inside a protected area, only unidentified specimens were collected for further identification in the laboratory. On a few occasions, specimens were collected opportunistically from fishers' catches from the subtidal creeks, bay, or the river mouth.

Identifications were made using the FAO Fish Catalogue (Fischer & Whitehead 1974; Fischer & Bianchi 1984) and other taxonomic keys available for the region (Day 1888; Jayaram 2010). The correct taxonomy of the species was updated in accordance with the California Academy of Sciences' online repository, the Catalog of Fishes (Fricke et al. 2021). The functional guilds and migratory behavior of the species were confirmed following FishBase (Froese & Pauly 2021) while the threatened status of each of the species followed the latest IUCN Red List of Threatened Species (IUCN 2021).

Image 3. Intrusion of sand into the mangrove forests noticed on the seaward side of the Coringa Wildlife Sanctuary, Andhra Pradesh. © Giridhar Malla.

RESULTS AND DISCUSSION

Diversity and distribution of fishes in the estuary

In the present study, total of 231 species of finfish belonging to 27 orders, 81 families, and 167 genera were recorded (Table 1; Images 4–7). Order Perciformes was the most speciose with 41 species, 22 genera, and 10 families. It was followed by Carangiformes (30 species, 29 genera, and 12 families), and Clupeiformes (25 species, 16 genera, and five families). Among the families (Figure 2), Carangidae was represented by the highest number of species (16 species), followed by Gobiidae and Sciaenidae (both represented by 12 species each). Of all the recorded species, 179 were carnivorous, 45 were omnivorous and two were herbivorous.

In comparison to the earlier study carried out by Krishnan & Mishra (2001), fewer finfish species were recorded during this study. This difference may not necessarily suggest a decline in the overall number of species in the estuary, but is more reflective of the taxonomic and nomenclatural changes. As an example, Krishnan & Mishra (2001) reported seven species of *Stolephorus* from this estuary: *S. andhraensis, S. baganensis, S. commersonii, S. dubiosus, S. indicus, S. insularis*, and *S. waitei*. However, Hata et al. (2020, 2021) made several revisions to the genus *Stolephorus* including updating the species' distribution records. The authors suggested the non-occurrence of *S. baganensis*, *S. commersonii* and *S. waitei* in India, thus making the records of these three species in the Godavari estuary questionable.

On the other hand, species including *Plectorhinchus gibbosus*, *Diagramma pictum,* and non-native species such as *Oreochromis mossambicus* and *Piaractus brachypomus* were recorded for the first time from this estuary. Moreover, the study by Krishnan & Mishra (2001) had a broader scope, having included other distributaries of Godavari River, in comparison to the current study whose focus was the Gowthami-Godavari system. Likewise, the number of species recorded in this study is relatively lower than other large estuaries or mangrove forests located on the east coast of India, including the Sundarbans mangroves (Bhattacharya et al. 2018) and Chilika Lake (Mohanty et al. 2015), from where 312 and 299 species have been recorded, respectively.

Many of the species recorded during this study have also been recorded from other Indian estuaries (Bijukumar & Sushama 2000; Ghosh et al. 2011; Mohanty et al. 2015; Bhattacharya et al. 2018; Sreekanth et al. 2020; Roshni et al. 2021). A number of freshwater species belonging to orders Cypriniformes and Siluriformes were recorded from the mangrove creeks. While a few of them, such as *Mystus gulio* and *Etroplus suratensis* (Image 7a) are known to occur in brackish water habitats (Bijukumar & Sushama 2000), the occurrence of carp species including *Labeo rohita, L. calbasu*, and *L. fimbriatus* were recorded in a few creeks during the post-monsoon season. This is the time when the mangrove forest gets flushed annually with sediment-laden fresh water from the river. The occurrence of these freshwater fishes in the mangrove creeks, however, may also be explained by the stocking of these species in aquaculture ponds abutting the mangroves, creeks, and canals across the East Godavari district. The number of species recorded from the mangrove-lined creeks (150 species), river mouth (151 species), and the Kakinada Bay (149 species) was similar. Nearly 67% of the total species occurred in at least two habitat types showing a high degree of overlap between the estuarine habitats of the delta. Of these, 64 species were found in all three habitat types. The high degree of overlap in species between the habitats indicates the importance of connectivity within this estuarine complex. Fishes recorded exclusively from the bay and the river mouth respectively, constituted nearly 16% and 11% of the total number of species recorded during this study.

Connectivity between the three estuarine habitats and the seascape of East Godavari district is crucial for migratory species occurring in the estuary. The flagship migratory species is *Tenualosa ilisha*, which undertakes large-scale migration from the sea into the Godavari River during the monsoon, when they contribute to important fisheries. It is popularly known as 'Pulasa' in Andhra Pradesh (or 'Hilsa' throughout the Indian sub-continent) and has high commercial value. Other important migratory species occurring in the estuary include *Tenualosa toli*, *Anodontostoma chacunda*, *Lates calcarifer* (Image 4a), and many eel species. Other species, such as mullets (Mugilidae), undertake migrations in the creeks on shorter temporal scales, mainly driven by the tidal regimes and food availability.

