Biodiversity of macrobenthos in selected major ports and an estuary of India

A Thesis submitted in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

in

School of Earth, Ocean and Atmospheric Sciences

By

Noyel V

Goa University,

Taleigao Goa

September *2021*

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Research Guide

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Dedicated to my mother

Contents

DECLARATION

I, Noyel V hereby declare that this thesis represents work which has been carried out by me and that it has not been submitted, either in part or full, to any other University or Institution for the award of any research degree.

Place: Dona Paula
Date: 17.09.2021.

Noyel V

CERTIFICATE

I hereby certify that the above Declaration of the candidate, Noyel V is true and the work was carried out under my supervision.

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Noyel V

Abbreviations

ANOVA- Analysis of variance

CB- Cochin backwaters

Chl *a*- Chlorophyll *a*

CCA- Canonical correspondence analysis

DIN- Dissolved inorganic nitrogen

DIP- Dissolved inorganic phosphate

DO- Dissolved oxygen

GF/F- Glass fiber filter

HDC – Haldia dock complex

IMD- Indian meteorological department

KOPT- Kidderpore port trust

MON- Monsoon

NBW- Near bottom waters

NEM- North east monsoon

NSD- Netaji Subhas Dock

POM- Post-monsoon

POL- Petroleum Oil Lubricants

PreM- Pre-monsoon

RDA- Redundancy analysis

S (Number)-Station

N- Number

SWM- South west monsoon

TRIX- Trophic index

TSI- - Trophic status index

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Chapter 1.

Introduction

1.1 Macrobenthic diversity and environment

"Biodiversity is an attribute of an area and specifically refers to the variety within and among the living organisms, assemblages of living organisms, biotic communities, and biotic processes whether naturally occurring or modified by humans. Biodiversity can be measured in terms of genetic diversity and the identity and number of different types of species, assemblages of species, and the amount (e.g., abundance, biomass) and structure of each community. It can be observed and measured at any spatial scale ranging from microsites and habitat patches to the entire biosphere" Delong, (1996). Studies relevant to marine biodiversity of different ecosystems are important from the perspectives of food web dynamics and ecosystem functioning. Biodiversity of benthic organisms, especially the macrobenthos diversity act as an integral part of the benthic ecosystems including fresh water, estuarine, coastal and deep sea and these are the bottom dwelling fauna. Benthic biodiversity comprises of organisms belonging to micro-, meio- and macro fauna (Mare, 1942; Zajac, 2008) and their distribution and community structure depends upon various biotic and abiotic conditions of an ecosystem. The distribution, and community structure of macrobenthic organisms mainly depend on the nature of the sediment, its stability, levels of hydrogen sulphide in the sediment, oxygen concentrations and its flux and nutrient concentrations (Anbuchezhian et al, 2009). For a healthy ecosystem, well developed macrobenthic community is crucial (Paolo Magni, 2003).

Understanding the complexity of biotic and abiotic environmental factors that have developed in an ecosystem, and the spatial and temporal variations is environmental heterogeneity (Cisneros et al, 2011). In tropics, the changes in the benthic environment are greater compared to the higher latitudes and this results in the wide variation of macrobenthic diversity (Alongi, 1990). They are used as bio-indicators for pollution monitoring studies owing to their short life cycle and limited mobility, tertiary level feeders and food for several bottom dwelling higher invertebrates and fishes (Gray, 2009). The influence of eutrophication on the macrobenthic community can be identified by the variations in environmental factors such as salinity, temperature, eutrophic and hypoxic conditions in the substratum (Tsujimoto et al, 2006). Benthic organisms are significantly diverse, abundant and have ecologically important functions in coastal waters as they provide sediment stability and have higher ability to adapt to different environments (Simboura, 2000). Benthic organisms also play an important role in maintaining ecological balance in the marine ecosystem. Due to their various feeding and burrowing behaviour, these organisms manage the physio-chemical and biological activities and also an interacting factor between sediment and water column. Polychaetes, bivalves and crustaceans are the dominant macrobenthic fauna and mostly considered as biological indicators of benthic environment (Ingole, 2009). Polychaetes are the most abundant and dominant group in the benthic community which contribute to ~80% of the total macrobenthic population and they are being used for biomonitoring organic pollution and to check the quality of marine environment. The macrofauna in the benthic sediments plays an important role in the ecosystem processes such as the nutrient cycling, secondary productivity, burial, dispersion and metabolism of the pollutants, and understanding these lead to understanding the biodiversity in the marine sediments (Snelgrove, 1998). The present study is carried out at major ports and an estuarine environments to understand spatio-temporal variation in the macrobenthic diversity, community structure and their population which will help in understanding the natural environment and anthropogenic stressors which influence the ecology and biodiversity and this will also help in resource management.

1.2 Literature review

The research related to the benthic community has a long history and understanding the past and present studies help in understanding the organisms and the factors influencing their diversity. ‘Benthos’ was first coined by Haeckel, and this originated from the Greek word ‘Depths of the sea’, these terms refer all the organisms living in, on or under the bottom of an aquatic body. Distribution of benthic fauna and their community structure are well documented by Jones, (1940, 1951, 1952 and 1956), and biology and diversity of macrofauna was reported by Sanders, (1956, 1958 and 1968). Studies on Black and Caspian Sea macrobenthic fauna was reported by Zenkevitch, (1959, 1963), on Buzzards bay by Weiser, (1960) and of the coast of Washington by Lie, (1960). Studies on macrobenthic community on Northumberland coast and sediment characteristics were carried out by Buchanan et al, (1978, 1980). Pearson and Rosenberg (1978) were considered as pioneers on the studies of macrobenthic fauna related to organic pollution, whereas, Pearson and Gray, (1982) reported the effects of pollution on benthic community. Ecology and distribution of estuarine benthos (Wolff, 1983), benthic fauna of Greek Gulf (Bogdanos and Satsmadjis, 1985), variation in macrobenthos of Jamaica Bay (Franz and Harris, 1988) and Austen et al, (1989) studied the benthic organisms of Southern Portugal. The macrobenthic epi-fauna and in-fauna were reported by Basford et al, (1990), and Snelgrove and Bhutman, (1994) gave a detailed account on the macrobenthos and their relationship with the sediment. Various methods for the collections and analysis of benthic sediment and their associated organisms was detailed by Sommerfield and Clark (1995 and 1997). Brown studied the effects of sediment pollutants on the macrobenthic community (Brown et al, 2000) and Daur et al, (2000) reported the influence of environmental factors on benthic community.

Benthic community of Indian sub-continent were studied during the period of British Raj, by Annandale, (1907), Annandale and Kemp, (1915) reported the benthic organisms of Bengal and Chilka lake. Panikkar and Aiyar, (1937) studied the fauna of Madras presidency, Samuel, (1944) reported the organisms from brackish waters of the Madras coast. Benthic fauna of the continental shelf of the east India was reported by Ganapathy and Rao, (1959), Vellar estuary ecology and the polychaete community was studied by Balasubramanyan, (1964). Benthic fauna of Indian Ocean were studied by Neyman (1969), and Parulekar, (1973, 1975, 1980 and 1986) reported the macrobenthos of the Goa estuaries. Harkantra, (1975) analysed the macrobenthos abundance and their distribution in Kali estuary, Karwar. The benthos of the Mumbai coast was studied by Parulekar et al. (1976). Ansari et al. (1977) reported the shallow water macrobenthos along the west coast of India. Harkantra and Parulekar, (1981) studied the ecology and diversity of benthic fauna in relation to the demersal fishes. Benthos of the Bay of Bengal was reported by Harkantra et al, (1982). Govindan et al, (1983) studied the benthos of the Gujarat estuaries. Fernando et al, (1984) reported the distribution of benthic organisms at Vellar estuary and Ramachandra et al, (1984) studied the sediment texture effects on Mulki estuary. Macrobenthic fauna of Siridao beach, Goa was studied by Parulekar, (1985). Annapurna and Rama Sarma, (1986) studied the diversity and community structure of benthos in the Bimili estuary, along east coast of India. Ansari et al. (1986) reported the polychaetes of the Mandovi estuary, Goa. The macrobenthos of Nethravathi Gurupur estuary were reported by Bhat and Gupta, (1986). Vellar estuary macrofauna were documented by Chandran, (1987). Ecology of nematodes of the Hoogly estuary was studied by Choudhury and Sinha, (1987). Seasonal abundance of benthic invertebrates of the Hoogly-Matlah estuary was studied by Bandyopadhyay and Datta (1988). Adiseshasai, (1989) reported the macrobenthic fauna of Visakhapatnam and Raveenthiranath Nehru, (1990) documented diversity of macrobenthos of Coleroon estuary. Sediment and bottom water salinity and its relation to benthic organisms of Konkan coast was documented by Vizakat et al. (1991). Ansari et al, (1994) reported the distribution of benthos in the soft sediments of Mormugao harbour, Goa. Anzari and Parulekar (1994) described the benthic fauna in the Mandovi-Zuari estuarine system. Soft sediment living benthos of Rajapur Bay in the Central west coast of India was documented by Harkantra and Parulekar (1994).

Studies on the macrobenthic fauna near the coastal shore off Bombay was reported by Mathew and Govindan (1995) and Ansari et al, (1996) reported the benthic fauna of EEZ of India. Krishnan and Nair (1998), conducted studies on the benthos distribution of Mangalore coast and Vashishti estuary, Maharashtra. Mohana Rao et al. (2001) assessed the macrobenthic fauna of Orissa coast. Bouillon *et al.* (2002) described the benthic invertebrates in mangrove forest located at the south east coast of India. Levin et al, (2000) and Martin *et al,* (2000) reported the benthic fauna of North West Arabian Sea and Tamaraparani river. Rao et al. (2001) documented the benthic fauna of Gopalpur Coast. The distribution of benthic foraminifera of Palk Strait was documented by Gandhi et al, (2002). Harkantra and Rodrigues, (2003) assessed the benthic macro fauna in the estuaries of Goa. Ingole, (2003) studied the benthos of the Central Indian Ocean. The distribution of benthic organisms of Gopnath, Mahuva and Veraval coasts were reported by Raghunathan *et al,* (2003) and new indicator organism of pollution and diversity indices in pollution monitoring were studied by Ajmal Khan et al, (2004). Sediment and macrobenthos distribution and its effects at Chitrapur coast was documented by Kumar et al, (2004).

In 2005, Ajmal Khan and Murugesan reported polychaete distribution of Indian estuaries, Vargis (2005) documented benthic fauna of Minicoy Island. Ingole and Koslow (2005), Pavithran and Ingole, (2005), identified the benthic fauna of Central Indian Ocean. Ganesh and Raman (2007) studied the benthic fauna of the Bay of Bengal and Jayaraj *et al.* (2007) documented the ecology and distribution of benthos on the North West Indian shelf. Joydas and Damodaran (2009) reported the in-fauna along the shelf waters of the West Coast of India. Musale and Desai (2011) reported the distribution and abundance of macrobenthos of South Indian coast. Soniya Sukumaran *et al.* (2011) assessed the benthic polychaetes at Ratnagiri, Maharashtra. Khan (2013) examined the distribution and diversity of benthic macro invertebrate fauna in Pondicherry mangroves. Ansari *et al.* (2014) investigated the effect of organic enrichment on benthic fauna. Devi *et al.* (2014) studied the water and sediment quality characteristics near the vicinity of the industrial area of Vadinar, Gulf of Kachchh, (Gujarat). Bhadja *et al.* (2014) studied the distribution pattern of invertebrate fauna at the shores the Kathiawar Peninsular coast line off the Arabian Sea. Ramasamy *et al.* (2014) reported the environmental influence on the population density of marine molluscs along the Coast of South India. Rashid and Pandit (2014) documented that macro invertebrates as indicators of pollution.

1.3 Estuarine environment

Estuaries are among the most productive natural ecosystems and perform crucial ecological functions, which include ecosystem services such as nutrient cycling, organic matter decomposition and food for resident and migratory fauna, shoreline protection, and fisheries resources. At the same time, estuaries often serve as commercial harbours (Kennish, 2002; Dolbeth et al., 2003; Paerl, 2006; Dolbeth et al., 2007). Since estuaries are the connecting point of freshwater, sea, and land, they are supplied with large amounts of nutrients and pollutants derived from agricultural, industrial and urban effluents (Lillebøn et al., 2005; Paerl, 2006; Dolbeth et al., 2007). As reported by Ramaraju et al. (1979), typically the estuary is highly stratified with respect to salinity during the monsoon season and during the post and pre-monsoon, they are partially mixed owing to a balance between river flow and the tidal influence. The estuaries in India cover about 2.14×10^6 ha, and mostly influenced by semi-diurnal tides. There are 33 estuaries flowing across east coast and 34 estuaries along the west coast of India (Khan and Murugeshan, 2004).

1.4 Port environment

Ports, which are considered as the lifeline of a country's economic development and the port areas are one among the highly altered coastal habitats due to heavy traffic owing to shipping, port related activities such as dredging, accidental spillage of cargo and oil, and also due to human activities (Darbra et al. 2005). Ports are considered as focal point of anthropogenic activity and are related to continuous discharge and release of industrial, agricultural, and municipal waste and other contaminants (McCarthy et al., 1991; Bailey et al., 2007). Along with this the increased shipping traffic is also responsible for non-indigenous species invasion through the discharge of ballast water and hull fouling (BW; Minchin and Gollasch, 2003), and to prevent fouling usage of antifouling agents to paint ship hulls leading to contamination of the environment (Cassi et al., 2008). Coastal ports, fishing harbours and waterways used for navigation are an important accessing point for economic growth (Engler et al, 1991). They are often located in the coastal environments and estuaries and are subjected to various forms of anthropogenic pressure such as untreated sewage or municipal runoff, terrestrial runoff during the monsoon, and port related activities such as dredging, oil spill, petroleum effluents, out-fall of variety of cargo handled by the port etc. (Musale et al, 2015).

Port waters are often characterized by low dissolved oxygen and presence of pollutants in the sediment and water (Danulat et al. 2002; Rivero et al. 2005; Ingole, 2009). Dredging and disposing these waste is considered as a major problem in coastal zone management (Van Dolah et al., 1984). The evaluation of the changes in the coastal ecosystems can be monitored with the help of benthic organisms, since most pollutants end up settling on the sediment layer, and the benthic community play a decisive role in the transfer of energy from primary production to higher trophic levels via detrital pool (Bryan and Langston, 1992; Ingole et al. 2006). Disposal of sewage in the marine environment is common globally, despite its destructive effects on water and sediment quality as well as bottom communities through increased organic content, nutrients and heavy metals (Kress et al. 2004). As harbour areas have empty niches, they are prone to marine bio-invasion especially due to discharge of ship's ballast water (Rilov and Crooks, 2009; Mandal and Harkantra, 2013), which is of global concern due to its adverse effect on the ecosystem (Anil et al. 2002). Thus the studies relevant port environment with respect to biodiversity of macrobenthos and their ecology will provide information on both pelagic and benthic ecosystem of the dynamics environment. Studying spatio-temporal variation in the diversity and community structure of macrobenthic fauna and understanding the interactions between physio-chemical and biological activities in the sediment and water column is of prime importance for ecosystem functioning. Taking into consideration the above, this study was carried out under following objectives.

Objectives

1. Spatial and temporal variation in the diversity of macrobenthic organisms in the selected ports and estuaries of India.

2. Influence of changing environment and anthropogenic stressors on the diversity of the macrobenthic population.

3. Biochemical and chemical composition of selected macrobenthic organisms.

4. Laboratory experiment to understand the ecology and biology of selected macrobenthic organisms on changing environment on their life cycle.

Chapter 2.

Materials and methods

2.1 Study area

2.1A Cochin port

Cochin port is located in the state of Kerala at the northern part of the Cochin backwaters and is one of the two permanent openings, the other one being at Azhikode, that flush the river water into the Arabian Sea. Sampling was carried out in and around Cochin port (9° 34′48″ N, 76° 08′ 24″E) (Fig. 2.1.1).

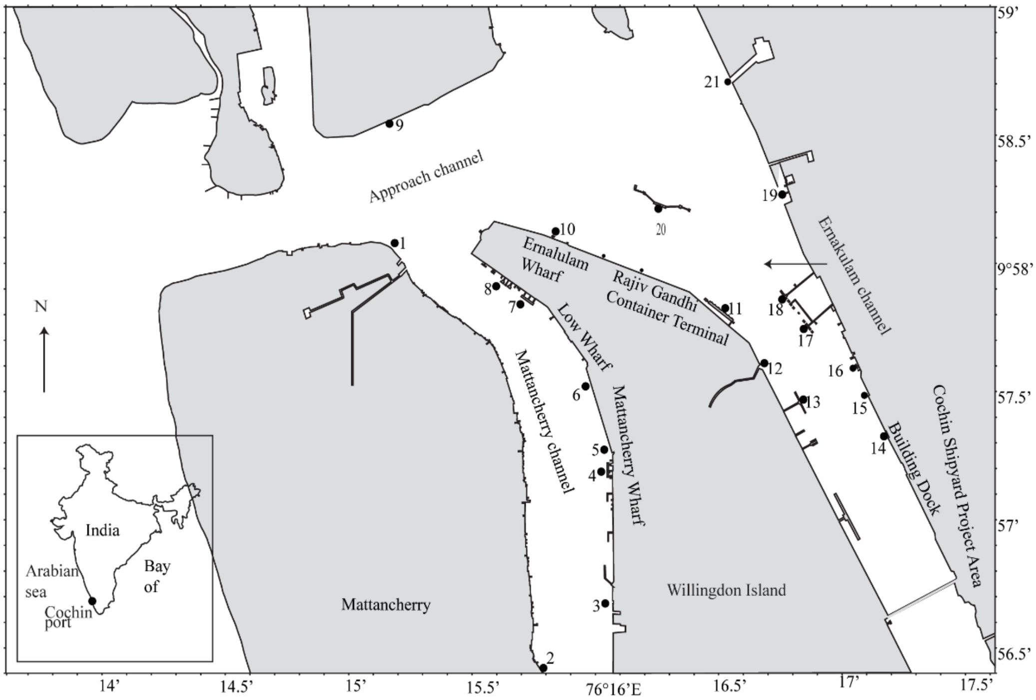


Figure 2.1.1. Sampling stations located in the Cochin port, west coast of India. (1) Custom buoy, (2) Fishery harbor, (3) Dry dock, (4) South coal berth, (5) Quay-1, (6) Quay-2, (7) North coal berth, (8) Boat train pier, (9) Container terminal, (10) DC jetty, (11) Quay-10, (12) Ro-Ro jetty, (13) Naval jetty, (14) Cochin shipyard, (15) Bunker oil jetty, (16) Integrated fisheries project jetty, (17) South tanker berth, (18) north tanker berth, (19) Ernakulam ferry jetty, (20) Cochin oil terminal, (21) Ernakulam creek mouth.