Threatened and exotic species

Four species recorded from this estuarine complex are assessed as threatened on the IUCN Red List. These include the Endangered *Silonia childreni,* and the Vulnerable *Tenualosa toli, Cirrhinus cirrhosus* and *Wallago attu*. The Godavari River is an important habitat for *Silonia childreni*, a highly threatened catfish species occurring in the large river systems of peninsular India. On

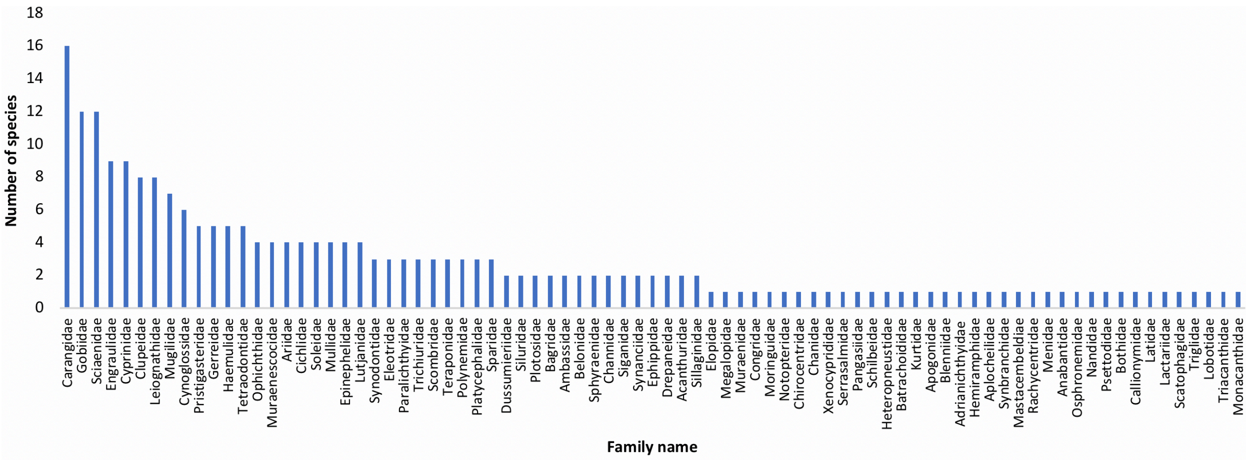

Figure 2. Family-wise number of species recorded in this study.

multiple occasions, the authors recorded its distribution from various parts of the river stretch in Andhra Pradesh, including the estuarine part of the river. Despite this, catches of this large catfish species has been declining, as observed by the local fishers. Additionally, three Near Threatened species: *Ompok bimaculatus, Harpadon nehereus*, & *Protonibea diacanthus* and 10 Data Deficient species: *Platycephalus indicus*, *Epinephelus tauvina*, *Acanthopagrus datnia*, *Rastrelliger kanagurta*, *Scomberomorus guttatus*, *Parapocryptes rictuosus*, *Taenioides cirratus*, *Psettodes erumei*, *Cynoglossus arel*, & *Megalops cyprinoides* were recorded during this study (Table 2). Of the 10 Data Deficient species, *P. indicus* was among the more commonly occurring species in the estuary, which was recorded from all the three habitat types during this study. The two eel species, *Parapocryptes rictuosus* and *Taenioides cirratus*, were recorded only on one occasion in a fisher's catch from the mangrove creek of Tulyabagha inside the CWS.

Five exotic species were also recorded during this study. These include *Oreochromis mossambicus, O. niloticus, Ctenopharyngodon idella, Cyprinus carpio*, and *Piaractus brachypomus*. The first four species are recognized as worst invasive species' of the world by the IUCN Global Invasive Species Database (2021) due to their negative impacts on native fauna. Alarmingly, *O. mossambicus* was found to be among the most dominant species in the CWS. This species appeared to have established a self-sustaining wild population within the Thulyabagha and Coringa creeks of the sanctuary, where the salinities annually ranged from 2 ppt to 20 ppt. The remaining exotic species were recorded only from the riverine zone of the estuary complex.

The main pathway of exotic fish introduction is likely to be through the aquaculture ponds that stock these exotic species. *Piaractus brachypomus* (Pirapitinga), a native of South America, was first recorded from the fish landing centre by the authors in 2013. Since then, this species has become a popular fish in the region (and across the country) and is being extensively stocked in aquaculture ponds along the river, mangrove creeks and canals. It is commonly sold in the local fish markets under the guise of 'white pomfret' or 'freshwater pomfret' and is even being recorded in the catches made by the local fishers in the river (Paromita Ray and Giridhar Malla pers. obs.). This could indicate its possible escape from the aquaculture farms into, and possible establishment within, the river. The authors also noted two occurrence records of *Pterygoplichthys* sp. (family Loricariidae) from the freshwater upstream zone of the river in the East Godavari district. Local fishers recorded this species during the flood season.

Major threats

The Godavari River delta and the estuarine complex have been greatly altered by human activities. The Godavari River delta, along with the Krishna River delta to its south, constitutes one of the largest offshore natural gas reserves in India. The Kakinada Bay also acts as a natural harbour as well as an important port for the state. Additionally, the industrial city of Kakinada (also the headquarters of the East Godavari district) is located adjacent to the mangroves and the estuary. Some of the main causes for degradation of the estuarine ecosystems and the mangrove forests include: diversion for aquaculture, agriculture, salt pans and industries; and rapid and unplanned urbanization (Jayanthi et al. 2018; Bagaria et al. 2021). Other threats include discharge of untreated effluents from anthropogenic sources such as aquaculture farms and industries into the river, canals

Table 1. Habitat-wise list of finfish species recorded during this study from the Godavari River estuary complex.

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
1	Elopiformes	Elopidae	*Elops machnata* (Fabricius, 1775) (Image 5e)	0	1	0
2		Megalopidae	*Megalops cyprinoides* (Broussonet, 1782)	1	1	1
3	Anguilliformes	Muraenidae	*Strophidon sathete* (Hamilton, 1822)	1	1	0
4		Ophichthidae	*Bascanichthys deraniyagalai* Menon, 1961	1	1	1
5			*Cirrhimuraena playfairii* (Günther, 1870)	1	1	0
6			*Pisodonophis boro* (Hamilton, 1822)	1	1	0
7			*Pisodonophis cancrivorus* (Richardson, 1848)	1	1	0
8		Muraenescocidae	*Congresox talabonoides* (Bleeker, 1852)	1	1	0
9			*Congresox talabon* (Cuvier, 1829)	1	1	0
10			*Muraenesox cinereus* (Forsskål, 1775)	1	1	0
11			*Muraenesox bagio* (Hamilton, 1822)	1	1	0
12		Congridae	*Uroconger lepturus* (Richardson, 1845)	1	0	0
13		Moringuidae	*Moringua raitaborua* (Hamilton, 1822)	1	1	1
14	Osteoglossiformes	Notopteridae	*Notopterus notopterus* (Pallas, 1769)	1	0	0
15	Clupeiformes	Clupeidae	*Anodontostoma chacunda* (Hamilton, 1822)	1	1	0
16			*Escualosa thoracata* (Valenciennes, 1847)	1	1	1
17			*Hilsa kelee* (Cuvier, 1829)	1	1	1
18			*Nematalosa nasus* (Bloch, 1795)	1	0	0
19			*Sardinella longiceps* Valenciennes, 1847	1	1	1
20			*Sardinella fimbriata* (Valenciennes, 1847)	1	1	1
21			*Tenualosa ilisha* (Hamilton, 1822)	1	0	0
22			*Tenualosa toli* (Valenciennes, 1847)	1	1	0
23		Dussumieriidae	*Dussumieria acuta* Valenciennes, 1847	0	1	1
24			*Dussumieria elopsoides* Bleeker, 1849	0	1	1
25		Engraulidae	*Coilia dussumieri* Valenciennes, 1848	1	1	1
26			*Coilia reynaldi* Valenciennes, 1848	1	1	1
27			*Setipinna taty* (Valenciennes, 1848)	1	1	1
28			*Setipinna tenuifilis* (Valenciennes, 1848)	1	1	1
29			*Stolephorus commersonnii* Lacepède, 1803	1	1	1
30			*Stolephorus indicus* (van Hasselt, 1823)	0	0	1
31			*Thryssa mystax* (Bloch & Schneider, 1801)	1	1	1
32			*Thryssa malabarica* (Bloch, 1795)	1	1	1
33			*Thryssa baelama* (Fabricius, 1775)	1	1	1
34		Chirocentridae	*Chirocentrus dorab* (Fabricius, 1775)	1	0	1
35		Pristigasteridae	*Ilisha melastoma* (Bloch & Schneider, 1801)	1	1	1
36			*Ilisha megaloptera* (Swainson, 1838)	1	1	1
37			*Opisthopterus tardoore* (Cuvier, 1829) (Image 4c)	1	1	1
38			*Pellona ditchela* Valenciennes, 1847	1	1	1
39			*Raconda russeliana* Gray, 1831	1	0	1
40	Gonorynchiformes	Chanidae	*Chanos chanos* (Fabricius, 1775)	1	0	1
41	Cypriniformes	Cyprinidae	*Cirrhinus cirrhosus* (Bloch, 1795)	1	1	0
42			*Cirrhinus mrigala* (Hamilton, 1822)	1	0	0
43			*Cyprinus carpio* Linnaeus, 1758	1	0	0