The port is at the entrance of the Cochin backwaters, which is a shallow brackish water system within a tropical estuary (Qasim and Reddy, 1967). It is a complex microtidal estuary receiving 2×10^{10} m^3 $year^{-1}$ of freshwater through six rivers (Srinivas et al., 2003). The annual rainfall of the region is around 320 cm, of which more than 60% is accounted for during the southwest monsoon (June–September). During pre-monsoon (February–May), increased tidal activity considerably modifies the flushing characteristics of the estuary (Balachandar et al., 2016). The estuarine mouth connected to the sea is a ~450 m wide channel through which the water is flushed out during the ebb tide, and the seawater enters the port during the flood tide. The depth of the estuary varies considerably and the major portion of the estuary has a depth range of 2–7 m. A total of 21 sampling stations (will be abbreviated as 'S' followed by station number) (see Fig. 1) were selected along the two channels (Mattancherry channel and Ernakulam channel) in the Cochin port area for the collection of samples: S01 — Custom bay, S02 — Fishery harbour, S03 — Dry dock, S04 — South coal berth, S05 — Quay 1, S06 — Quay 2, S07 — North coal berth, S08 — Boat train pier, S09 — Container terminal, S10 — DC jetty, S11 — Quay-10, S12 — Ro-Ro jetty, S13 — Naval jetty, S14 — Cochin shipyard, S15 — Bunker oil jetty, S16 — Integrated fisheries project jetty, S17 — South tanker berth, S18 — North tanker berth, S19 — Ernakulam ferry jetty, S20 — Cochin oil terminal, and S21 — Ernakulam creek mouth. The tides at the port stations were mixed semidiurnal with a range of about 1 m (Qasim and Gopinathan, 1969). Cochin port has three dredged channels where the stations are located, one being the approach channel and other two are inner channels (Fig. 2.1.1).

Table 2.1.1: - Details of sampling stations and their positions at Cochin port.

Stn.No.	Stn. Name	Latitude (N)	Longitude (E)
1	Custom buoy	9.968	76.253
2	Fishery harbour	9.94	76.263
3	Dry dock	9.945	76.267
4	South coal berth	9.953	76.267
5	Quay-1	9.954	76.267
6	Quay-2	9.958	76.265
7	North coal berth	9.964	76.261
8	Boat train pier	9.965	76.26
9	Container terminal	9.975	76.252
10	DC jetty	9.969	76.264
11	Quay-10	9.964	76.275
12	Ro-Ro jetty	9.96	76.278
13	Naval jetty	9.957	76.281
14	Cochin shipyard	9.955	76.286
15	Bunker oil jetty	9.958	76.285
16	Integrated fisheries project jetty	9.96	76.284

17	South tanker berth	9.962	76.28
18	North tanker berth	9.964	76.279
19	Ernakulam Ferry jetty	9.971	76.279
20	Cochin oil terminal	9.97	76.27
21	Ernakulam creek mouth	9.978	76.275

The approach channel is around 10 km in length and ~450 m wide and five sampling stations are located in this channel (S1, S9–10, and S19–21). The other two inner channels sampled were the Ernakulam Channel (eight stations: S11–S18) which is ~5 km long and 250–500 m wide and the Mattancherry Channel (seven stations: S2–S8), which is about 3 km long with a width ranging about 170–250 m. The Ernakulam channel and the Mattancherry channel are located on the either side of the Willingdon Island (Menon et al., 2000). Water depth at the port stations varied between 8–10 m. Sampling was carried out during October 2011 (Post Monsoon I — POM I), May 2012 (Pre-monsoon – PreM), August 2012 (Monsoon - MON) and November 2012 (Post Monsoon II — POM II) representing different seasons.

2.1B Haldia Port

Haldia port is a major riverine port located (22° 1″ 13′ N; 88° 4″ 20′ E) approximately 50 kms. southwest of Kolkata near the mouth of the Hooghly river, one of the distributaries of the Ganges. Haldia is a major trade port for Kolkata with modern and composite cargo handling facilities (Fig. 2.1.2). The Haldia port is an indispensable part of Kolkata Port Trust (KoPT), since it handles a major share of Kolkata port activities. The dock complex has the cargo handling capacity of 46.70 million tonnes, which includes bulk cargo, crude/POL traffic and container cargo and consists of 17 berths for handling the cargo. Out of 17 berths, three are located on the Hooghly river and the rest are in an enclosed dock. Even though this port is considered as major port, Haldia dock was not able to attract large volumes of cargo due to the vessel movement. The movement of cargo is carried out twice a day during high tides, and this leads to the movement of only smaller vessels for operation. At the same time, vessel movement in and out of the Dock takes place only during the high tide window which is also twice in a day.

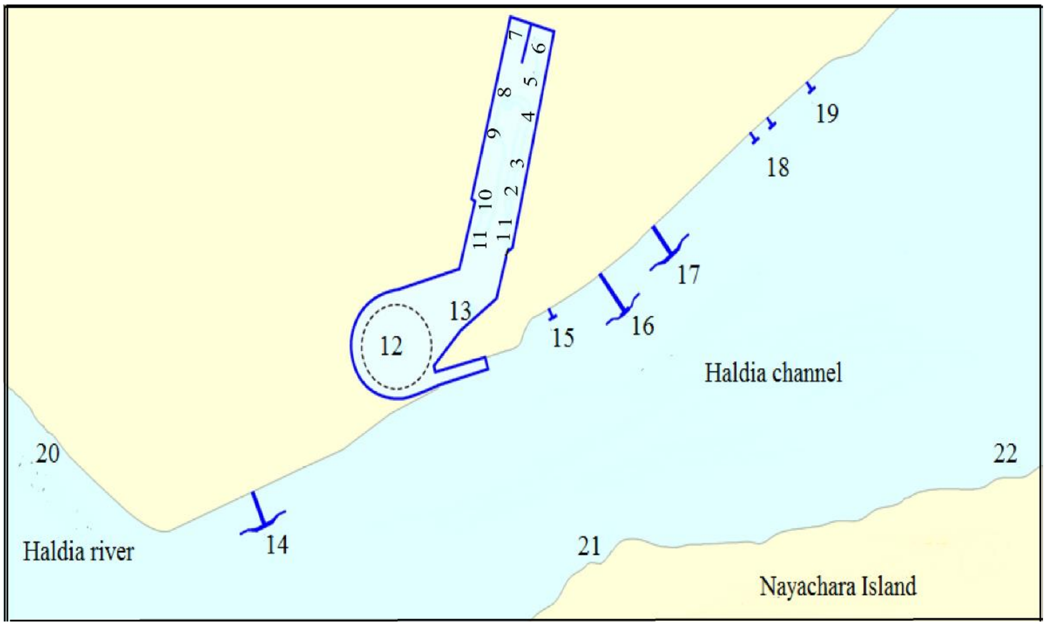


Figure 2.1.2: Sampling stations located in the Haldia port, east coast of India. (1) HDC berth 3, (2) HDC berth 4, (3) HDC berth 4A, (4) HDC berth 4B, (5) HDC berth 5, (6) HDC berth 6, (7) HDC berth 7, (8) HDC berth 9, (9) HDC berth 10, (10) HDC berth 12, (11) HDC berth 13, (12Turning basin, (13) Inner tug jetty, (14) HDC oil jetty, (15) River tug jetty, (16) HDC.Oil jetty-2, (17) HDC.Oil jetty-1, (18) HDC.Barge Jetty-1, (19) HDC.Barge Jetty-2, (20) Haldia river mouth, (21) Nayachar island 1 and (22) Nayachar island-2.

This has resulted in only smaller vessel/ vessel with smaller parcel size calling at Haldia Port. Haldia has a typical moderate climate with winter temperatures ranging from 14.7 °C to 30 °C and summer season with a highest temperature of around 33.7 °C. Sampling in Haldia port was carried out during September 2013 (Monsoon I–MON I), February 2014 (Post-monsoon – POM), September 2014 (Monsoon II – MON II) and August 2015 (Pre-monsoon - PreM) representing different seasons. This is a major port along the east coast of India (20°15′N, 86°40′E; Figure 2.1.2). The stations were S01 - HDC. Berth-3, S02 - HDC. Berth-4, S03 - HDC. Berth-4A, S04 - HDC. Berth-4B, S05 - HDC. Berth-5, S06 - HDC. Berth-6, S07 - 7, S08 - 9, (S09). HDC. Berth-10, S10 - HDC. Berth-12, S11 - HDC. Berth-13, S12 - Turning Basin, S13 - Inner Tug Jetty, S014 - HDC.Oil jetty-3, S15 - River Tug Jetty, S16 - HDC.Oil jetty-2, S17 - HDC.Oil jetty-1, S18 - HDC. Barge Jetty-1, S19 - HDC. Barge Jetty-2, S20 - Haldia River Mouth, S21 - Nayachar Island-1, S22 - Nayachar Island-2.

Table 2.1.2: - Details of sampling stations and their positions at Haldia port.

	Station	Latitude	Longitude
1	HDC. Berth-3	22°01'46.5"N	88˚ 05'13.2"E
2	HDC. Berth-4	22˚01'56.5"N	88˚ 05'17.8"E
3	HDC. Berth-4A	22˚02'08.4"N	88˚ 05'19.1"E
4	HDC. Berth-4B	22˚02'17.1"N	88˚ 05'22.6"E
5	HDC. Berth-5	22˚02'26.1"N	88˚ 05'25.9"E
6	HDC. Berth-6	22˚02'30.5"N	88˚ 05'25.8"E
7	HDC. Berth-7	22˚02'33.0"N	88˚ 05'22.1"E
8	HDC. Berth-9	22˚02'22.4"N	88˚ 05'14.3"E
9	HDC. Berth-10	22˚02'12.2"N	88˚ 05'12.5"E
10	HDC. Berth-12	22˚02'04.3"N	88˚ 05'10.0"E
11	HDC. Berth-13	22˚01'53.9"N	88˚ 05'08.5"E
12	Turning Basin	22˚01'29.5"N	88˚ 04'45.0"E
13	Inner Tug Jetty	22˚01'34.5"N	88˚ 05'00.7"E
14	HDC. Oil jetty-3	22˚00'58.5"N	88˚ 04'13.4"E
15	River Tug Jetty	22˚01'38.0"N	88˚ 05'31.3"E
16	HDC. Oil jetty-2	22˚01'40.2"N	88˚ 05'48.8"E
17	HDC. Oil jetty-1	22˚01'53.2"N	88˚ 06'00.8"E
18	HDC. Barge Jetty-1	22˚02'12.3"N	88˚ 06'22.3"E
19	HDC. Barge Jetty-2	22˚02'18.0"N	88˚ 06'33.0"E
20	Haldia River Mouth	22°00'46.0"N	88°03'36.6"E
21	Nayachar Island-1	22˚01'06.3"N	88˚ 05'46.3"E
22	Nayachar Island-2	22˚01'26.1"N	88˚ 06'57.1"E

2.1C Kolkata port

Kolkata Port is one of the oldest Port in India and is a major port located on the banks of Hooghly in the state of West Bengal. This riverine port became operational in 1870 and became a major Port after promulgation of Major Port Trust Act by the Parliament in the year 1963. The coordinates to the port are 22°32′53″N; 88°18′05″E and it is about 203 kms (126 miles) upstream from the Bay of Bengal. The pilot station is at Gasper/ Saugor roads, 145 Kilometreskms to the south of the Kidderpore docks (around 58 kms from the sea). This port consists of Kidderpore Docks (K.P. Docks): 18 Berths, 6 Buoys / Moorings and 3 Dry Docks, Netaji Subhas Docks (N.S. Docks): 10 Berths, 2 Buoys / Moorings and 2 Dry Docks, Budge Budge River Moorings : 6 Petroleum Wharves, and Anchorages: Diamond Harbour. Kolkata port is the only major riverine port in India with the longest navigational channel amongst the major ports of India and its navigational channel is one of the longest in the world. Hooghly river is a part of the Ganges riverine system and it flows through a heavily industrialised locations and also considered as most polluted river.

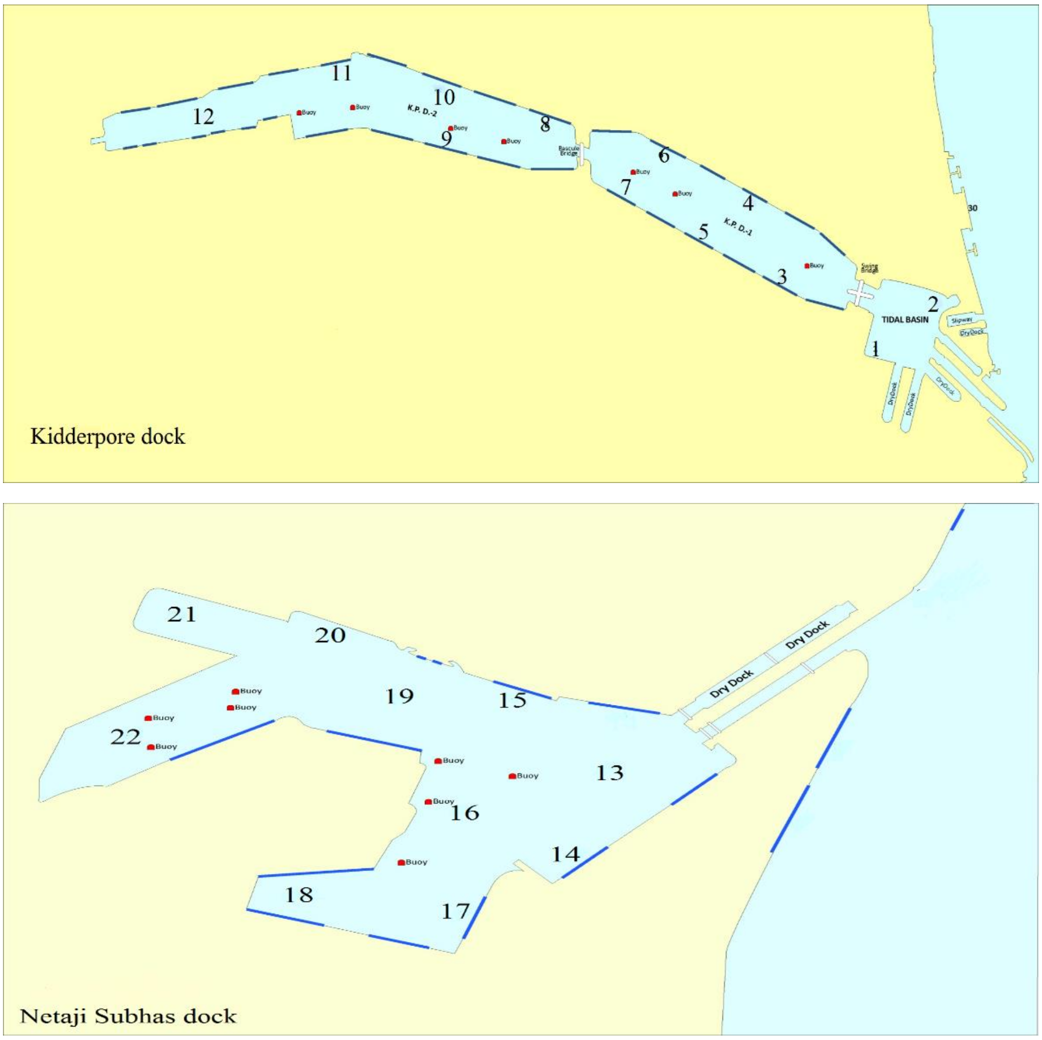


Figure 2.1.3: Sampling stations located in the Kolkata port, east coast of India. (1) K.P.D. Tidal basin-1, (2) K.P.D. Tidal basin-2, (3) K.P.D. Berth-3, (4) K.P.D. Berth-6, (5) K.P.D. Berth-7, (6) K.P.D. Berth-10, (7), K.P.D. Berth-11 (8) K.P.D. Berth-15, (9) K.P.D. Berth-24, (10) K.P.D. Berth-17, (11) K.P.D. Berth-19, (12). K.P.D. Berth-28, (13) N.S.D. Berth-1-14, (14), N.S.D. Berth-2 (15) N.S.D. Berth-3 (16), N.S.D. Dolphin mooring-1 (17). N.S.D. Berth-3, (18) N.S.D. Berth-5-16, (19) N.S.D. Berth-7-12, (20) N.S.D. Ship breaking-1, (21) N.S.D. Ship breaking-2 and (22) N.S.D. Dolphin mooring-2.

Tidal variation is important for the operations in Kolkata port as the port activities are dependent on the tides, and tidal amplitude which is 6.5 m during spring and during neap 4.2 m (IMD). Sea water intrusion is restricted to 70 kms from the mouth (Sadhuram et al., 2005) in the Hoogly river. Sampling at Kolkata port was carried out during September 2013 (Monsoon-MON), February 2014 (Pre-monsoon I – PreM I), January 2015 (Pre-monsoon – PreM II) and December 2015 (Post monsoon - POM) representing different seasons. The stations were S01 - K.P.D. Tidal basin-1, S02 - K.P.D. Tidal basin-

2, S03 - K.P.D. Berth-3, S04 - K.P.D. Berth-6, S05 - K.P.D. Berth-7, S06 -K.P.D.Berth-10, S07 - K.P.D.Berth-11, S08 - K.P.D.Berth-15, S09 - K.P.D.Berth-24, S10 - K.P.D.Berth-17, S11 - K.P.D.Berth-19, S12 - K.P.D.Berth-28, S13 - N.S.D.Berth-1-14, S014 - N.S.D.Berth-2, S15 - N.S.D.Berth-13, S16 - N.S.D. Dolphin mooring-1, S17 - N.S.D. Berth-3, S18 - N.S.D. Berth-5-6, S19 - N.S.D.Berth-7-12, S20 - N.S.D. Ship breaking-1, S21 - N.S.D. Ship breaking-2, S22 - N.S.D. Dolphin mooring-2 respectively.

Table 2.1.3: - Details of sampling stations and their positions at Kolkata port**.**

No.	Station	Latitude	Longitude
1	K.P.D. Tidal basin-1	22°32'43"N	88˚ 19'07"E
2	K.P.D. Tidal basin-2	22°32'48"N	88˚ 19'03"E
3	K.P.D. Berth-3	22°32'33"N	88˚ 18'54"E
4	K.P.D. Berth-6	22°32'25"N	88˚ 18'50"E
5	K.P.D. Berth-7	22°32'35"N	88˚ 19'01"E
6	K.P.D.Berth-10	22°32'27"N	88˚ 18'57"E
7	K.P.D.Berth-11	22°32'21"N	88˚ 18'53"E
8	K.P.D.Berth-15	22°32'14"N	88˚ 18'46"E
9	K.P.D.Berth-24	22°32'06"N	88˚ 18'48"E
10	K.P.D.Berth-17	22°32'05"N	88˚ 18'44"E
11	K.P.D.Berth-19	22°32'55"N	88˚ 18'42"E
12	K.P.D.Berth-28	22°32'46"N	88˚ 18'46"E
13	N.S.D.Berth-1-14	22°32'40"N	88˚ 18'01"E
14	N.S.D..Berth-2	22°32'41"N	88˚ 17'54"E
15	N.S.D.Berth-13	22°32'36"N	88˚ 17'05"E
16	N.S.D.Dolphin mooring-1	22°32'30"N	88˚ 18'12"E
17	N.S.D..Berth-3	22°32'33"N	88˚ 18'10"E
18	N.S.D..Berth-5-6	22°32'23"N	88˚ 18'54"E
19	N.S.D.Berth-7-12	22°32'28"N	88˚ 17'50"E
20	N.S.D.Ship breaking-1	22°32'25"N	88˚ 17'50"E
21	N.S.D.Ship breaking-2	22°32'14"N	88˚ 17'49"E
22	N.S.D.Dolphin mooring-2	22°32'17"N	88˚ 17'57"E

2.1D Paradip port

Paradip port is an artificial deep-water port on the East coast of India in Jagatsinghpur district of Odisha. It is one of the twelve major ports of India and the only major Port in the State of Odisha situated 210 nautical miles south of Kolkata and 260 nautical miles north of Visakhapatnam on the east coast on the shore of Bay of Bengal. Paradip port acts as the main gateway for the sea-borne trade on the eastern part of the country covering states such as Odisha, Madhya Pradesh, Chhattisgarh, Jharkhand and Bihar. It is also the nearest deep water port for the entire east and north-east part of the country. With dredged depth of about 15 m, the port is located inside a lagoon which offers all weather berthing facility throughout the year. The present estate of Paradip Port stretches over an area of Atharabanki creek 2545 Ha. This comprises of (a) Harbour Area-1000 Ha, (b) Township-758 Ha, (c) Industrial Area-688 Ha, and (d) Others-99 Ha. The harbour area of 1000 Ha is surrounded by a boundary wall. The port has a turning circle with a diameter of 520 m. The total number of berths presently is 15. On the northern side, 14 berths are located in two docks namely Eastern and Central dock.0

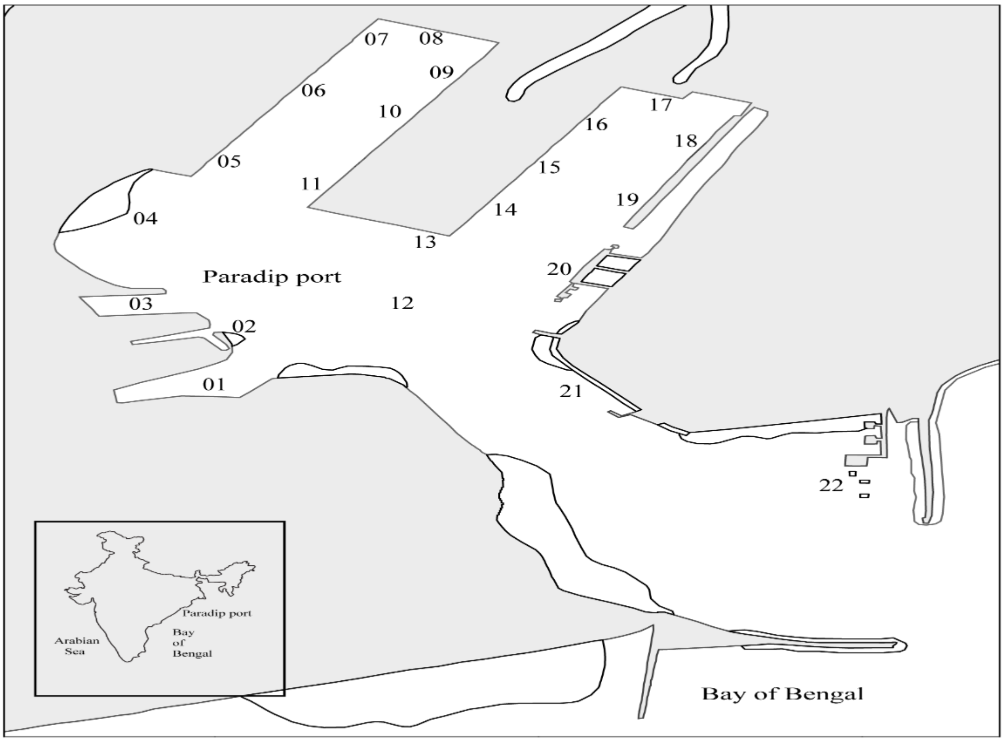


Figure 2.1.4: Map showing the sampling stations of various berths in Paradip port. S01-Boat Basin, S02 - Slip Way, S03 - Deep Sea Trawler Berth, S04 - Area Adjacent to Fertilizer Berths, S05 - Fertilizer Berth-I, S06 - Fertilizer Berth-II, S07 - Multipurpose Berth, S08 - North Quay-II, S09 - Central Quay-III, S10 - Central Quay-II, S11 - Central Quay-I, S12 - Turning Circle, S13 - South Quay, S14 - East Quay-I, S15 - East Quay-II, S16 - East Quay-III, S17 - North Quay-I, S18 - Coal Berth-I, S19 - Coal Berth-II, S20 - Iron Ore Berth, S21 - Stone Pitching Side and S22 - Oil Berth.

The Central Dock with South Quay has five general cargo berths and 2 fertiliser berths, while the Eastern dock has 3 general cargo berths, 2 coal berths, an iron ore berth and an oil jetty on the lee of north breakwater. On the southern side, 1 berth is located viz. the south oil jetty. Besides, there are three offshore Single Point Mooring (SPM) Buoys of 37 MTPA for IOCL to handle Very Large Crude Carrier (VLCC) up to 3,50,000 DWT size.

Sampling in Paradip port was carried out during August 2014 (Monsoon I -MON I), December 2014 (Post-monsoon - POM), May 2015 (Pre-monsoon - PreM) and August 2015 (Monsoon II - MON II) representing different seasons. This is a major port along the northeast coast of India in Odisha (20°15′N, 86°40′E; Figure 2.1.4). The port is influenced by the south–west monsoon (June–September) and receives 75–80% of rainfall during these months, and remaining during the northeast monsoon (October–December). Even though this is a natural deep water port, artificial bunds (breakwaters) were built to reduce the severe wave intensity in the port; thus it resembles an artificial lagoon. The breakwaters are: (1) south breakwater with a length of 1217 m and (2) north breakwater with a length of 538 m. Paradip port handles various cargo such as crude oil, petroleum, oil and lubricants (POL), iron ore, thermal coal, chrome ore, coking coal, manganese and other ores, fertilizer raw materials and containers, etc. The samples were collected from 22 stations in accordance to berths, and Table 2.1.4 provides their details.

Table 2.1.4: - Details of sampling stations and their positions at Paradip port**.**

Stn. No.	**Stn. Name**	**Latitude**	**Longitute**
1	Boat Basin	N 20°16'07.6"	E 86°40'03.1"
2	Slip Way	N 20°16'12.1"	E 86°40'07.4"
3	Deep Sea Trawler Berth	N 20°16'18.3"	E 86°40'02.4"
4	Area Adjacent to Fertilizer Berths	N 20°16'27.8"	E 86°40'02.9"
5	Fertilizer Berth-I	N 20°16'38.1"	E 86°40'06.2"
6	Fertilizer Berth-II	N 20°16'45.3"	E 86°40'11.2"
7	Multipurpose Berth	N 20°16'52.7"	E 86°40'14.8"
8	North Quay-II	N 20°16'54.0"	E 86°40'19.4"
9	Central Quay-III	N 20°16'50.2"	E 86°40'19.1"
10	Central Quay-II	N 20°16'43.2"	E 86°40'15.5"
11	Central Quay-I	N 20°16'35.3"	E 86"40'11.6"
12	Turning Circle	N 20°16'15.2"	E 86°40'15.5"
13	South Quay	N 20°16'27.3"	E 86°40'14.2"
14	East Quay-I	N 20°16'30.5"	E 86°40'22.5"
15	East Quay-II	N 20°16'37.9"	E 86°40'26.3"
16	East Quay-III	N 20°16'46.7"	E 86°40'29.7"

17	North Quay-I	N 20°16'46.1"	E 86°40'35.6"
18	Coal Berth-I	N 20°16'38.7"	E 86°40'34.9"
19	Coal Berth-II	N 20"16'30.3"	E 86°40'29.0"
20	Iron Ore Berth	N 20°16'23.4"	E 86°40'25.5"
21	Stone Pitching Side	N 20°16'08.8"	E 86°40'30.0"
22	Oil Berth	N 20°15'52.6"	E 86°40'43.1"

2.1E Zuari estuary

Zuari estuary is part of the Mandovi–Zuari estuarine system and is a west ward flowing estuary that flows 70 kms from the Western Ghats and drains in the Arabian Sea (Qasim and Sen Gupta, 1981) (Fig. 2.1.5). The Zuari estuary transports large amount of fresh water during monsoon seasons (South west monsoon) but during the non-monsoon seasons it acts as a sea water inlet (Qasim and Sen Gupta, 1981; Vijith et al., 2009). This is a tropical monsoon influenced river. The monsoonal rainfall in Goa ends up as surface runoff (52%) and only a small amount (16%) charges the ground water (Ghosh, 1985). The terrain of Goa is made of laterite rock structures which are known to contain water reservoirs which helps to store water during non-monsoon seasons (Chachadi, 2009). Leakages in the laterite rocks leads to high water discharges in these rivers and tributaries of Goa all along their course during post-monsoon seasons (Subramaniam, 1981). The estuary harbours one of the finest deep water ports in the Indian subcontinent, the Mormugao port located on the banks of the Zuari estuary and handles ~40% of the country's iron ore exports and ranks within the ten leading iron ore exporting ports of the world. This estuary is also a lifeline of the local population since there are small fishing jetties, wharfs and small workshops providing water related mode of living. Zuari estuary is surrounded by mangroves which makes the region biologically productive and also helps in sustaining a rich fishery resources such as prawns, fishes and clams which are commercially exploited from the region. Mormugao port along with various small scale ship building industries located along the Zuari estuary have important socio-economic role in the society but this results in potential environmental impacts, so studies were carried out on the physico-chemical properties (Shetye et al., 2007; Bhosle et al., 2004), and phytoplankton variability (Patil and Anil, 2008). Studies were also carried out on the macrobenthic organisms in this estuary (Parulekar et al., 1980, Ansari et al., 1986, 1995, 2007; Harkantra and Rodrigues 2003), however, they lack the minute changes of monthly variations in the diversity of macrobenthos, and there is a lack of knowledge regarding the temporal variability and makes it difficult to distinguish between natural and anthropogenic disturbance (Hewitt and Thrush 2007; Clarke and Warwick 1994).

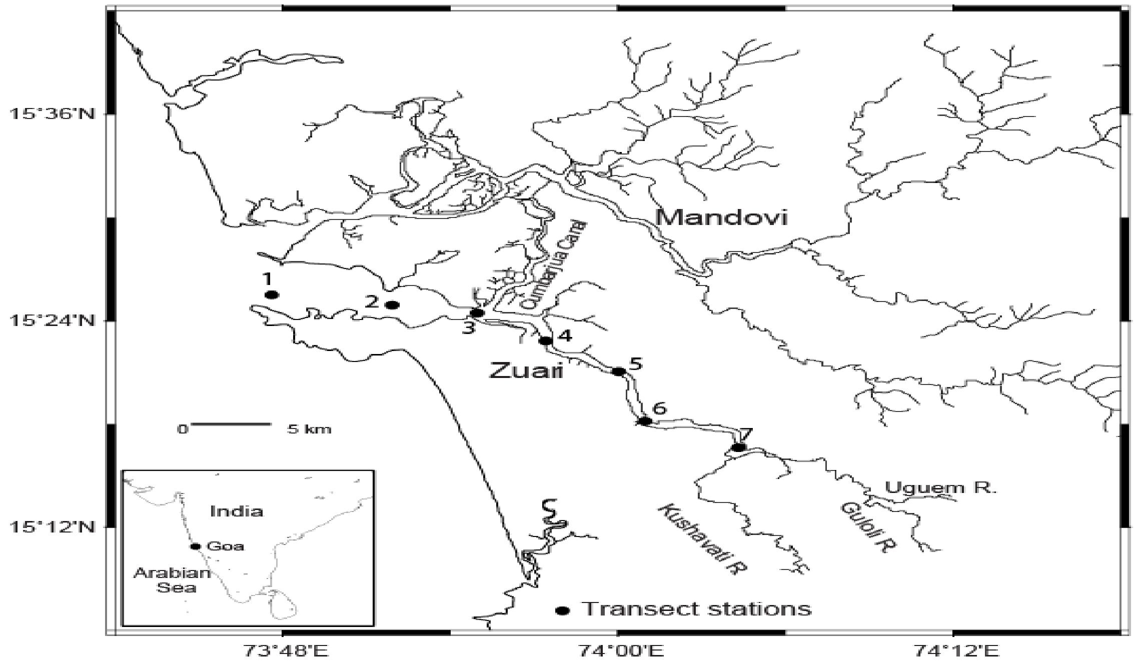


Figure 2.1.5: Map of sampling locations along the Zuari estuary. The seven stations are Dona Paula (1), Chicalim (2), Cortalim (3), Loutolim (4), Borim (5), Shiroda (6) and Kushavati (7).

In this study the spatio-temporal variation in the macrobenthos was carried out at regular monthly intervals from November 2013 to September 2015 during the period of spring or neap tide. Along with the macrobenthos community structure the role of sediment characteristics and water column parameters in structuring the benthic community was carried out. In order to understand the biology of macrobenthic organism, laboratory experiments were carried out by choosing two dominant polychaetes reported from this estuary.

2.2 Methodology

2.2A Methods for analysis of environmental parameters

The surface and near-bottom water samples were collected in triplicate using a Niskin water sampler for the analysis of Chlorophyll *a*, salinity, dissolved oxygen (DO), temperature, and suspended particulate matter. The analysis of these parameters was carried following the methods described by Parsons et al. (1984). Temperature was measured using standard calibrated thermometer. Nutrients such as nitrate (NO_3), phosphate (PO_4), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_4) were analysed by SKALAR SAN plus analyser. Sediment samples were collected from an average depth of 8–10 m using a Van Veen grab (0.04 m^2). At each station, sediment samples were collected in triplicate and washed separately through a 500 µm nylon mesh at sea and then transferred to polythene bags and preserved in 10% formaldehyde in seawater containing Rose Bengal stain. In the laboratory, the sediment samples were sieved through a 500 µm metal sieve, and all macrobenthic fauna were sorted and preserved in plastic vials containing 10% formaldehyde solution for further microscopic analysis. Polychaetes were identified to the highest taxonomic level (genus or species) possible with the help of available identification keys (Fauvel, 1953; Day, 1967; Fauchald and Jumars, 1979; Theodore and William, 1979). The macrobenthos other than polychaetes were identified to family or genus level. The numerical abundance of each species was recorded and expressed as the number of individuals per square metre (no. m^{-2}). Biomass was determined by wet weight method and expressed as milligram per metre square (mg. m^{-2}) (Mason et al., 1985). Organic carbon (OC) and percentage composition of sediment (sand, silt and clay) were determined by standard titration method and pipette analysis, respectively (Wakeel and Riley, 1957; Buchanan, 1984). Total carbon (TC) and inorganic carbon (IC), and percentage composition of sediments (sand, silt and clay) that are expressed as the percentage of sediment dry weight were determined using CHNS Analyser (Vario MICRO Select, Germany) and pipette analysis respectively (Masan et al., 1985; Kristenson and Abdersen, 1987). The total organic carbon (TOC) content was obtained by the difference between TC and IC (TOC = TC–IC). Organic carbon was expressed as the percentage of sediment dry weight. Macrobenthic fauna, especially polychaetes, reflect the ecological and environmental status of the seabed and this was assessed in terms of the number of individuals or specimens (N), number of taxa (S), total abundance (A), Margalef species richness (d), Pielou's evenness (J′) and Shannon index (H′) using log2 scale at each station (Clarke and Gorley, 2006). Bray–Curtis similarity for species diversity of macrobenthic polychaetes was determined using PRIMER-v5 (Clarke and Gorley, 2006). Seasonal variation in the total macrobenthic community, polychaetes and other invertebrate taxa were performed using SURFER-6 (developed by Golden Software Inc., USA). Canonical correspondence analysis (CCA) was performed to evaluate the relationship between environmental variables and macrobenthic polychaetes as well as other taxonomic groups. The multivariate index of trophic state (TRIX) method was used to evaluate the trophic status (Vollenweider et al., 1998; Malhadas et al., 2014), which was later used to assess the relationship between sediment and trophic status of water. TRIX was calculated where chlorophyll *a* is in mg m^{-3}, a%O2 is the absolute value of the percentage using the equation TRIX = (log10 (Chl *a* × a%O2× DIN× DIP) + k)/m, of DO saturation (abs |100 − %O2| = %O2) [DIN = dissolved inorganic nitrogen including NO_3, NO_2, NH_4 in mg. m^{-3}, DIP = dissolved inorganic PO_4 in mg. m^{-3}]. The constants, k - 3.5 and m - 0.8 are scale values obtained from (Vollenweider et al., 1998) to adjust TRIX scale values (reads from 0 to 10) with a level of eutrophication. According to this method, TRIX scores less than 4 indicate high state of water quality with low eutrophication; scores between 4 and 5 indicate good state of water quality with medium eutrophication; scores between 5 and 6 indicate bad state of water quality with high eutrophication and scores greater than 6 indicate poor state of water quality with elevated levels of eutrophication.

Chapter 3.

Spatio-temporal variation in the macrobenthic community structure and the influence of environmental parameters on macrobenthic organisms in ports and the estuary.

3.1 Spatio-temporal variation in the macrobenthic community structure and the factors influencing the macrobenthic diversity at Cochin port

3.1.1 Introduction

Cochin port is located in the northern part of the Cochin backwaters and is one of the two permanent openings, the other one being at Azhikode, that flush the river water into the Arabian Sea. The backwaters mouth connected to the sea is a ∼450 m wide channel through which the water is flushed out during the ebb tide, and the seawater enters the port during the flood tide. The depth of the estuary varies considerably and the major portion of the estuary has a depth range of 2–7 m. A total of 21 sampling (port) stations were located along the two channels (Mattancherry channel and Ernakulam channel) in the port area. Cochin port has three dredged channels where the stations are located with one being the Approach Channel and two inner channels. The Approach Channel is around 10 km in length and ∼450 m wide where five stations were located (S1, S9–10, and S19–21). The other two inner channels sampled were the Ernakulam Channel which is ∼5 km long and 250–500 m wide and the Mattancherry Channel, which is about 3 km long with a width of around 170–250 m. The Ernakulam channel and the Mattancherry channel are located on the either side of the Willingdon Island. Water depth at the port stations varied between 8–10 m.

3.1.2 Results

3.1.2a Variations in environmental parameters

Seasonal variation in temperature, salinity and dissolved oxygen across all 21 stations in Cochin port are shown in Figure 3.1.1. The average value of these parameters were given along with the standard deviation of the stations collected. The average seawater temperature during monsoon season was 25.3±0.4 °C and it ranged from 29.0±0.7 °C to 31. ±0.2 °C during PreM and POM respectively. The near bottom water temperature in general was 1±0.8°C lower than the surface water temperature. During POM I and POM II, the difference in the tidal amplitude was 0.50 – 0.91(±0.10) m.