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
44			*Labeo catla* (Hamilton, 1822)	1	0	0
45			*Labeo calbasu* (Hamilton, 1822)	1	1	0
46			*Labeo fimbriatus* (Bloch, 1795)	1	1	0
47			*Labeo rohita* (Hamilton, 1822)	1	1	0
48			*Puntius sophore* (Hamilton, 1822)	1	1	0
49			*Pethia ticto* (Hamilton, 1822)	1	0	0
50		Xenocyprididae	*Ctenopharyngodon idella* (Valenciennes, 1844)	1	0	0
51	Characiformes	Serrasalmidae	*Piaractus brachypomus* (Cuvier, 1818)	1	0	0
52	Siluriformes	Plotosidae	*Plotosus canius* Hamilton, 1822	1	1	0
53			*Plotosus lineatus* (Thunberg, 1787)	0	0	1
54		Ailiidae	*Silonia childreni* (Sykes, 1839)	1	0	0
55		Bagridae	*Mystus gulio* (Hamilton, 1822)	1	1	0
56			*Mystus vittatus* (Bloch, 1794)	1	1	0
57		Pangasiidae	*Pangasius pangasius* (Hamilton, 1822)	1	1	0
58		Siluridae	*Wallago attu* (Bloch & Schneider, 1801)	1	0	0
59			*Ompok bimaculatus* (Bloch, 1794)	1	0	0
60		Heteropneustidae	*Heteropneustes fossilis* (Bloch, 1794)	1	1	0
61		Ariidae	*Arius arius* (Hamilton, 1822)	1	1	1
62			*Arius gagora* (Hamilton 1822)	1	1	1
63			*Arius maculatus* (Thunberg, 1792)	1	1	1
64			*Plicofollis dussumieri* (Valenciennes, 1840)	0	0	1
65	Aulopiformes	Synodontidae	*Saurida tumbil* (Bloch, 1795)	0	0	1
66			*Synodus indicus* (Day, 1873)	0	0	1
67			*Harpadon nehereus* (Hamilton, 1822)	1	1	1
68	Batrachoidiformes	Batrachoididae	*Allenbatrachus grunniens* (Linnaeus, 1758) (Image 7c)	1	1	0
69	Scombriformes	Scombridae	*Katsuwonus pelamis* (Linnaeus, 1758)	0	0	1
70			*Rastrelliger kanagurta* (Cuvier, 1816)	1	0	1
71			*Scomberomorus guttatus* (Bloch & Schneider, 1801)	0	0	1
72		Trichiuridae	*Eupleurogrammus muticus* (Gray, 1831)	1	1	0
73			*Lepturacanthus savala* (Cuvier, 1829)	1	0	1
74			*Trichiurus lepturus* Linnaeus, 1758	1	0	1
75	Syngnathiformes	Mullidae	*Upeneus sulphureus* Cuvier, 1829	1	1	1
76			*Upeneus vittatus* (Forsskål, 1775)	1	0	0
77			*Upeneus moluccensis* (Bleeker, 1855)	0	0	1
78			*Upeneus taeniopterus* Cuvier, 1829	1	1	1
79		Callionymidae	*Callionymus carebares* Alcock, 1890	0	1	0
80	Kurtiformes	Kurtidae	*Kurtus indicus* Bloch, 1786 (Image 7d)	0	1	1
81		Apogonidae	*Jaydia queketti* (Gilchrist 1903) (Image 6d)	0	0	1
82	Gobiiformes	Eleotridae	*Eleotris fusca* (Bloch & Schneider, 1801)	1	1	0
83			*Butis butis* (Hamilton, 1822) (Image 5d)	0	1	0
84			*Butis humeralis* (Valenciennes, 1837)	0	1	0
85		Gobiidae	*Aulopareia cyanomos* (Bleeker, 1849) (Image 5b)	0	1	1
86			*Apocryptes bato* (Hamilton, 1822)	0	1	0
87			*Boleophthalmus boddarti* (Pallas, 1770)	0	1	1

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
88			*Glossogobius giuris* (Hamilton, 1822)	1	1	0
89			*Oxyurichthys microlepis* (Bleeker, 1849) (Image 7b)	0	1	0
90			*Parapocryptes rictuosus* (Valenciennes, 1837)	0	1	0
91			*Periophthalmus chrysospilos* Bleeker, 1853	0	1	0
92			*Taenioides anguillaris* (Linnaeus, 1758)	1	1	0
93			*Taenioides cirratus* (Blyth, 1860)	1	1	0
94			*Trypauchen vagina* (Bloch & Schneider, 1801) (Image 6e)	1	1	0
95			*Yongeichthys nebulosus* (Forsskål, 1775)	1	0	0
96			*Stigmatogobius sadanundio* (Hamilton, 1822)	1	0	0
97	Synbranchiformes	Mastacembelidae	*Macrognathus pancalus* Hamilton 1822	1	0	0
98		Synbranchidae	*Ophisternon bengalense* McClelland, 1844	1	0	0
99	Anabantiformes	Anabantidae	*Anabas testudineus* (Bloch, 1792)	1	1	0
100		Osphronemidae	*Trichogaster fasciata* Bloch & Schneider, 1801	1	0	0
101		Channidae	*Channa punctata* (Bloch, 1793)	1	0	0
102			*Channa striata* (Bloch, 1793)	1	0	0
103		Nandidae	*Nandus nandus* (Hamilton, 1822)	0	1	0
104	Carangiformes	Latidae	*Lates calcarifer* (Bloch, 1790) (Image 4a)	1	1	0
105		Lactariidae	*Lactarius lactarius* (Bloch & Schneider, 1801)	1	0	1
106		Sphyraenidae	*Sphyraena obtusata* Cuvier, 1829	0	0	1
107			*Sphyraena jello* Cuvier, 1829	0	0	1
108		Polynemidae	*Eleutheronema tetradactylum* (Shaw, 1804)	1	1	1
109			*Polydactylus sextarius* (Bloch & Schneider, 1801)	1	1	1
110			*Leptomelanosoma indicum* (Shaw, 1804)	1	1	1
111		Psettodidae	*Psettodes erumei* (Bloch & Schneider, 1801)	1	0	1
112		Bothidae	*Bothus myriaster* (Temminck & Schlegel, 1846)	0	1	1
113		Paralichthyidae	*Pseudorhombus arsius* (Hamilton, 1822)	0	1	1
114			*Pseudorhombus triocellatus* (Bloch & Schneider, 1801)	0	1	1
115			*Pseudorhombus elevatus* Ogilby, 1912	1	1	1
116		Soleidae	*Aesopia cornuta* Kaup, 1858	0	0	1
117			*Solea ovata* Richardson, 1846	0	1	1
118			*Dagetichthys albomaculatus* (Kaup, 1858)	1	1	1
119			*Zebrias synapturoides* (Jenkins, 1910)	1	1	1
120		Cynoglossidae	*Cynoglossus arel* (Bloch & Schneider, 1801)	1	1	1
121			*Cynoglossus bilineatus* (Lacepède, 1802)	1	1	1
122			*Cynoglossus puncticeps* (Richardson, 1846)	1	1	1
123			*Cynoglossus lingua* Hamilton, 1822	1	1	0
124			*Cynoglossus cynoglossus* (Hamilton, 1822)	1	1	1
125			*Paraplagusia bilineata* (Bloch, 1787)	1	1	1
126		Menidae	*Mene maculata* (Bloch & Schneider, 1801)	0	1	0
127		Carangidae	*Megalaspis cordyla* (Linnaeus, 1758)	0	0	1
128			*Scyris indica* (Rüppell, 1830)	1	0	1
129			*Alepes djedaba* (Fabricius, 1775)	1	0	1
130			*Alepes kleinii* (Bloch, 1793)	1	0	1
131			*Atropus atropos* (Bloch & Schneider, 1801)	0	0	1

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
132			*Atule mate* (Cuvier, 1833)	1	0	1
133			*Platycaranx malabaricus* (Bloch & Schneider, 1801)	0	0	1
134			*Caranx ignobilis* (Forsskål, 1775)	0	1	1
135			*Caranx sexfasciatus* Quoy & Gaimard, 1825	0	1	1
136			*Caranx heberi* (Bennett, 1830)	0	0	1
137			*Decapterus russelli* (Rüppell, 1830)	0	0	1
138			*Parastromateus niger* (Bloch, 1795)	0	1	1
139			*Scomberoides commersonnianus* Lacepède, 1801	0	0	1
140			*Scomberoides tol* (Cuvier, 1832)	0	0	1
141			*Selar crumenophthalmus* (Bloch, 1793)	0	0	1
142			*Trachinotus mookalee* Cuvier, 1832. (Image 6a)	0	1	1
143		Rachycentridae	*Rachycentron canadum* (Linnaeus, 1766)	0	0	1
144	Cichliformes	Ambassidae	*Ambassis gymnocephalus* (Lacepède, 1802)	1	1	0
145			*Chanda nama* Hamilton, 1822	1	1	0
146		Cichlidae	*Etroplus suratensis* (Bloch, 1790) (Image 7a)	1	1	0
147			*Pseudetroplus maculatus* (Bloch, 1795)	1	0	0
148			*Oreochromis mossambicus* (Peters, 1852)	1	1	0
149			*Oreochromis niloticus* (Linnaeus, 1758)	1	0	0
150	Cyprinodontiformes	Aplocheilidae	*Aplocheilus blockii* Arnold, 1911	1	1	0
151	Beloniformes	Belonidae	*Strongylura strongylura* (van Hasselt, 1823)	1	0	1
152			*Xenentodon cancila* (Hamilton, 1822)	1	1	0
153		Hemiramphidae	*Hyporhamphus limbatus* (Valenciennes, 1847)	1	1	1
154		Adrianichthyidae	*Oryzias dancena* (Hamilton 1822)	0	1	0
155	Mugiliformes	Mugilidae	*Mugil cephalus* Linnaeus, 1758	1	1	1
156			*Chelon parsia* (Hamilton, 1822)	1	1	1
157			*Planiliza subviridis* (Valenciennes, 1836)	1	1	1
158			*Planiliza planiceps* (Valenciennes, 1836)	1	0	0
159			*Planiliza tade* (Fabricius, 1775)	1	1	0
160			*Rhinomugil corsula* (Hamilton, 1822)	1	1	0
161			*Crenimugil seheli* (Fabricius, 1775)	1	1	1
162	Blenniiformes	Blenniidae	*Omobranchus ferox* (Herre, 1927)	1	1	0
163	Perciformes *sedis mutabilis*	Sillaginidae	*Sillaginopsis domina* (Cuvier, 1816)	0	0	1
164			*Sillago sihama* (Fabricius, 1775)	1	1	1
165		Lutjanidae	*Lutjanus johnii* (Bloch, 1792) (Image 4b)	1	1	1
166			*Lutjanus russellii* (Bleeker, 1849)	0	1	1
167			*Lutjanus argentimaculatus* (Forsskål, 1775) (Image 5c)	0	1	1
168			*Lutjanus fulviflamma* (Forsskål, 1775)	0	1	1
169		Gerreidae	*Gerres filamentosus* Cuvier, 1829	1	1	1
170			*Gerres limbatus* Cuvier, 1830	1	1	1
171			*Gerres setifer* (Hamilton, 1822)	1	1	1
172			*Gerres oyena* (Fabricius, 1775)	1	1	1
173			*Gerres longirostris* (Lacepède, 1801)	0	0	1
174		Haemulidae	*Pomadasys kaakan* (Cuvier, 1830)	1	1	1