The tidal amplitude during PreM and MON season was 0.4 - 0.6 (±0.1) m and 0.6 - 0.7 (±0.5) m respectively. The salinity of near bottom water during post monsoon I was 31.2±5.5, during pre-monsoon (24.3±5.5), during monsoon (5.3±1.3) and in post monsoon II it was 20.5±10.8 respectively indicating a wide seasonal variation in the salinity and depth stratification (Figure 3.1.1; Table 3.1.1). The tidal amplitude during PreM and MON season was 0.4 - 0.6 (±0.1) m and 0.6 - 0.7 (±0.5) m respectively. The salinity of near bottom water during post monsoon I was 31.2±5.5, during pre-monsoon (24.3±5.5), during monsoon (5.3±1.3) and in post monsoon II it was 20.5±10.8 respectively indicating a wide seasonal variation in the salinity and depth stratification (Figure 3.1.1; Table 3.1.1).

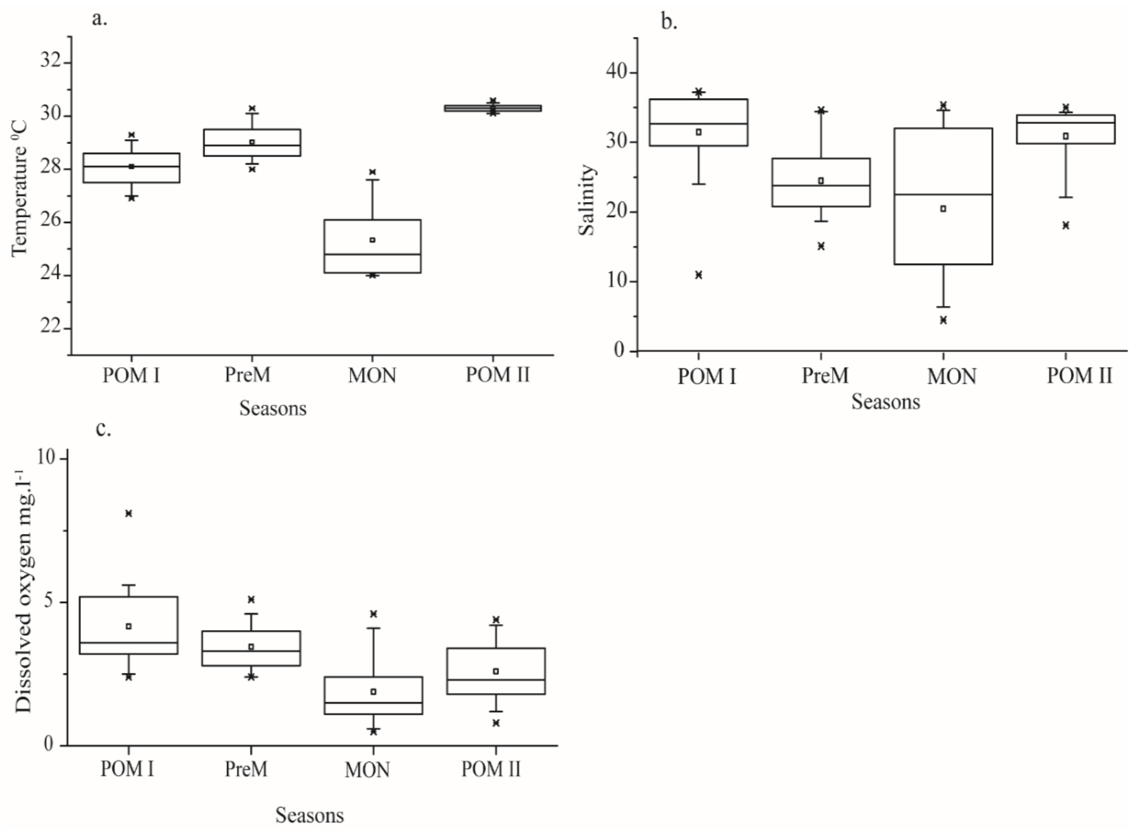


Figure 3.1.1: - Box-plot to illustrate the seasonal changes in the a). Temperature, b). Salinity and c). Dissolved oxygen during the different seasons at Cochin port.

The mean dissolved oxygen of near bottom water during POMI and POMII was 4.2±1.4 mg. l^{-1} and 2.6±1.1 mg. l^{-1} respectively, while during PreM season the mean DO was 3.5±0.8 mg. l^{-1}.

Table 3.1.1: - Salinity, Temperature and Dissolved oxygen of bottom water of Cochin port during different seasons (POM I - post monsoon I, PreM – pre-monsoon, MON – monsoon, POM II – post monsoon II).

Stations	Salinity				Temperature (0 °C)				Dissolved oxygen mg.L^{-1}			
	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II
1	36	21.6	22.5	31	28.1	29.5	25.5	30.3	8.1	3.5	1	3.2
2	31	25.4	8.9	28.8	28.5	29.3	27.5	30.6	3.1	4	4.1	3
3	24	29.1	4.5	29.1	28.6	28.9	27.9	30.5	3.2	2.8	4.6	3.4
4	35		14.6	32.4	28	28.4	24.8	30.3	5.3	3.3	1.1	2.2
5	29	27	13.2	32.5	28.4	28.9	24.7	30.2	2.4	4.4	0.6	0.8
6	37	30.5	12.5	34	28.6	28.5	24.8	30.2	5	2.5	2.4	4.4
7	25		10.7	33.1	28.5	28.2	24.8	30.5	5.6	2.8	0.5	1.6
8	31	23.8	22.8	22.1	29.1	28.5	25.6	30.2	3.8	2.5	1	2.4
9	37	34.6	23.6	35	28.1	28.8	24.1	30.1	5.3	3.3	1.1	3.3
10	30	25.5	9.6	30.1	29.1	28.8	24.9	30.4	4.6	3.3	1.7	4.2
11	36	20.8	34.6	33.6	27.5	29.4	24	30.2	3.6	4.2	1.6	4
12	30	21.4	32	34.3	27	29.5	24.1	30.2	3.2	3.7	1.7	3.6
13	33	18.7	34.2	29.8	28	30	27.6	30.5	4.9	3.9	4	1.3
14	32	27.7	33.3	34.2	27.8	28.6	24.5	30.4	3.2	3	1.5	1.6
15	33		33.6	33.5	27.9	28.4	24.1	30.3	3.1	2.7	1.4	1.8
16	36	19.4		32.8	27.1	29.3	26.1	30.3	3.4	4.5	1.8	2.2
17	37	15.1	13.3	33.9	27	28.2	24	30.2	3.2	2.4	1.3	2.2
18	37	34.4	35.3	33.8	26.9	28	24	30.2	2.5	2.4	0.9	1.9
19	36	19.5	14.3	22.6	27.5	30.3	27.2	30.1	3.3	4.6	2.9	1.2
20	24		29.7	33.9	29.1	30.1	24.2	30.2	5.4	5.1	1.5	2.3
21	11	21.5	6.4	18.1	29.3	30	27.6	30.5	5	3.7	3	3.9

The concentration of nutrients varied across seasons and stations during the study (Appendix Figure 3.1.7). The average value of TRIX is 5.15 during the study, indicating poor water quality which is highly eutrophic. The TRIX scores ranged from 1.64 to 7.37 during the course of this study (October 2011 to November 2012). PreM and MON seasons showed a rise in eutrophication, which was moderate during the post monsoon seasons (POM I and POM II).

3.1.2b Variations in the sediment parameters

Sediment composition varied spatio-temporally within the port (Figure 3.1.2). In general silt was the most dominant component - 49.5±22.5% followed by clay - 32.2±25.4% and sand - 18.3±15.6% during all the seasons at most of the stations. The percentage of silt in the sediment ranged between 10% at S-20 to 91% at S-06 (Figure 3.1.2). Percentage of sand was comparatively lower ranging from 0.3% to 62% and dominated during POM I (Figure 3.1.2A), and was merely present during the POM II (Figure 3.1.2D).

Among the sediment texture, sand showed significant variation during the pre and post-monsoon seasons (PreM 18.98±14.2%, MON 10.7±12.6% POM I and POM II 29.8±11.3% and 10.7±12.6% respectively) (Figure 3.1.2). Clay is the second most dominant componant of the sediment and ranged between 0.2% at S-08 to 85% at S05. Sediment total organic carbon ranged from 1.4% to 3.6% during all the seasons. During POM I and II (Figure 3.1.2a, d) higher organic carbon content was observed in the sediment, and it was 2.7±0.40% and 2.6±0.30% respectively. During MON and PreM, the average organic carbon content was low, and it was 1.9±0.8% and 1.7±0.6% respectively (Figure 3.1.2c, d). The sediment characteristics indicated clayey-silt, silty-sand and silt were dominant at the Cochin port (Figure 3.1.2e). The chlorophyll *a* content was high in near bottom water during MON at S-19 (82.9 mg. m^{-3}), and low at S-09 during POM I (0.5 mg. m^{-3}) (Figure 3.1.3a). The average chlorophyll *a* content during POM I was 2.2±1.8 mg. m^{-3}, PreM 21.6±21.4 mg. m^{-3}, MON 13.6±7.1 mg. m^{-3} and during POM II it was 14.6±0.4 mg. m^{-3} (Figure 3.1.3a). Sediment chlorophyll *a* content during POM I, PreM, MON and POM II were 0.77±0.1 mg. m^{-2}, 0.74±0.3 mg. m^{-2}, 0.60±0.4 mg. m^{-2} and 0.56±0.2 mg. m^{-2} respectively (Figure 3.1.3b). The maximum sediment chlorophyll *a* was observed during PreM at S-14, and minimum during MON at S-21 (Figure 3.1.3b).

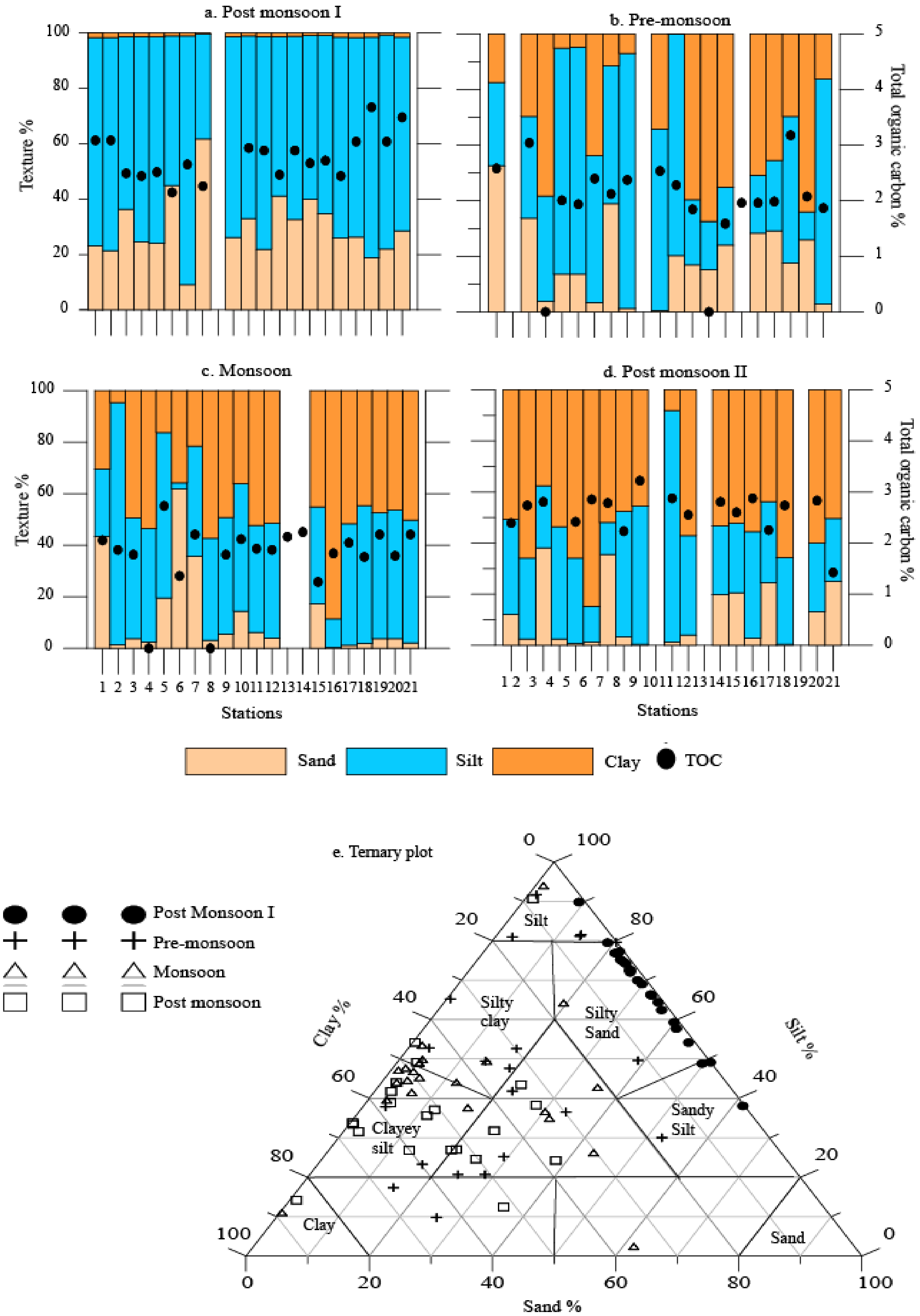


Figure 3.1.2: - Variation in the sediment texture and organic carbon during different seasons (a) Post monsoon I, (b) Pre-monsoon, (c) Monsoon (d) Post monsoon II (e).Ternary plot indicating the changes in the sediment texture at Cochin port.

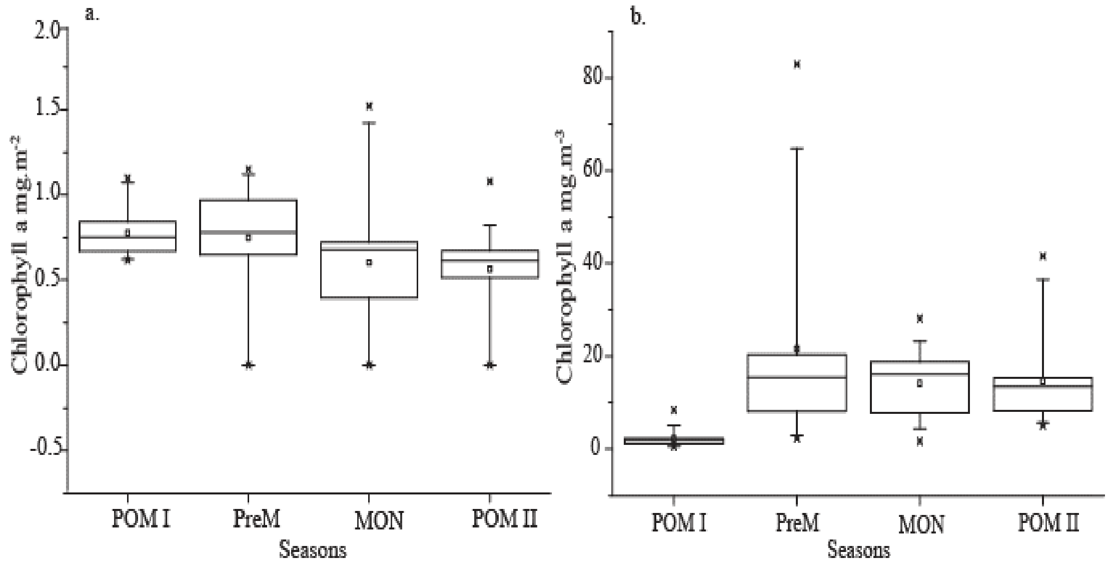


Figure 3.1.3: - Box plot indicating the seasonal changes in the Chlorophyll *a* (a). Sediment and (b). Bottom water content during different seasons.

3.1.2c Seasonal variation in the macrobenthic community

The macrobenthos collected during the study at Cochin port comprised of Annelida (Polychaeta and Oligochaeta), Arthropoda (amphipods, and isopods and tanaids), Mollusca (bivalves) and Gobiidae (mud skippers). Among these groups, polychaetes were the most common and abundant organisms during all the seasons. Among the 36 macrobenthic forms, 21 were polychaetes contributing more than 50% to the total macrobenthic abundance. Spionid and nephtyid polychaetes were observed during all the seasons. The maximum abundance of macrobenthos was found during POM II (9487 no. m^{-2}), followed by POM I (6222 no. m^{-2}), PreM (2171 no. m^{-2}) and MON season (416 no. m^{-2}) (Table 3.1.2). The stations with maximum abundance during POM I, PreM, MON and POM II were S17- South tanker berth (2494 no. m^{-2}), S10-DC jetty (2279 no. m^{-2}), S08-boat train pier, S13-Naval jetty (323 no. m^{-2}) and S19-Ernakulam ferry jetty (92 no. m^{-2}) respectively (Table 3.1.2). During POM I, the maximum abundance of macrobenthic organisms at S10 was contributed by the spionid, *Prionospio* sp. (1910 no. m^{-2}) which was the dominant taxon (Figure 3.1.4; Table 3.1.2). The abundance of *Prionospio* sp. was high during POM I season contributing about 77% to the total abundance, followed by Oligochaeta (8%) and *Ancistrosyllis* sp. (3%) (Table 3.1.2).

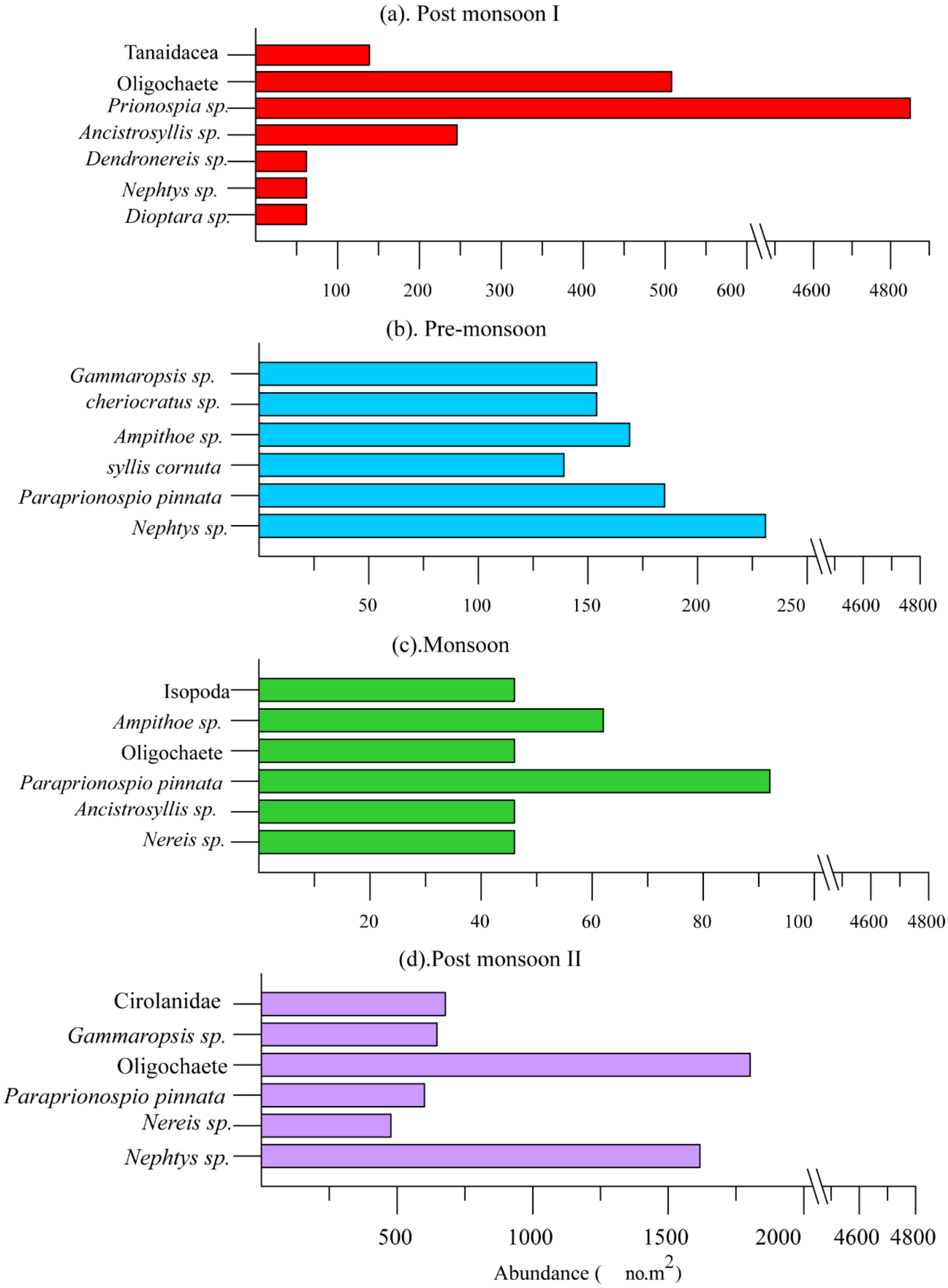


Figure 3.1.4: - Bar-chart showing the variations in the dominant taxa during different seasons (a) Post monsoon I, (b) Pre-monsoon, (c) Monsoon (d) Post monsoon II at Cochin port.