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
175			*Pomadasys argenteus* (Forsskål, 1775)	1	1	1
176			*Pomadasys maculatus* (Bloch, 1793)	1	1	1
177			*Plectorhinchus gibbosus* (Lacepède, 1802)	0	0	1
178			*Diagramma pictum* (Thunberg, 1792)	0	0	1
179		Sparidae	*Acanthopagrus berda* (Fabricius, 1775)	0	0	1
180			*Acanthopagrus datnia* (Hamilton, 1822)	0	0	1
181			*Rhabdosargus sarba* (Gmelin, 1789)	0	0	1
182		Sciaenidae	*Chrysochir aurea* (Richardson, 1846)	0	1	1
183			*Daysciaena albida* (Cuvier, 1830)	0	1	1
184			*Dendrophysa russelii* (Cuvier, 1829)	1	1	1
185			*Johnius belangerii* (Cuvier, 1830)	0	1	1
186			*Johnius coitor* (Hamilton, 1822)	1	1	1
187			*Johnius dussumieri* (Cuvier, 1830)	0	1	1
188			*Kathala axillaris* (Cuvier, 1830)	0	1	1
189			*Nibea maculata* (Bloch & Schneider, 1801)	0	1	1
190			*Nibea soldado* (Lacepède, 1802)	0	1	1
191			*Otolithes ruber* (Bloch & Schneider, 1801)	1	1	0
192			*Panna microdon* (Bleeker, 1849)	0	1	1
193			*Protonibea diacanthus* (Lacepède, 1802)	0	1	1
194	Perciformes	Epinephelidae	*Epinephelus coioides* (Hamilton, 1822)	0	1	1
195			*Epinephelus malabaricus* (Bloch & Schneider, 1801)	0	1	1
196			*Epinephelus melanostigma* Schultz, 1953	0	0	1
197			*Epinephelus tauvina* (Fabricius, 1775)	0	0	1
198		Platycephalidae	*Grammoplites scaber* (Linnaeus, 1758)	1	1	0
199			*Cociella crocodilus* (Cuvier, 1829)	1	0	0
200			*Platycephalus indicus* (Linnaeus, 1758)	1	1	1
201		Triglidae	Lepidotrigla sp.	0	0	1
202		Synanceiidae	*Minous monodactylus* (Bloch & Schneider, 1801) (Image 4f)	0	1	1
203			*Minous inermis* Alcock 1889	0	0	1
204	Centrarchiformes	Terapontidae	*Terapon jarbua* (Fabricius, 1775) (Image 6c)	1	1	0
205			*Terapon puta* Cuvier, 1829	1	1	0
206			*Pelates quadrilineatus* (Bloch, 1790)	1	0	1
207	Acanthuriformes	Lobotidae	*Lobotes surinamensis* (Bloch, 1790)	1	0	1
208		Drepaneidae	*Drepane longimana* (Bloch & Schneider, 1801)	1	1	0
209			*Drepane punctata* (Linnaeus, 1758)	0	1	0
210		Ephippidae	*Ephippus orbis* (Bloch, 1787)	0	0	1
211			Platax sp.	0	0	1
212		Leiognathidae	*Leiognathus equula* (Forsskål, 1775)	1	1	1
213			*Eubleekeria splendens* (Cuvier, 1829)	1	1	1
214			*Leiognathus berbis* (Valenciennes, 1835)	0	1	1
215			*Photopectoralis bindus* (Valenciennes, 1835)	1	1	1
216			*Gazza minuta* (Bloch, 1795)	0	0	1
217			*Deveximentum insidiator* (Bloch, 1787)	1	1	1
218			*Nuchequula blochii* (Valenciennes, 1835)	0	1	1

	Order	Family	Species	Main River	Mangroves	Kakinada Bay
219			*Leiognathus ruconius* (Hamilton, 1822) (Image 4d)	1	1	1
220		Scatophagidae	*Scatophagus argus* (Linnaeus, 1766)	1	1	1
221		Siganidae	*Siganus canaliculatus* (Park, 1797)	1	1	1
222			*Siganus javus* (Linnaeus, 1766) (Image 4e)	1	1	1
223		Acanthuridae	*Acanthurus mata* (Cuvier, 1829) (Image 5a)	1	0	0
224			*Acanthurus xanthopterus* Valenciennes, 1835	1	1	1
225	Tetraodontiformes	Triacanthidae	*Triacanthus biaculeatus* (Bloch, 1786) (Image 6b)	0	0	1
226		Tetraodontidae	*Takifugu oblongus* (Bloch, 1786)	0	0	1
227			*Chelonodontops patoca* (Hamilton, 1822)	1	1	1
228			*Dichotomyctere fluviatilis* (Hamilton, 1822)	1	1	1
229			*Lagocephalus lunaris* (Bloch & Schneider, 1801)	1	0	1
230			*Lagocephalus inermis* (Temminck & Schlegel, 1850)	1	0	1
231		Monacanthidae	*Aluterus monoceros* (Linnaeus, 1758)	0	0	1
			Total	**151**	**150**	**149**

1—Presence recorded | 0—Presence not recorded.

Image 4. Images of fish species recorded in this study along with their standard lengths whenever available: a—*Lates calcarifer* | b—*Lutjanus johnii* (137 mm) | c—*Opisthopterus tardoore* (98 mm) | d—*Leiognathus ruconius* (48 mm) | e—*Siganus javus* (78 mm) | f—*Minous monodactylus* (72 mm). © Paromita Ray.

and the mangrove creeks (Rao et al. 2018); sand mining at the river bed, dredging of the creeks and river mouth (Malini & Rao 2004) alteration of the natural flow of Godavari River and obstructing freshwater discharge and sediment load into the estuary and mangroves (Malini & Rao 2004). Large-scale deforestation and loss of aquatic habitats in the upper catchments of Godavari River, such as that found in and around the Papikonda National Park (Aditya & Ganesh 2019) which is ~80 km upstream of the estuary, also exacerbates the negative impacts on the estuarine biodiversity.