Table 3.1.2. Variation in the abundance of macrobenthos in Cochin port during different seasons (Table 3a - Post monsoon I, Table 3b - Pre-monsoon, Table 3c - Monsoon, Table 3d - Post monsoon II.

Table 3.1.2a. Abundance (no.m^{-2}) of macrobenthic organisms in Cochin port during Post monsoon I.

Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Total
Capitella capitata								46														46
Mediomastus sp.							31			31		15										77
Cossura coasta										31										15		46
Dioptara sp.													15		46							62
Glycera sp.										15												15
Nephtys sp.					31			15			15											61
Dendronereis sp.	15				15					31												61
Ancistrosyllis sp.	15							46		124	15									46		246
Pilargis sp.										15												15
Prionospia sp.	92				724	15	339	431	108	1910	231	15	15	15	139	31		647		139		4851
Paraprionospio pinnata				15																		15
Polydora kempi	15																					15
Oligochaeta	31	15								108			15			93				246		508
Corophium sp.																		15				15
Tanaidacea			31	46				31						15							15	139

Table 3.1.2b. Abundance (no.m^{-2}) of macrobenthic organisms in Cochin port during Pre monsoon.

Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	Total
Capitella capitata													15									15
Cossura coasta						15						31			15		15					77
Goniada sp.													15									15
Nephtys sp.						31				15		62		15	15		92					231
Nereis sp.					15																	15
Owenia sp.															15							15
Aricidae sp.														15			15					30
Ancistrosyllis sp.	31											46										77
Prionospia sp.															31							30
Paraprionospio pinnata						77									61		46					186
Polydora kempi	15																					15
Streblospio sp.														15			46					61
Syllis cornuta	15																15			15	92	137
Oligochaeta						46						123	293									462
Amphipoda					15	15						31								46		108
Ampelisca sp.	31							15														46
Ampithoe sp.	46							123														169
Cheriocratus sp.	15							92		46												154
Gammaropsis sp.								92													62	154
Cirolanidae																				15		15
Tanaidacea																				46		46

Table 3.1.2c. Abundance (no.m^{-2}) of macrobenthic organisms in Cochin port during monsoon.

Stations	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	Total
Bivalvia		15																				15
Cossura coasta					15																	15
Nereis sp.																46						46
Ancistrosyllis sp.																			46			46
Paraprionospio pinnata				62	32																	92
Oligochaeta					15											32						46
Amphipoda					15												15					30
Ampithoe sp.										46									15			61
Gammaropsis sp.																				15		15

Table 3.1.2d. Abundance (no.m^{-2}) of macrobenthic organisms in Cochin port during Post monsoon II.

Stations	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	Total
Bivalvia										62												61
Capitella capitata													92					108				200
Cossura coasta												31		62	62		31	15				200
Hesione sp.																	293					293
Nephtys sp.		62		15		77			262	92		92		139	262		416	200				1617
Nereis sp.		46			354						31									46		477
Dendronereis sp.					92					46											62	200
Owenia sp.														31			31					61
Ancistrosyllis sp.	62																					62
Prionospia sp.		31		15										169			185	62				462
Paraprionospio pinnata		77				200					46			46	108		123					601
Polydora kempi	31													31	92			46				200
Streblospio sp.											15											15
Syllis cornuta	77																			77		154
Oligochaeta						123		169	62		62	277			108		893				108	1802
Amphipoda					15						77				123					123		339
Ampelisca sp.	123			31	77																	231
Ampithoe sp.	46								15								108					169
Cheriocratus sp.	31							92									46					169
Gammaropsis sp.					139			92		323											92	647
Cirolanidae								524		139										15		678
Tanaidacea								385														385

Other polychaetes observed during this season were *Capitella capitata* at S08, *Mediomastus* sp.at S07, S10, S12 and *Cossura coasta* at S10 and S20 stations (Table 3.1.2). Errantiate polychaetes found during this season were *Nephtys* sp. at S05, S08 and S11 and *Dendronereis* sp. at S01, S05 and S10. The most abundant errantiate polychaete was *Ancistrosyllis* sp. with total abundance of 246 no. m^{-2} (Figure 3.1.4) at S08, S10, S11 and S20 (Table 3.1.2).

During PreM season higher abundance of macrobenthic organism was observed at S08 and S13 (Figure 5D). The most abundant taxa were Oligochaeta (21%), *Paraprionospio pinnata* (8%) and *Ampithoe* sp. (7%) (Table 3.1.3). Of the four genera of amphipods collected, three were observed during PreM season, namely *Ampelisca* sp. (S01, S08), *Ampithoe* sp. (S01, S08) and *Cheirocratus* sp. (S01, S08, S11, S20) with a total abundance of 631 no. m^{-2} (Figure 3.1.4; Table 3.1.3). Macrobenthic diversity and abundance were at their lowest during monsoon season compared to other seasons with *Paraprionospio pinnata* and *Ampithoe* sp. contributing 22% and 15% followed by *Ancistrosyllis* sp., *Nereis* sp., oligochaete and tanaids each contributing 11% respectively (Table 3.1.3) with a total abundance of 416 no. m^{-2} (Figure 3.1.4). In contrast, during POM II, the abundance (9487 no. m^{-2}) (Table 3.1.2) were highest compared to other seasons. The most abundant macrobenthos taxa were Oligochaeta, *Nephtys* sp. and cirolanid isopod which contributed 19%, 17% and 7% respectively to the total abundance (Table 3.1.2). Variation in the diversity and abundance at all the stations were observed during POM II, unlike other seasons when organisms were reported only at few stations. The most abundant polychaetes were *Capitella capitata* which was observed at S13 and S18 (200 no. m^{-2}), *Cossura coasta* at S12, S14, S15, S17 and S18 with total abundance of 200 no. m^{-2} (Table 3.1.2).

Nephtys sp. was the second most dominant (1617 no. m^{-2}) taxon during POM II season and were observed at most of the stations (Table 3.1.2). Spionids were the most dominant polychaete family, represented by four genera that were observed at many stations. There were *Paraprionospio pinnata* (600 no. m^{-2}), *Prionospio* sp. (462 no. m^{-2}), *Polydora kempi* (200 no. m^{-2}) and *Streblospio* sp. (15 no. m^{-2}) (Figure 3.1.4). Amphipods found during POM II were *Ampelisca* sp. (S01, S04, S05) with a total abundance of 231 no. m^{-2}, as well as *Ampithoe* sp. and *Cheirocratus* sp. which had similar abundance (169 no. m^{-2}). The amphipod *Gammaropsis* sp. had maximum abundance (646 no. m^{-2}) at S05, S08, S10 and S20 (Figure 3.1.4 & 6; Table 3.1.3). Oligochaeta was the second most abundant group among annelids observed in Cochin port. They were found during all the seasons at most of the stations with maximum abundance during POM II with a total count of 1801 no. m^{-2} (Figure 3.1.4) (S06, S08, S09, S11, S12, S15, S17 and S21) (Table 3.1.2). Juvenile fishes (Gobiidae) were also observed during POM II at S08.

Variations in the diversity of macrobenthos

Species diversity index at all the stations was estimated based on Margalef species richness (d), Shannon-Weiner index (H′) and evenness (J′). The maximum number of species were encountered during POM II at S07 (Table 3.1.3). The correspondence values of the Shannon–Weiner index (H′) were high during PreM and POM II, which were 1.77 and 1.92 respectively. During the monsoon period, species diversity was low compared to other three seasons (Table 3.1.3), and four species were observed during this season (Table 3.1.3). Bray–Curtis similarity index was applied for grouping of the stations according to macrobenthic abundance. At 50% similarity level, three and four groups were revealed during POM I and POM II (Figure 3.1.5) respectively. Post monsoon season showed maximum diversity of macrobenthos with low DO in near bottom water (Table 3.1.2 and Figure 3.1.6). The group I stations were dominated by *Prionospio* sp. (contribution to abundance - 21.3%), *Ancistrosyllis constricta* (contribution to abundance - 2.1%) and *Nephtys sp.* (contribution to abundance - 2.6%). In group I (Figure 3.1.5) stations S05, 07, S08, S11 and S18 were closely similar with the dominant taxa being *Prionospio* sp. In group II (Figure 3.1.5), (S01, S09, S15 and S20), *Prionospio* sp. as less abundant (11%) compared to Group I and *Ancistrosyllis constricta* was the more abundant taxon with 3% contribution to the total abundance respectively (Figure 3.1.5). Group III had *Prionospio* sp. as the common organism in these stations which contributed 4% to the total abundance. During PreM season the organisms that contributed for clustering of different station in groups I (S06, S12 and S15), II (S14 and S17) and III (S01 and S08) were *Ampithoe* sp. (4.3%), *Ampelisca* sp. (3.1%), *Cheirocratus* sp. (3.6%), *Nephtys* sp. (3.4%), *Cossura coasta* (3%), Oligochaeta (2.8%), *Streblospio* sp. (3.3%) and *Aricidea* sp. (2.8%) (Figure 3.1.5B).

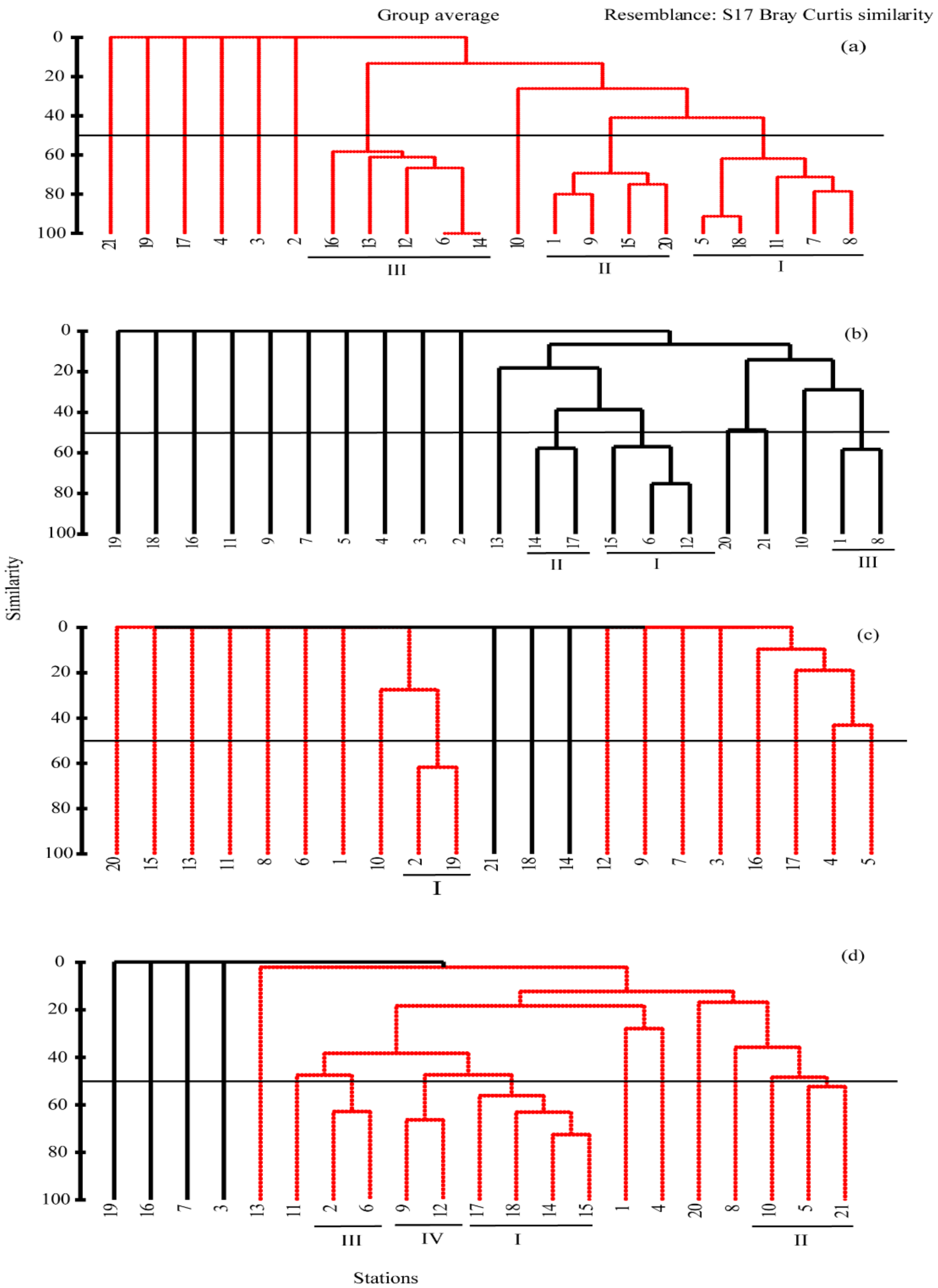


Figure 3.1.5: - Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons (a) Post-monsoon I (b) Pre-monsoon (c) Monsoon (d) Post monsoon II. Stations are grouped with respect to their similarity.

Table 3.1.3. Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou’s evenness (J′), Shannon index (H), of macrobenthic polychaetes during different seasons in Cochin port.

	Post monsoon I						Pre-monsoon						Monsoon						Post-monsoon II				
Stn	S	N	d	J'	H'(loge	Stn	S	N		J'	H'(loge	Stn	S	N		J'	H'(loge	Stn	S	N	d	J'	H'(loge
1	3	1	0.70	0.91	1.00	1	5	1	1.4	0.99	1.60	2	1	3	0.0	....	0.00	1	4	1	1.09	0.99	1.38
5	3	3	0.56	0.68	0.75	6	4	1	1.1	0.99	1.37	4	1	4	0.0	....	0.00	2	5	1	1.37	0.99	1.60
6	1	4	0.00	....	0.00	8	4	1	1.0	0.99	1.37	5	4	1	1.2	1.00	1.38	4	3	9	0.91	1.00	1.09
7	2	2	0.31	0.78	0.54	10	2	7	0.5	0.98	0.68	10	1	4	0.0	....	0.00	5	4	2	1.01	1.00	1.38
8	3	3	0.58	0.79	0.87	12	3	1	0.7	0.99	1.09	16	2	7	0.5	1.00	0.69	6	4	1	1.05	0.98	1.36
9	1	1	0.00	....	0.00	13	1	6	0.0	....	0.00	17	1	3	0.0	....	0.00	8	5	2	1.22	0.99	1.60
10	4	6	0.72	0.71	0.99	14	3	8	0.9	1.00	1.10	19	2	6	0.5	0.99	0.69	9	3	1	0.79	0.97	1.06
11	3	2	0.64	0.80	0.88	15	4	1	1.1	0.99	1.37							10	4	1	1.02	0.99	1.38
12	2	8	0.49	1.00	0.69	17	6	2	1.6	0.99	1.77							11	4	1	1.13	0.99	1.38
13	2	8	0.49	1.00	0.69	20	1	3	0.0	....	0.00							12	3	1	0.77	0.98	1.08
14	1	4	0.00	....	0.00	21	2	9	0.4	1.00	0.69							13	1	5	0.00	....	0.00
15	2	1	0.34	0.95	0.66													14	5	2	1.30	0.99	1.60
16	1	6	0.00	....	0.00													15	5	2	1.27	1.00	1.61
18	1	2	0.00	....	0.00													16	0	0	....	....	0.00
20	2	1	0.34	0.95	0.66													17	7	3	1.69	0.99	1.92
21	0	0	....	....	0.00													18	5	2	1.32	0.99	1.59
																		20	2	7	0.53	0.98	0.68
																		21	3	1	0.77	1.00	1.10

The presence of *Nephtys* sp., and *Cossura coasta* in all the three stations indicated resemblance in the occurrence of polychaete species in group I stations. In group II, *Nephtys* sp., *Streblospio* sp. and *Aricidea* sp. were commonly found. In group III stations during PreM, amphipods such as *Ampithoe* sp., *Ampelisca* sp. and *Cheirocratus* sp. dominated (Figure 3.1.5b). During the MON season there was least similarity among the stations due to low species diversity and abundance. Only two stations, S02 and S19 showed resemblance due to the occurrence of isopods at these stations (Figure 3.1.5c). During POM II, the similarity in the stations and the organisms present was higher, and the presence of *Paraprionospio pinnata* (4.8%), *Nephtys* sp. (4.2%), gastropods (2.8%), *Gammaropsis* sp. (4.7%), *Dendronereis* sp. (4.3%), Oligochaetae (4.8%) and *Cossura coasta* (3.6%) were responsible for such grouping (Figure 3.1.5d). POM II season had four groups with 50% resemblance. In group I (S14, S15, S17 and S18) *Nephtys* sp. and *Cossura coasta* were found in all the stations. Group II (S5, S10 and S21) stations had Nereid, *Dendronereis* sp. and amphipod, *Gammaropsis* sp. in all the stations, with maximum abundance of *Nereis* sp. (354 no. m^{-2}). Group III (S02 and S06) and group IV (S09 and S12) had *Nephtys* sp. common in all their stations (Figure 3.1.5d).