During the present study, we noticed a number of aquaculture ponds located very close to the mangrove forests, and adjoining the feeder creeks and canals (Image 2). This not only increases the risk of release of exotic fishes and causes degradation of the fringe mangroves, but also increases the risk of introduction of disease in the wild fish community. During the study period, two instances of fish kills were also observed in the Coringa creek draining into the CWS. On further enquiry by the authors, the local fishers informed us that fish kills have become a regular occurrence in the creeks due to the release of untreated effluents by the aquaculture ponds and the industries located upstream. The coastal zones of the East Godavari district are considered among the most polluted in the state (Muktha et al. 2018).

The mangroves of CWS are well-protected and support a diverse aquatic community. However, the mangrove patches at the edge of the sanctuary or the unprotected patches in the district are highly vulnerable to loss and conversion to other land uses, including aquaculture and industries. Bagaria et al. (2021) estimated a loss of 5.81 sq. km of unprotected mangroves in the delta between 1977 and 2015, complemented with a simultaneous rise of 177 km^2 in the area under aquaculture. The study has also highlighted the rapid increase in human settlements and industries and a loss of other natural coastal features, including coastal scrub, mudflats, and riverine vegetation. A recent report by Rao (2021) inferred that an unprotected patch of mangrove drained by a creek near Kakinada harbour had been reported to be reclaimed for city development.

As the unprotected mangroves on the landward side are being lost to land-use changes, climate change is

Image 5. Images of fish species recorded in this study along with their standard lengths whenever available: a—*Acanthurus mata* (56 mm) | b—*Acentrogobius cyanomos* (110 mm) | c—*Lutjanus argentimaculatus* (153 mm) | d—*Butis butis* (120 mm) | e—*Elops machnata*. © Paromita Ray.

Table 2. List of threatened, Near Threatened, and Data Deficient species as per the IUCN Red List of Threatened Species.

	Species name	Main river	Mangroves	Bay	IUCN Red List status
1	*Silonia childreni* (Sykes, 1839)	+	-	-	EN
2	*Tenualosa toli* (Valenciennes, 1847)	+	+	-	VU
3	*Cirrhinus cirrhosus* (Bloch, 1795)	+	+	-	VU
4	*Wallago attu* (Bloch & Schneider, 1801)	+	-	-	VU
5	*Ompok bimaculatus* (Bloch, 1794)	+	-	-	NT
6	*Harpadon nehereus* (Hamilton, 1822)	+	+	+	NT
7	*Protonibea diacanthus* (Lacepède, 1802)	-	+	+	NT
8	*Platycephalus indicus* (Linnaeus, 1758)	+	+	+	DD
9	*Epinephelus tauvina* (Fabricius, 1775)	-	-	+	DD
10	*Acanthopagrus datnia* (Hamilton, 1822)	-	-	+	DD
11	*Rastrelliger kanagurta* (Cuvier, 1816)	+	-	+	DD
12	*Scomberomorus guttatus* (Bloch & Schneider, 1801)	-	-	+	DD
13	*Parapocryptes rictuosus* (Valenciennes, 1837)	-	+	-	DD
14	*Taenioides cirratus* (Blyth, 1860)	+	+	-	DD
15	*Psettodes erumei* (Bloch & Schneider, 1801)	+	-	+	DD
16	*Cynoglossus arel* (Bloch & Schneider, 1801)	+	+	+	DD
17	*Megalops cyprinoides* (Broussonet, 1782)	+	+	+	DD

+—Presence recorded | ——Presence not recorded | EN—Endangered | VU—Vulnerable | NT—Near Threatened | DD—Data Deficient.

driving mangrove loss on the seaward side of the delta. An estimated 15 km^2 of mangroves in the East Godavari district have been lost due to sea-level rise between 1977 and 2015 (Bagaria et al. 2021). Visible signs of seaward changes, including degradation and intrusion of sand into the mangrove forests, were also observed by the authors during the present study (Image 3). This region is also among the coastal stretches of India that are most vulnerable to natural disasters including cyclones and storm surges (Mohapatra et al. 2012). The effects of sea-level rise compounded with the increasing degradation and conversion of the mangroves on the landward side is possibly driving them towards a situation of 'mangrove squeeze'.

In addition to the above threats, regulation of the Godavari River driven by the Polavaram Dam, a large dam being constructed nearly 100 km upstream of the river mouth, will potentially lead to drastic reductions in freshwater and sediment flow into the mangroves and the estuary. Studies from Portugal (Chicharo et al. 2006), China (Jiao et al. 2007) and other parts of the world have shown the negative impacts of damming on estuaries and marine habitats, including changes in salinity regime, nutrient flow, primary productivity and the fish community. Ezcurra et al. (2019) found a rapid coastal recession in otherwise accreting tropical river basins after they were dammed, coupled with losses in fisheries and other ecosystem services. With the presence of nine large dams and a number of smaller dams and irrigation projects, the Godavari River is a highly regulated river system of India. The annual sediment flux in the river basin has already decreased by an estimated 74% (Gupta et al. 2012). The Polavaram Dam has a high likelihood of exacerbating the downstream impacts by restricting the sediment discharge and further altering the freshwater flow regime, both of which play important roles in the sustenance of the mangroves as well as in structuring the estuarine fish assemblages. It will, therefore, be crucial to regularly monitor the estuary and its fish community once the dam becomes functional in the near future.