CCA and Redundancy analysis (Figure 3.1.6 a to d) indicated sediment characteristics and organic carbon were important in determining the community structure of benthic organisms at the sampling stations during different seasons. Length of gradient value >2 was shown during POM and PreM seasons and during MON it was <2. The correlation percentages between macrobenthic abundance and the environmental variables during PreM was 95%, followed by 82% during MON, and during POM II and POM I, the percentage were 77% and 76% respectively. The canonical correspondence analysis for POM I (Figure 3.1.6a) revealed that silt and organic carbon influenced the abundance of the organisms. Sampling stations such as S05, S09, S10S18 and S20 with high silt and low organic carbon were dominated by sedentary annelids including *Prionospio* sp. and oligochaetes, whilst at S08 with higher sand content, *Ancistrosyllis* sp., Tanaidacea and isopods were observed (Table 3.1.2). *Prionospio* sp. appeared to be unaffected by changes in the environmental variables as they were reported at majority of the stations during POM I season. Higher temperatures and salinities (above 28) of bottom water also influenced the abundance of macrobenthos at these stations during POM I.

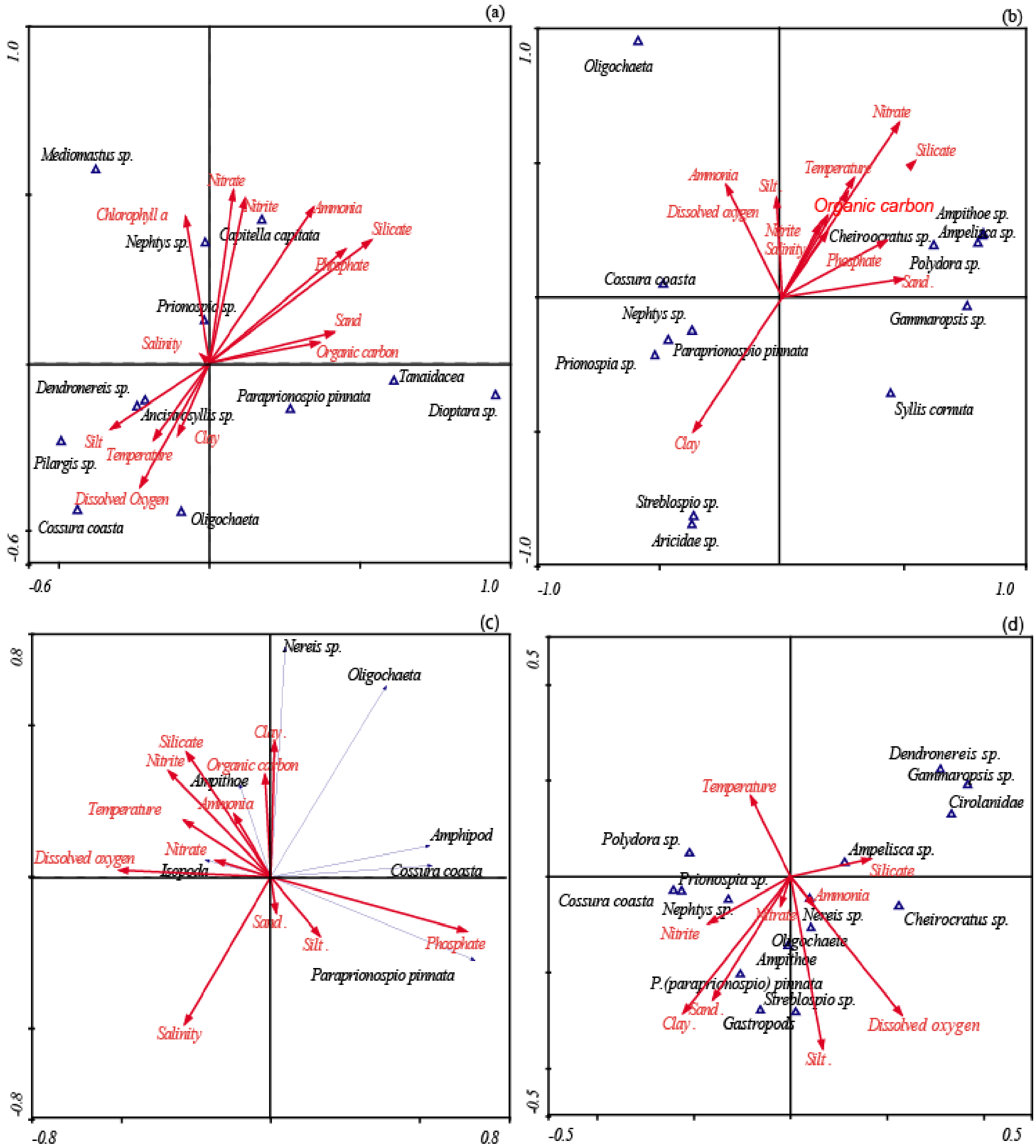


Figure 3.1.6: CCA and RDA plots to illustrate the correlation between environmental parameters and species diversity during different seasons (a) Post monsoon I (b) Pre-monsoon (c) Monsoon (d) Post monsoon II at Cochin port.

During POM II (Figure 3.1.6d) the abundances was maximum when the percentage of clay was the maximum in the sediment. Increased clay and organic carbon content correlated with a higher abundance of the organisms. Stations with high DO, high temperature and salinity of 30 and above generally correlated with higher abundance. The stations S5, S8, S10, S14, S15 and S17 had the abundance of *Nereis* sp., *Nephtys* sp., *Dendroneries* sp., *Prionospio* sp., *Polydora* sp., oligochaetes, amphipods (*Gammaropsis* sp.), and cirolanid isopods (Table 3.1.2). Pre-monsoon (Figure 3.1.6b) season showed the highest correlation in diversity of macrobenthos with environmental variables. The stations with maximum abundance of macrobenthic taxa were S6, S8, S12, S13, S15, S17, S20 and S21 (Table 3.1.2). In the sediment, sand was present at all the stations which shared highest abundance and with an average organic carbon of 2.5%. The organisms found are mostly free living and active predators such as *Nephtys* sp., and *Syllis* sp. except *Prionospio* sp., which is sedentary. Amphipods such as *Ampelisca* sp., *Ampithoe* sp. *Cheirocratus* sp., *Gammaropsis* sp. were also reported. Environmental parameters also influenced the distribution and abundance during MON season (Figure 3.1.6c) when temperature, salinity and DO in bottom water was low (Table 3.1.1). The sediment composition during the previous seasons (POM I and PreM) had higher sand content compared to MON and POM II seasons and this may be due to the riverine runoff during the monsoon season thereby influencing the abundance and diversity of the macrobenthic community. During POM II, *Paraprionospio* sp. observed in sandy-silt sediment and they could survive in low DO, nutrients and organic carbon.

3.1.3 Discussion

Fluctuations in physical and chemical parameters are often associated with the changes in regional climatic and biological activity, alterations in the surface water due to evaporation, fresh water influx, intensity of solar radiation, as well as cooling and mixing with the ebb and flow from adjoining shallow waters (Kumar and Khan, 2013). Earlier studies carried out indicated contamination of Cochin back waters by anthropogenic pollutants due to poor flushing of sediment, enclosed nature of the estuary and adsorption of pollutants in the sediments leading it in to a sensitive ecosystem (Martin et al., 2012; Anu et al., 2014). In the present study, the 21 stations located in all three channels were influenced by the incoming sea waters during high tide and outgoing fresh water during the low tide. Water in the Cochin port region derive a large proportion of nutrient load throughout the year from land drainage, agricultural activities and river discharge during the monsoon (Devi et al., 1991; Madhu et al., 2007). Tropic index (TRIX) scores showed that Cochin backwaters is highly eutrophic. The hydrography of the Cochin backwaters reflected tropical estuarine conditions where sea water temperature gradually increased from post monsoon to pre-monsoon season, after which a considerable decrease during monsoon was observed. In the monsoon season, stratification intensified due to increased freshwater influx, which also led to a decrease in salinity from the mouth of the Cochin backwaters to the upstream. High nutrient supply during monsoonal rainfall is a unique characteristic of an estuary influenced by monsoon (Qasim and Sen Gupta, 1982). During non-monsoon period, freshwater influx to the backwaters is reduced, and salt water intrusion can be seen up to 40 kms inland from the mouth (Jacob et al. 2013). As reported in earlier studies, high concentrations of phosphate were observed during the post and pre-monsoon periods from December to April (Sankaranarayanan and Qasim, 1969; Martin et al, 2012). This may be due to the result of high salinity/pH combined with tidal activity during the pre-monsoon, which causes removal of phosphate from the suspended particles (Martin et al., 2008). Near bottom water had low concentrations of DO compared to the surface waters during day time. This net reduction of oxygen reflected typical tropical estuarine conditions, with stratification in salinity during monsoon and partially mixed condition during non-monsoon seasons.

The distribution of sediment grain size and organic matter determine metal concentrations as well as anthropogenic pollutants such as total nitrogen (TN) and total phosphorus (TP). They are also in turn correlated with the distribution of rare elements in sediments (Aloupi and Angelidis 2001; Liaghati et al., 2003; Rodríguez et al., 2010). Sediment texture shows significant fluctuations in their characteristics due to water discharge in riverine and backwater areas, leading to considerable intermixing of sand, silt and clay (Nair and Ramachandran, 2002). Even though sediment showed fluctuations in Cochin port, higher percentage of sandy sediment is seen at the bar mouth (stations S07, S08 and S10; see Figure 3.1.2) due to estuarine bed load movement (Nair et al., 1990; Nair et al., 1993; Martin et al., 2012). High silty sediment in this backwater port during PreM is associated with sedimentation processes leading to the settlement of fine silt particles at the bottom due to weak currents (Joy et al., 1990; Menon et al., 2000). Sediment quality is one of the most important factors that determine the spatio-temporal distribution and abundance of benthic organisms. These are related to various properties of sediment such as permeability, penetrability which are in turn controlled by sediment erosion and resuspension, and water content in the sediment (Sarkar et al., 2005). The present study indicated changes in the sediment quality with the seasons, which may have been affected by dredging, tidal flow, sediment erosion and accumulation, currents and monsoon floods. Such changes will determine the dominance of particular group of organisms in the sediment in a respective season. Dredging activity in the dock area of Cochin port is of great concern as it leads to turbidity, which also reduces productivity affecting greatly the benthic faunal distribution (Rasheed and Balchand, 2001). Dredging activity carried out in the port area and Cochin backwaters has had negative impact on benthic species composition and population density, resulting in decreased diversity (Desprez, 2000; Sarda et al., 2000; Van Dalfsen et al., 2000; Rehitha et al., 2017). The present study showed continuous changes in the percentage of silt-clay composition of the sediment during the monsoon season which in turn has led to the changes in composition of organic carbon in the sediment. The higher silt composition in the sediment comprised of mostly decomposable organic matter, which are the food particles for deposit feeders (Sanders, 1958, 1960; Sanders et al., 1962; Jayaraj et al., 2008b). The change in the sediment composition may have led to eradication and dominance by a few species in some stations and seasons (Figures 3.1.2 and 3.1.6).

The organic carbon input in to estuarine sediments is mostly determined by the supply of terrestrial material, deposition rate of organic to inorganic constituents, primary productivity and sediment texture (Muraleedharan and Ramachandran, 2002). Organic enrichment observed in the Cochin backwaters is a sign of environmental deterioration, possibly leading to the reduction in the diversity of macrobenthic community (Martin et al., 2011). The build-up of pollutants, contaminated inputs from fresh water and discharge of sewage waste in the estuary all contribute to environmental degradation (Menon et al., 2000). Organic carbon enrichment in the sediments may lead to hypoxia, faunal depletion and ultimately an abiotic environment (Pearson and Rosenberg, 1978). In the present study, even though organic enrichment is observed at various stations and it was in higher percentage during monsoon season, decrease in the macrobenthic organisms during monsoon seasons can be attribute to flow of freshwater as a resultant of the monsoon and sediment flushing. The distribution of organic carbon in the sediment is dependent on the sediment grain size as they possess higher surface area of fine sediments (Valdés et al., 2005; Rodríguez et al., 2010, Paneer Selvam et al., 2012). The present study showed significant spatial variation in the organic carbon than temporal variation, which may be due to the changes in the sediment constituents in different stations in and around the Cochin port.

Macrobenthic polychaetes comprised the dominant group among the organisms present in Cochin port, and this observation agrees with other locations along the south west coast of India (Joydas and Damodaran, 2009; Musale and Desai 2011). Spionids were the most dominant among the polychaetes. Studies on Calcasieu estuary (Louisiana), shows spionids as one of the most dominant taxa throughout the estuary in different seasons (Gaston and Nasci, 1988). The change in the abundance and diversity of benthic organisms such as polychaetes, may be due to the influence of discharge in Cochin backwaters as the amount of organic carbon and organic matter are very high and this may lead to eutrophication in the estuary (Devi and Venugopal, 1989; Devi et al 1991; Geetha et al., 2010). Seasonal variation was also observed in the diversity of macrobenthos as changes in the sediment texture resulted in qualitative difference in each season (Figure 3.1.2). Influence of waste water has varying effect on the primary producers and consumers with ensuing alterations in food web structure (Geetha et al., 2010). The areas with lower abundance of organisms were mostly dominated by silt and clay sediments, associated with low chlorophyll *a* in both bottom water and sediment. Earlier studies (Cloern, 2001; Bode et al., 2006; Jayaraj et al., 2007; Musale and Desai, 2011) have indicated that clayey and clayey-silt sediments had low abundance of organisms, as fine clay particles causes clogging of the feeding apparatus of the filter feeders. The dominant polychaetes in the present study area was the spionid *Prionospio* sp., a deposit feeder preferring fine grain sediment and shallow depths (Jayaraj et al., 2008).

As observed by Hoey et al. (2004) and Jayaraj et al. (2008), benthic faunal distribution is affected by sediment texture. *Nephtys* sp. was found in the fine sandy sediment, whilst *Cossura coasta* preferred both sandy and muddy sediment due to the availability of food particles and increased organic matter which increases the abundance of this species (Lange, 2013). Most of the polychaetes such as *Capitella capitata, Mediomastus* sp.*, Prionospio* sp. and *Streblospio* sp. found in the study area are indicator species of anthropogenic pollution and organic enrichment (Sivadas et al., 2010; Balachandar et al., 2016). High organic enrichment may lead to hypoxic conditions, as well as smothering and reduction in the density of organisms, which result in the dominance of the deposit feeders in estuaries (Pearson and Rosenberg, 1978; Ansari et al., 1986; Mojtahid et al., 2008; Martin et al., 2011). Extreme changes in the diversity during each season was observed e.g., *Prionospio* sp. was dominant during POM I followed by oligochaetes during PreM and POM seasons, except MON season when *Paraprionospio* sp. was dominant. Dominance of single opportunistic species (*Prionospio* sp.) in the present study area was likely due to the prolonged stress in the environment as observed by Gray (1989). The presence of *Prionospio* sp. shows oxygen depletion and *C. coasta* is an indicator species for sediment instability indicating disturbed environment (Abdul Jaleel et al., 2014; Rehitha et al., 2017). Most of the above-mentioned organisms are deposit feeders those feed on the freshly settled organic matter on the sediment as observed by Muniz and Pires, (1999) and Dolbeth et al. (2007). The present study shows that the influence of monsoon which brings high fresh water inflow from catchment area, tidal flow and dredging in Cochin port are major factors influencing change in the percentage of sediment texture and organic carbon leading to the change in the species abundance and diversity in each season (Table 3.1.2).

Other macrobenthic organisms observed in Cochin port were the oligochaetes, crustaceans (amphipods, tanaids and isopods), molluscs, as well as larval and juvenile gobiid fishes. Opportunistic species such as oligochaetes have shown dominance where dredging is carried out regularly and there is a correspondingly lower concentration of amphipods and polychaetes at these stations (Rehitha et al., 2017). It has been observed that the stable conditions may allow organisms to thrive well and unfavourable conditions may lead to decline in their density, and this coincides with the previous studies (Duineveld et al, 1991; Musale and Desai, 2011). The study indicated that the Cochin port is a stressful environment for the benthic fauna, and this observation is supported by Shannon index (H') and species richness (d) values which are 0.6-1.9. For a healthy environment, d should be in the range of 2.5 to 3.5 (Magurran, 1988). Previous studies by Jayaraj et al. (2008) and Musale and Desai (2011) showed that *Prionospio* sp. was found in high numbers along the south west coast of India especially off Cochin backwaters and Cochin port which is organically polluted (Remani et al., 1983). Several studies in south west coast showed higher benthic abundance (Neyman, 1969; Harkantra et al., 1980; Parulekar et al., 1982; Jayaraj et al., 2007). Pillai. (2001) has described 30 species belonging to 25 genera of polychaetes in the Cochin estuary, but the present study showed 21 polychaetes taxa in the study stations which is lower than those reported in Cochin estuary or backwaters. However, the observed changes in the diversity and density may be attributed to high organic carbon content in the port sediment and influence of anthropogenically deposited effluents. Cochin backwaters is influenced by petroleum hydrocarbons and dissolved and suspended organic matter in the surface and subsurface waters. These wastes get flushed out during monsoon season except at the bar mouth (port area) where the region gets accumulated with the waste from the estuary (Menon, 2000). As described by Martin et al. (2011), the above mentioned anthropogenic activities have affected the benthic organisms and lead to the survival of the tolerant and opportunistic species.

Chapter 3.2

Spatio-temporal variation in the macrobenthic community structure and the factors influencing the macrobenthic diversity in Haldia port

3.2.1 Introduction

Haldia port (HDC) is located on the bank of river Hooghly at a distance of about 104 km downstream of Kolkata. The coordinates of the port site are 22°02´ north and 88°06´ east. The Haldia port was commissioned during 1977, it is an integral part of Kolkata Port Trust (KoPT). Haldia port handles a major share of Kolkata Port traffic. Haldia Dock presently has 17 berths, of which three oil berths are located in the river and remaining 14 berths are inside the enclosed dock. At the same time, vessel movement in and out of the Dock takes place only during the high tide window which is twice in a day. This has resulted in only smaller vessel/ vessel with smaller parcel size calling at Haldia Port. Haldia has a typical moderate climate with winter temperatures ranging from 14.7 °C to 30 °C and summer season with a highest temperature of around 33.7 °C. The Haldia port 33.50 million metric tonnes of cargo during the financial year 2015-16, against capacity of 46.7 million tonnes.

3.2.2 Results

3.2.2a Variations in the environmental parameters

The variations in the near-bottom environmental parameters such as temperature, salinity and, dissolved oxygen are presented in Figure 3.2.1. The average near-bottom seawater temperature during MON I, POM, MON II and, PreM was 29.73±0.6 ˚C, 22.3±0.5 ˚C, 30.5±0.2 ˚C and, 26.4±0.4 ˚C respectively (Figure 3.2.1a; Table 3.2.1b) and it significantly varied with the seasons (One-way ANOVA; F = 1202.84, df = 3, p = $7.6*10^{-62}$). The salinity of near-bottom seawater ranged from 1.35±0.4 to 7.4±0.4 during the study (Figure 3.2.1c) (One-way ANOVA; F = 472.64, df = 3, p =$1.8*10^{-52}$) indicating near freshwater conditions at some stations during some seasons (Table 3.2.1b). The near-bottom DO concentration during MON I, POM, MON II and, PreM was 5.9±0.8 mg. l^{-1}, 7.9±0.1 mg. l^{-1}, 5.7±1.5 and, 5.6±1.3 mg. l^{-1} respectively (Figure 3.2.1b; One-way ANOVA; F = 21.16, df = 3, p =$2.5*10^{-10}$).

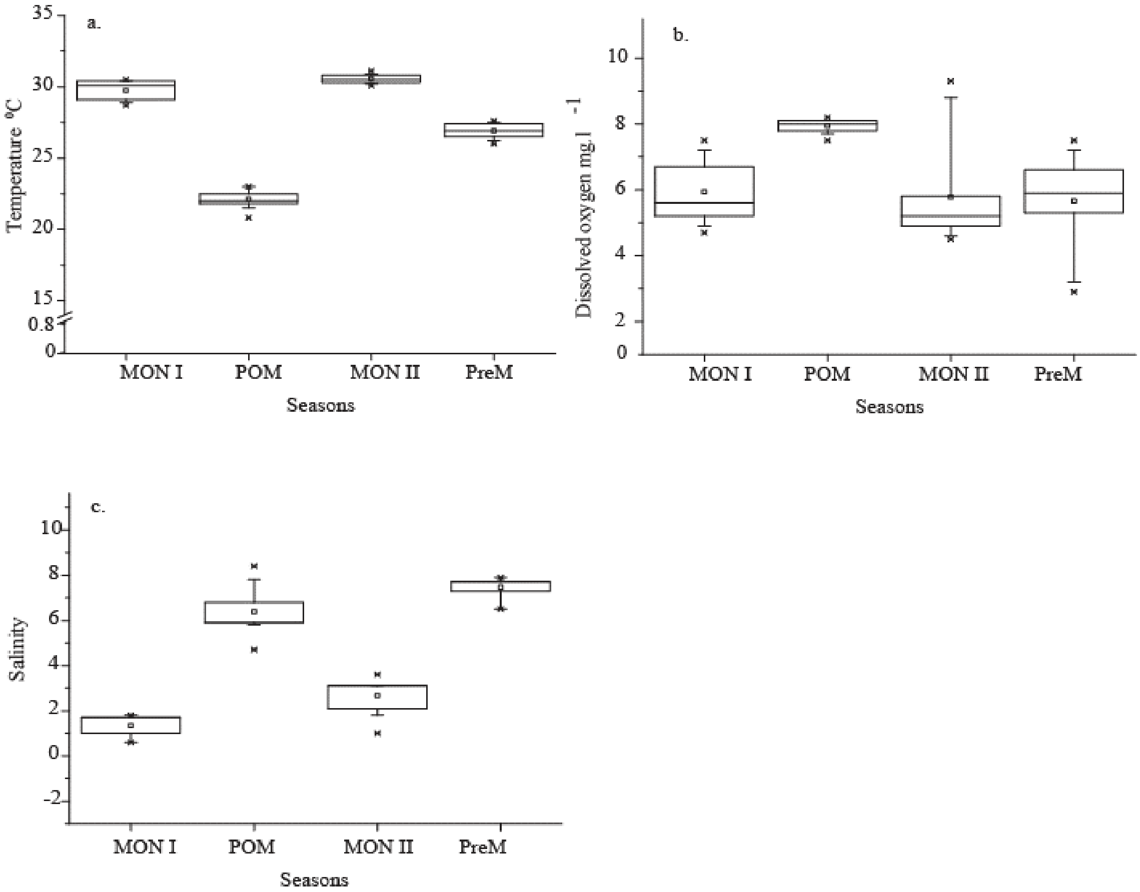


Figure 3.2.1: Box-plot illustrating the seasonal variation in the (a) Temperature (b) Dissolved oxygen and (c) Salinity during the different seasons at Haldia port.

The dissolved oxygen concentration in near bottom water was high during all the seasons indicating oxic conditions. The concentration of bottom water nutrients indicated spatio-temporal variation during the study (Supplementary Figure 3.2.7). The multivariate index of trophic state (TRIX) analysed for the bottom water during the study was 1.6±0.4 indicating good state of water quality with low levels of eutrophication. TRIX scores ranged from 0.4 to 2.7 during all the seasons indicating healthy bottom water conditions with high turbidity. The bottom water chlorophyll *a* during MON I, POM, MON II and Pre-M was 2.1±1.7 mg.m^{-3}, 1.5±0.8 mg.m^{-3}, 1.1±0.6 mg.m^{-3} and 0.8±0.7 mg.m^{-3} respectively (Figure 3.2.2b) (One-way ANOVA; $F = 5.81$, $df = 3$, $p = 0.001$), and chlorophyll *a* concentration during MON II season was low compared to MON I indicating inter-monsoon variation in the chlorophyll *a* concentration. Higher turbidity may have resulted in the lower chlorophyll *a*. The sediment chlorophyll *a* during MON I, POM, MON II and Pre-M

Table 3.2.1: Variation in Salinity, Temperature and Dissolved oxygen of bottom water at Haldia port during different seasons (MON I - Monsoon I, POM – Post monsoon, MON II – Monsoon II, PreM II – Pre-monsoon II, SED – Sediment and BW– bottom water).

Temperature ^{0}C				**Salinity**				**DO mg.m^{-3}**				**Chlorophyll a (BW-mg.m^{-3}; SED- mg.m^{-2})**							
												MON I		**POM**		**MON II**		**Pre-M**	
MON I	**POM**	**MON II**	**Pre-M**	**MON I**	**POM**	**MON II**	**Pre-M**	**MON I**	**POM**	**MON II**	**Pre-M**	**B**	**SED**	**BW**	**SED**	**BW**	**SED**	**BW**	**SED**
30.40	22.00	30.30	26.50	1.70	5.90	3.10	7.70	6.72	8.01	5.40	5.32	0.78	2.07	1.56	0.61	0.21	0.46	1.76	0.81
30.40	23.00	30.60	26.80	1.70	5.90	3.10	7.90	5.64	8.13	5.10	3.24	0.76	0.70	2.11	0.18	0.80	0.49	0.05	0.81
30.43	22.00	30.40	27.30	1.70	5.80	3.10	7.70	5.34	8.03	5.15	3.36	0.84	1.48	1.74	0.46	1.05	0.26	0.49	0.67
30.39	23.00	30.90	27.40	1.80	5.80	3.10	7.70	5.16	7.95	4.94	5.34	0.42	1.80	0.90		1.04	0.32	0.70	0.46
30.47	22.50	30.90	27.50	1.80	5.90	3.10	7.70	5.16	8.05	4.51	2.93	0.71	1.91	1.56	0.64	0.50	0.46	0.37	0.32
30.30	22.80	30.90	27.50	1.80	5.90	3.10	7.70	4.69	8.19	4.62	5.62	3.34	1.37	1.35	0.29	1.78	0.92	0.66	0.49
30.37	22.80	30.80	27.50	1.80	5.90	3.10	7.70	5.14	8.00	4.58	5.84	0.62	1.97	0.96	0.29	2.36	0.78	0.32	0.49
30.31	23.00	30.80	27.40	1.80	5.90	3.60	7.80	4.91	7.72	4.75	5.02	0.56		1.50	0.46	2.31	0.29	0.41	0.49
30.21	22.40	30.80	27.60	1.70	5.90	3.10	7.70	5.23	7.96	4.67	5.88	0.91	1.64	1.51		1.18	0.64	0.28	0.35
30.18	22.50	30.80	26.90	1.70	5.90	3.10	7.90	5.30	7.95	5.06	6.22	0.62		1.87	0.64	1.18	0.64	0.26	0.49
30.13	22.20	30.80	26.90	1.70	6.00	3.10	7.60	5.23	8.13	5.22	5.67	0.87	0.88	2.12	0.64	0.83	0.49	0.59	0.67
29.72	21.60	30.50	26.80	1.50	6.20	3.00	7.70	5.61	7.97	5.40	5.69	1.08	0.62	2.16	1.33	0.65	0.81	0.26	0.70
29.60	22.00	30.50	26.60	1.60	5.90	3.00	7.60	5.60	8.01	5.43	3.15	0.79	1.37	2.10		0.84	0.49	0.34	0.84
29.09	21.80	30.20	26.90	1.20	8.40	2.60	7.50	7.25	8.06	5.10	7.53	5.11	2.29	4.68	0.98	1.08	0.49	0.66	0.67
28.97	21.50	30.20	26.50	0.60	4.70	2.90	7.40	7.05	7.88	5.48	7.20	3.07	0.33	1.61		2.01		1.58	0.84
29.11	21.80	30.50	26.20	1.00	7.40	2.10	7.20	6.45	7.74	4.92	6.83	3.98	1.53	1.21		2.25	0.99	2.58	0.84
29.03	21.90	30.50	26.50	0.70	7.60	1.90	7.30	6.48	7.75	5.83	6.87	5.95	1.83	1.25	0.17	0.48	0.95	0.25	0.81
28.94	20.80	30.50	27.00	0.60	7.70	2.00	7.30	6.71	8.13	5.80	6.40	2.94	2.59	0.66	0.49	1.08	0.81	0.50	
29.28	21.80	31.10	27.00	0.70	6.80	2.10	6.80	6.53	7.78	8.36	6.57	4.78		0.81	0.03	1.14	0.81	2.24	0.84
28.66	21.50	30.30	27.00	0.60	6.60	1.80	7.20	6.28	7.53	8.69	6.62	4.39	0.67	0.46		0.73	0.14	1.10	
29.07	21.90	30.20	26.00	1.00	7.80	2.00	6.50	7.54	8.08	8.77	6.46	1.98	2.20	0.90	0.95	0.60	0.17	2.09	0.64
29.01	21.50	30.10	26.20	1.00	6.40	1.00	6.50	6.94	7.82	9.33	6.83	2.49	0.33	0.94	0.84	0.51		1.08	0.17

-was 1.4±0.6 mg.m^{-2}, 0.5±0.3 mg.m^{-2}, 0.5±0.2 mg.m^{-2} and 0.6±0.2 mg.m^{-2} respectively (Figure 3.2.2b) (One-way ANOVA; F = 20.5, df = 3, p = 1.1*10^{-9}), and chlorophyll *a* concentration during MON II season was low compared to MON I indicating inter-monsoon variation in the chlorophyll *a* concentration. Lower concentration of bottom water chlorophyll *a* and turbidity resulted in low sediment chlorophyll *a*.

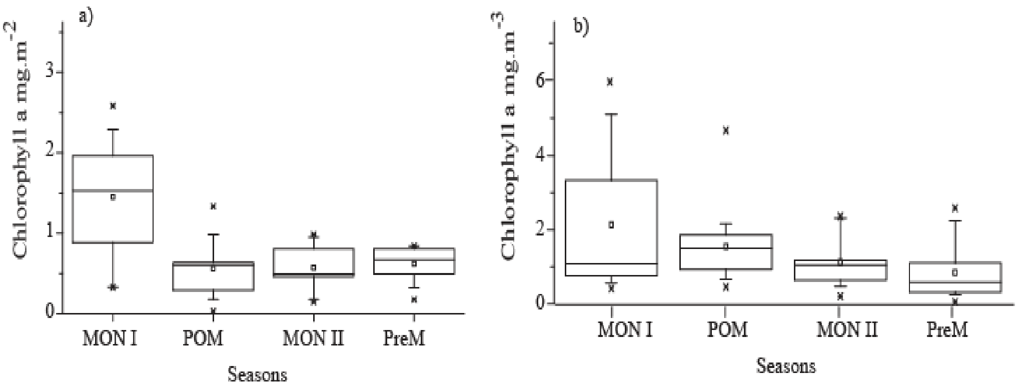


Figure 3.2.2: - Box plot indicating the seasonal variation in the Chlorophyll *a* content in (a) Sediment and (b) Bottom water during different seasons at Haldia port.

3.2.2b Variations in the sediment characteristics and organic carbon

Sediment texture was analysed for the composition of sand, silt and clay and it varied spatio-temporally within the port (Figure 3.2.3). The silt was the most dominant component 56.0±30.3% followed by sand - 26.3±23.7%, and Clay - 4.9±8.8% during all the seasons at most of the stations. During MON I, the percentage of sand in the sediment ranged between 7.4% (S-02 and S-11) to 92.6% at S03 (Figure 3.2.3a), and during POM it was 4.7% at S-01 to 59.8% at S-21 (Figure 3.2.3b). The percentage of sand was higher at few stations during MON II ranging from 4.1% (S-12) to 94.6% (S-03) (Figure 3.2.3c) and during PreM season with an overall percentage of 28.4±20.9% (Figure 3.2.3d). The percentage of sand was minimum during PreM (One-way ANOVA; F = 0.18, df = 3, p = 0.9). The silt in the sediment ranged from 3.1 to 94.6% and it was dominant during POM (71.4±20.4%) season (Figure 3.2.3b).

The percentage composition of silt was 48.5±18.3% during MON I, 71.4 ±20.4% - POM, 67.3±26.9 % - PreM and 69.1±20.0% during MON II (Figure 3.2.3) indicating signficant variation in its content with the seasons (One-way ANOVA; F = 4.65, df = 3, p = 0.005).

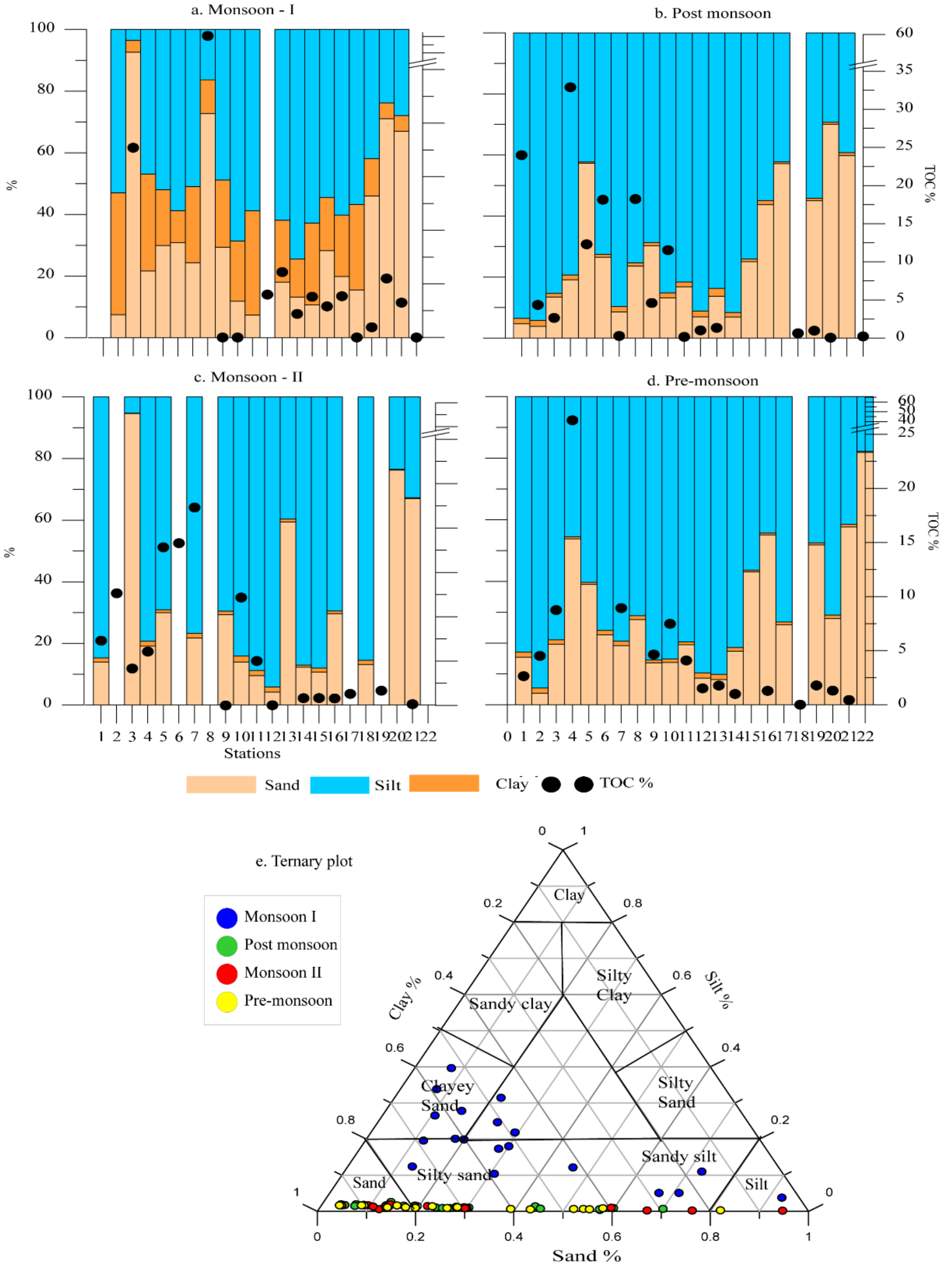


Figure 3.2.3: Variation in the sediment texture and organic carbon during different seasons (a) Monsoon I (b) Postmonsoon (c) Monsoon II (d) Pre-monsoon (e)Ternary plot indicating the changes in the sediment texture s at Haldia port.

The clay was minimum in the sediment and ranged between 0.2% at S-22 during PreM to 39.6% at S2 during MON I (Figure 3.2.3a) (One-way ANOVA; $F = 59.0$, $df = 3$, $p = 2.34*10^{-10}$). The ternary plot to determine the sediment textures indicated dominance of silty-sand and sandy silt sediment among the stations (Figure 3.2.3e). The sediment organic carbon was high in Haldia port and it showed wide variation in its range during different seasons. During MON I, organic carbon ranged from 0.1 to 61.0% indicating wide variation between the minimum and maximum organic carbon during this season, however, the higher range of organic carbon (61.0%) was reported only at two stations during MON II, and at other stations it was low. During MON II, it was 0.7 to 22.3%, POM - 0.2 to 32.8 % and PreM - 0.4 to 41.2% (Figure 3.2.3a) (One-way ANOVA; $F = 0.33$, $df = 3$, $p = 0.8$).

3.2.2c Seasonal variation in the macrobenthic community

The macrobenthic organisms in Haldia port comprised of Annelida (Polychaeta and Oligochaeta), Arthropoda (Alpheidae, Penaeidae, Copepoda, Tanaidacea and amphipoda), Mollusca (bivalves), and Echinoderms (Sea anemones). The polychaetes were the most diverse and abundant organisms during all the seasons. Among the 27 macrobenthic taxa, 14 were polychaetes contributing more than 70% to the total macrobenthic abundance. Polychaetes belonging to the genus *Nephtys* and *Cossura* were observed during all the seasons. The maximum abundance of macrobenthos was observed during POM (2268 no. m^{-2}), followed by MON II (949 no. m^{-2}), PreM (532 no. m^{-2}) and MON I (488 no. m^{-2}) season (Table 3.2.2; Figure 3.2.4e) indicating a seasonal variation (One-way ANOVA; $F = 6.70$, $df = 3$, $p = 0.0004$). The maximum abundance of macrobenthos during MON I was at station S02 (108 no. m^{-2}) and S04 (92 no. m^{-2}) (Table 3.2.2; Figure 3.2.4a).