CONCLUSION AND RECOMMENDATIONS

This study documented the rich finfish diversity of the dynamic Godavari River estuarine complex. This estuary complex, formed by India's largest peninsular river, is undergoing rapid changes driven by number of anthropogenic factors coupled with sea-level rise, coastal erosion and natural disasters including cyclones. While the protected mangroves of the CWS do provide a crucial refuge for estuarine and juvenile marine fishes, it

Image 6. Images of fish species recorded in this study along with their standard lengths whenever available: a—*Trachinotus mookalee* (86 mm) | b—*Triacanthus biaculeatus* (129 mm) | c—*Terapon jarbua* (37 mm) | d—*Jaydia queketti* (88 mm) | e—*Trypauchen vagina*. © Paromita Ray.

is important to adopt a holistic and prescient approach to protect the unprotected coastal habitats of the region. As this study suggests, various fish species are utilizing the different estuarine habitats of the Godavari delta. Few migratory and conservation-concern species such as the 'Hilsa' or 'Pulasa' have also been recorded in this estuary. Therefore, to better manage the threats, and to protect the aquatic ecosystems of the East Godavari district, it is crucial to understand and acknowledge the importance of maintaining the ecological connectivity, both between and within the riverscape and the various estuarine habitats, including the river mouth, the mangrove-lined creeks and the bay. The information collected in this study will serve as a baseline to monitor future changes in the fish community of this region, driven by various anthropogenic and natural stressors.

The Polavaram Dam is already under construction, but it is still important to focus on mitigating the negative impacts on the riverine habitats, both upstream and downstream. The minimum freshwater flows to the downstream habitats must be ensured by the dam authorities, taking in consideration the river's natural pattern of seasonal variation in freshwater discharge. Alongside this, it is also important to recognize the negative impacts of stocking and introduction of non-native fish species as a mitigation measure. Several non-native species have been recorded in this study that were introduced either through fisheries or accidentally through aquaculture and the aquarium industry. The district authorities and the fisheries department need to take immediate steps to address this issue, while strictly prohibiting the stocking of non-native fishes in the reservoir, canals or aquaculture ponds in the district. The fisheries department can encourage protection of the carp and catfish species that are native to the Godavari River basin such as the threatened *Silonia childreni*.

We recommend mapping of the unprotected and degraded patches of mangroves in the delta region of

Image 7. Images of fish species recorded in this study along with their standard lengths whenever available: a—*Etroplus suratensis* (71 mm) | b—*Oxyurichthys microlepis* (72 mm) | c—*Allenbatrachus grunniens* | d—*Kurtus indicus* (62 mm). © Paromita Ray.

the district that serve as important nursery habitats for the fish species. This would help in identifying and prioritizing the most vulnerable stretches for focused conservation efforts. Declaring the most degraded and vulnerable mangroves as 'eco-sensitive zones' or 'community reserves' would provide them with basic protection from future conversions and losses. The authorities may follow this with restoration of the degraded mangrove patches. A similar prioritization exercise should also be carried out for other coastal habitats of the estuary, including the unprotected creeks, intertidal zones, mudflats, river banks and the river mouth.

Additionally, a minimum buffer should be allowed around the mangrove forests and the creeks on the landward side to allow them to maintain their structural integrity and landward shift driven by sea-level rise. The aquaculture ponds should particularly be located at a minimum distance away from the mangrove forests and the creeks. Strict monitoring of the ponds, as per the guidelines prescribed by the Coastal Aquaculture Authority of India, should be carried out to prevent untreated effluent discharge and release of non-native species into the natural habitats. Since the area under aquaculture in the district continues to grow each year, a scientific study is recommended that would assess the ecological capacity of this estuarine region to support this industry along with assessing the extant negative ecological and socio-economic impacts of the same. The policies pertaining to captive fisheries should actively encourage sustainable aquaculture practices rather than focusing on maximization of short-term economic gains.

The district authorities should also enhance monitoring of destructive activities in the river basin such as sand-mining, deforestation of the riparian zones, and conversion of river banks to other land-uses. In addition, the government should especially take actions to stop illegal mining of the river bed in the district, proactively monitor the pollution levels in the river, mangroves, and the associated creeks and canals and initiate action against the industries and aquaculture ponds found releasing untreated effluents into the estuary, as prescribed by law.

Garnering the support of local communities and other stakeholders is crucial for the long-term conservation and management of the Godavari estuarine complex and its associated biodiversity. For generating local support, district and village-level organizations such as the panchayat, self-help groups, fishers' collectives, and aquaculture collectives can be leveraged. Regular and focused campaigns would be helpful to improve awareness as well as generating local stewardship for sustainable fisheries and biodiversity conservation. Such awareness programs should also be developed for policy makers, planners, and stakeholders from the agricultural and industrial sectors since their actions may also have serious impacts on the aquatic ecosystems of the district. Along with this, further inter-disciplinary studies are important to understand the different features of this estuarine complex including biological, ecological, social, cultural, and economic complexities.

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