The abundance of macrobenthos was minimum during MON I. The macrobenthos belonging to Nephtyidae, *Nephtys* sp. (168 no. m^{-2}) contributed maximum to the abundance followed by Alpheidae (107 no. m^{-2}) and Oligochaeta (77 no. m^{-2}) during this season (Figure 3.2.4). During POM, the abundance was maximum 2268 no. m^{-2} (Table 3.2.2) compared to other seasons. They were reported at stations, S01, S02, S03, S08, S09, S13, S15, S21 and S22 (Table 3.2.2a). The polychaete, *Pectinaria* sp. (339 no. m^{-2}) at S15, *Cossura* sp. (92 no. m^{-2}) at S01, S02, S17 and S18, *Nephtys* sp. (260 no. m^{-2}) reported at S02, S03, S04, S05, S09, S11, S13, S14, S15 and S17, and *Glycera* sp. with a total abundance of 62 no. m^{-2} contributed to the higher abundance of macrobenthos. Nematoda (184 no. m^{-2}) was the fourth abundant taxa found during this season.

Among the Annelida, Oligochaeta were the most abundant (1001 no. m^{-2}) during this season and The non-Annelid forms observed during this season were *Nototropis* sp. (30 no. m^{-2}) and *Penaeus* sp. (30 no. m^{-2}). During MON II, the abundance of macrobenthos was 949 no. m^{-2} and the polychaetes, *Nephtys* sp., *Namalycastis* sp., and *Namaneris* sp. were common during this season. The *Nephtys* sp. (338 no. m^{-2}) was reported at S04, S06, S07, S08, S09, S11, S16, S18 and S21 respectively. The polychaetes, *Namalycastis* sp. (138 no. m^{-2}) and *Namaneris* sp. (200 no. m^{-2}) were observed at S07. During PreM season, Oligochaeta were abundant (122 no. m^{-2}) and were observed at S07, S14 and S21 (Table 3.2.2 c). *Nephtys* sp. (77 no. m^{-2}) and *Penaeus* sp. (46 no. m^{-2}) were some of the commonly reported fauna followed by polychaetes, *Cossura sp.* (31 no. m^{-2}), *Mediomastus* sp. (31 no. m^{-2}) and *Streblospio* sp. (30 no. m^{-2}). Other than polychaetes, Nemertea (31 no. m^{-2}) and *Nototropis* sp. (30 no. m^{-2}) were also observed (Table 3.2.2 d).

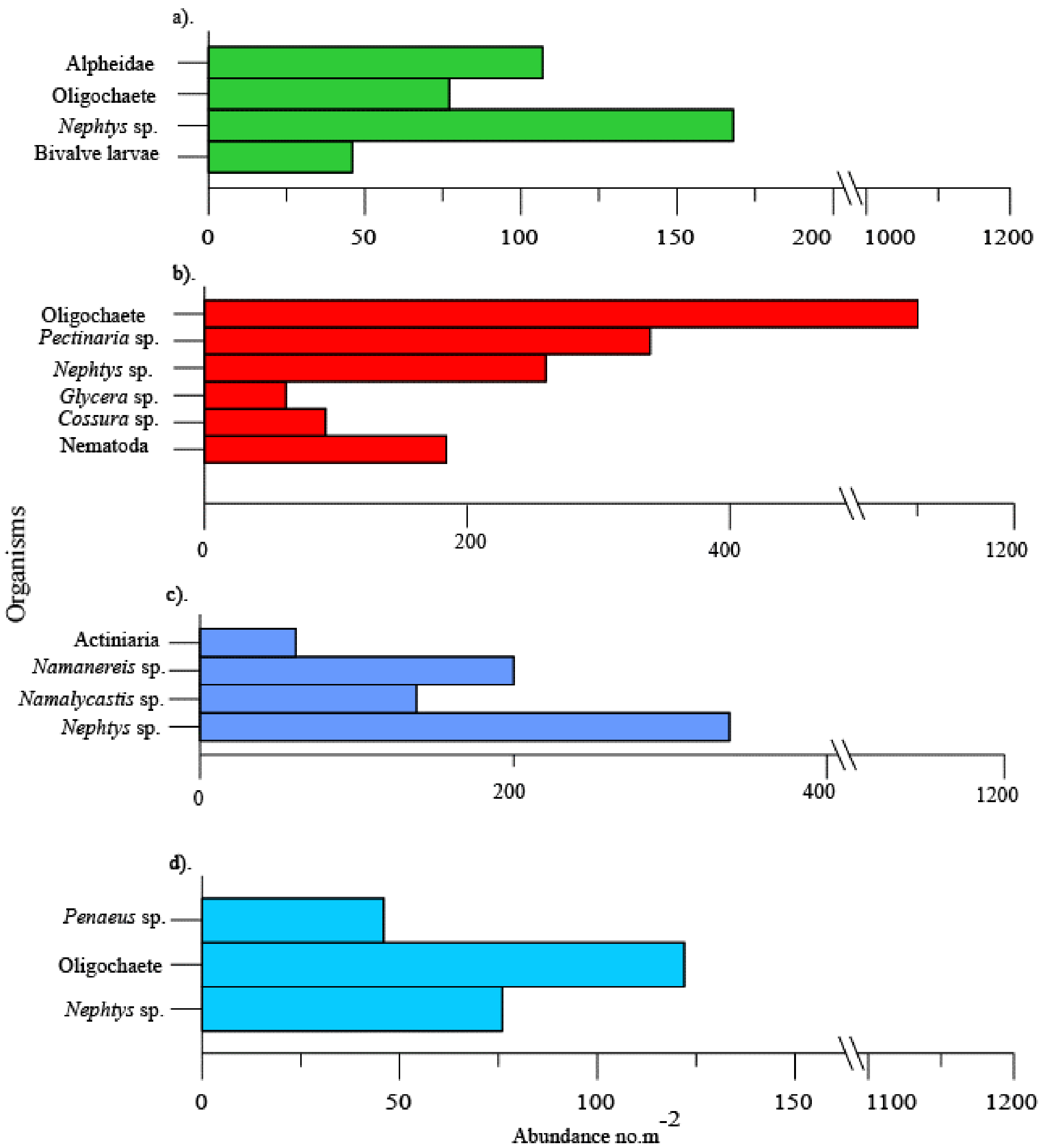


Figure 3.2.4: Bar-chart showing the variations in the abundance of dominant taxa during different (a) Monsoon I, (b) Postmonsoon (c) Monsoon II (d) Pre-monsoon at Haldia port.

Table 3.2.2. Variation in the abundance (no.m^{-2}) of macrobenthos in Haldia port during different seasons.

Table 3.2.2a. Abundance (no.m^{-2}) of macrobenthos in Haldia port during Monsoon I season.

Fauna	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Total**
Nephtys sp.		31	15	46	15	31	15		15														168
Family Alpheidae					15	15	31	15				31											107
Oligochaete		62		15																			77
Bivalve larvae				31			15																46
Cossura sp.	15	15																					30
Syllidae larvae						15																	15
Amphipoda								15															15
Periopthalmus sp.														15									15
Fish Larvae													15										15

Table 3.3.2b. Abundance (no.m^{-2}) of macrobenthos in Haldia port during Post monsoon season.

Faunal Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Total**
Oligochaete	108	31	200					154	62		46	154	139		15						77	15	1001
Pectinaria sp.															339								339
Nephtys sp.		31	15	15	15				46		15		46	15	31		31						260
Nematoda	15							15									154						184
Cossura sp.	31	31															15	15					92
Glycera sp.																					31	31	62
Magelona sp.										15											15		30
Nereis sp.	15						15																30
Nototropis sp.				15									15										30
Penaeus sp.			15		15																		30
Penaeid larvae							15																15
Veliger larvae															15								15
Capitella sp.											15												15
Glycinde sp.																						15	15
Nephtys capensis			15																				15
Namanereis sp.							15																15
Pisione sp.					15																		15
Polycirrus sp.									15														15
Copepoda																			15				15
Photis sp.														15									15
Perioculodes sp.																		15					15
Alpheidae									15														15
Tanaidacea													15										15
Fish Larvae												15											15

Table 3.3.2c. Abundance (no.m^{-2}) of macrobenthos in Haldia port during Monsoon II season.

Faunal Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Total**
Nephtys sp.				15		62	62	62	15		15					77		15				15	338
Namanereis sp.						77	123																200
Namalycastis sp.			15				123																138
Actiniaria							15	15		31													61
Veliger larvae																				31			31
Phyllodoce sp.											31												31
Oligochaete							15				15												30
Penaeus sp.						15				15													30
Pelecypoda						15																	15
Bivalve larvae																				15			15
Mediomastus sp.																						15	15
Glycera sp.																		15					15
Ampelisca sp.																					15		15
Family Tanaidacea							15																15

Table 3.3.2d. Abundance (no.m^{-2}) of macrobenthos in Haldia port during Pre-monsoon season.

Faunal Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Total**
Oligochaete							15							15							92		122
Nephtys sp.				31				15						15					15				76
Penaeus sp.					15		31																46
Nemertea						31																	31
Mediomastus sp.										31													31
Cossura sp.																					31		31
Streblospio sp.												15									15		30
Nototropis sp.				15						15													30
Gastropoda															15								15
Capitella sp.																			15				15
Goniada sp.			15																				15
Namanereis sp.							15																15
Ophelia sp.														15									15
Phyllodoce sp.					15																		15
Ampelisca sp.															15								15
Corophium sp.																				15			15
Penaeidae								15															15

Variation in the diversity of macrobenthos

Species diversity indices at all the stations were estimated based on Margalef species richness (d), Shannon-Weiner index (H′) and evenness (J′). The maximum number of species were encountered during POM season and the correspondence values of the Shannon–Weiner index (H′) during MON I, POM, MON II and PreM were 1.0, 1.2, 1.4 and 1.0 respectively (Table 3.2.3).

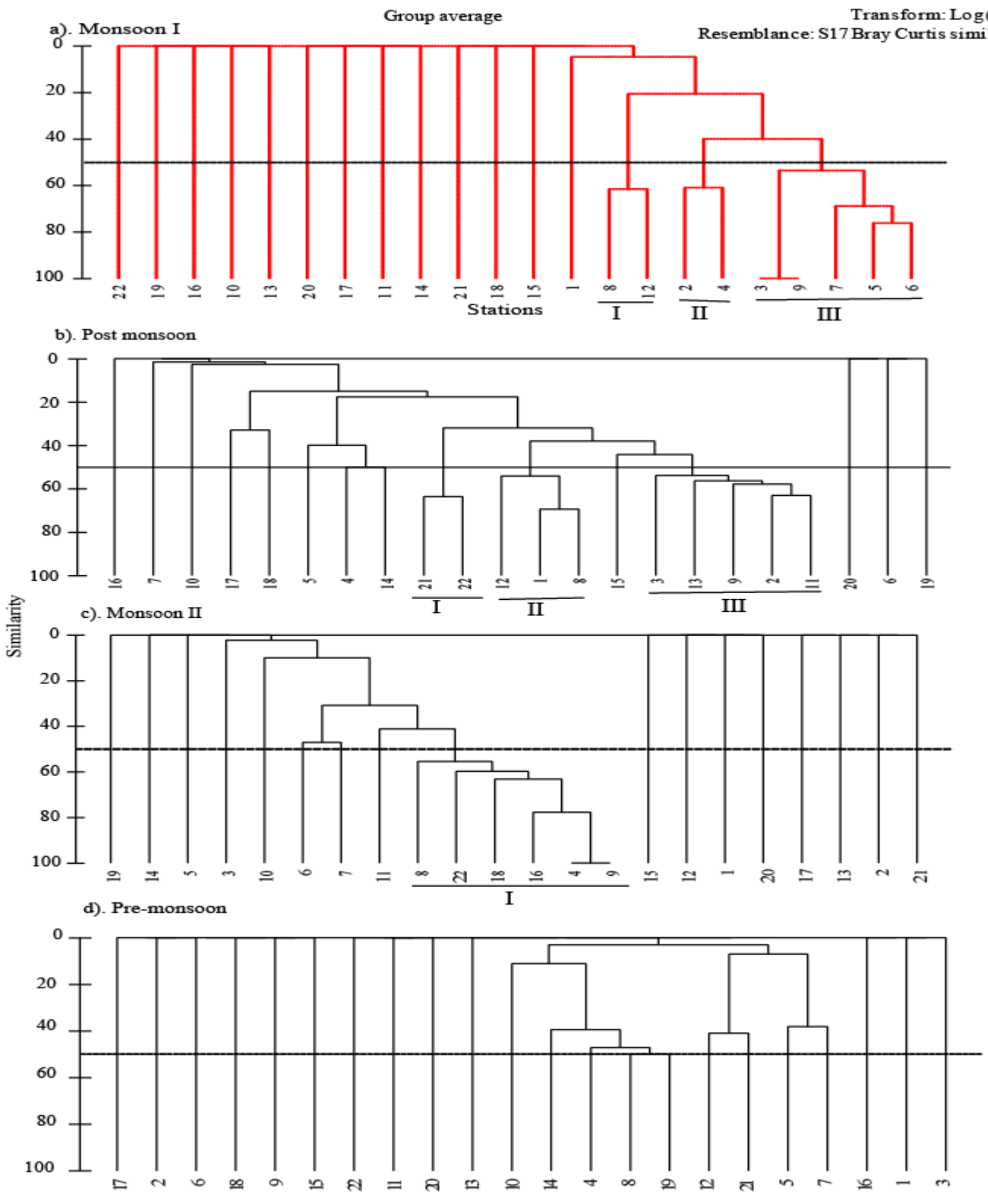


Figure 3.2.5: Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons (a) Monsoon I (b) Postmonsoon (c) Monsoon II (d) Pre-monsoon. Stations are grouped with respect to their similarity.

Table 3.2.3. Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou's evenness (J′), Shannon index (H), of macrobenthic polychaetes during different seasons at Haldia port.

	Monsoon I					Post monsoon					Monsoon II					Pre-monsoon				
St.	**S**	**N**	**d**	**J'**	**H'(loge)**	**S**	**N**	**d**	**J'**	**H'(loge)**	**S**	**N**	**d**	**J'**	**H'(loge)**	**S**	**N**	**d**	**J'**	**H'(loge)**
1	1	15	0	****	0	4	169	0.58	0.74	1.03	0	0	****	****	0	0	0	****	****	0
2	3	108	0.43	0.87	0.95	3	93	0.44	1	1.1	0	0	****	****	0	0	0	****	****	0
3	1	15	0	****	0	4	245	0.55	0.49	0.68	1	15	0	****	0	1	15	0	****	0
4	3	92	0.44	0.92	1.01	2	30	0.29	1	0.69	1	15	0	****	0	2	46	0.26	0.91	0.63
5	2	30	0.29	1	0.69	3	45	0.53	1	1.1	0	0	****	****	0	2	30	0.29	1	0.69
6	3	61	0.49	0.94	1.03	0	0	****	****	0	4	169	0.58	0.83	1.16	1	31	0	****	0
7	3	61	0.49	0.94	1.03	3	45	0.53	1	1.1	6	353	0.85	0.81	1.44	3	61	0.49	0.94	1.03
8	2	30	0.29	1	0.69	2	169	0.19	0.43	0.3	2	77	0.23	0.71	0.49	2	30	0.29	1	0.69
9	1	15	0	****	0	4	138	0.61	0.87	1.21	1	15	0	****	0	0	0	****	****	0
10	0	0	****	****	0	1	15	0	****	0	2	46	0.26	0.91	0.63	2	46	0.26	0.91	0.63
11	0	0	****	****	0	3	76	0.46	0.86	0.94	3	61	0.49	0.94	1.03	0	0	****	****	0
12	1	31	0	****	0	2	169	0.19	0.43	0.3	0	0	****	****	0	1	15	0	****	0
13	1	15	0	****	0	4	215	0.56	0.71	0.98	0	0	****	****	0	0	0	****	****	0
14	1	15	0	****	0	2	30	0.29	1	0.69	0	0	****	****	0	3	45	0.53	1	1.1
15	0	0	****	****	0	4	400	0.5	0.42	0.58	0	0	****	****	0	2	30	0.29	1	0.69
16	0	0	****	****	0	0	0	****	****	0	1	77	0	****	0	0	0	****	****	0
17	0	0	****	****	0	3	200	0.38	0.62	0.68	0	0	****	****	0	0	0	****	****	0
18	0	0	****	****	0	2	30	0.29	1	0.69	2	30	0.29	1	0.69	0	0	****	****	0
19	0	0	****	****	0	1	15	0	****	0	0	0	****	****	0	2	30	0.29	1	0.69
20	0	0	****	****	0	0	0	****	****	0	2	46	0.26	0.91	0.63	1	15	0	****	0
21	0	0	****	****	0	3	123	0.42	0.82	0.9	1	15	0	****	0	3	138	0.41	0.77	0.85
22	0	0	****	****	0	3	61	0.49	0.94	1.03	2	30	0.29	1	0.69	0	0	****	****	0

The maximum abundance (2268 no.m^{-2}) of macrobenthos was during POM compared to other three seasons (Table 3.2.2). The similarity among the stations with respect to the macrobenthic fauna is calculated at 50%. During MON I, the stations were grouped in three groups, group I (S03, S05, S06, S07 and S09) with an average similarity of 57% among the stations had *Nephtys* sp. and Alpheidae as the commonly reported organisms which contributed 84.1% and 15.1% to the total abundance. Group II (S08 and S12), had a similarity of 49% and Alpheidae was the dominant and common macrobenthos (Figure 3.2.5a) and group III (S02 and S04) had an average similarity of 46% with *Nephtys* sp. (67.4%) and oligochaete (32.6%) contributing maximum to the macrobenthos community. The stations that are not grouped under the Bar-Curtis similarity are S01, S10, S11, S13, S14, S15, S16, S18, S19 S21 and S22 are dissimilar due to absence of macrobenthic organisms and only one macrobenthic taxa is found in these stations (Figure 3.2.5a; Table 3.2.2a).

Post monsoon showed higher diversity of macrobenthos and 75% similarity among the groups at different stations (Figure 3.2.5b). The group I stations were dominated by Oligochaeta (contribution to abundance – 69.2%) and *Nephtys* sp., (30.7%). In group II, Oligochaeta were dominant with 96.1% contribution to the total macrobenthos and in group III, *Glycera* sp. was the dominant organism with an overall contribution of 67.3% (Figure 3.2.5). During POM the stations that are not grouped under the Bar-Curtis similarity are S06, S07, S16, S19 and S20 was not grouped together due to the absence of macrobenthic organisms and only one macrobenthic taxa is found in these stations (Figure 3.2.5b; Table 3.2.2b). During MON II season the similarity of organisms and their average abundance in group I (S04, S08, S09, S18 and S22) was 64% and the polychaete, *Nephtys* sp. was commonly reported macrobenthos among these stations (Figure 3.2.5c), that are not grouped under the Bay-Curtis similarity during MON II (S01, S02, S03, S05, S12, S13, S14, S15, S17, S19, S20 and S21) are without any macrobenthic fauna or a single taxon is observed in these stations (Figure 3.2.5b; Table 3.2.2b). During, PreM season there was no similarity shown among the stations. Haldia port, even though had good bottom water quality and high concentration of OC in the sediment had comparatively low diversity and abundance (Figure 3.2.5d). Redundancy analysis (RDA plots) (Figure 3.2.6) indicated sediment texture, sediment organic carbon and bottom water salinity as the important factors influencing the community structure of the macrobenthos at different stations during different seasons at this port. Length of gradient value >2 was observed during all the seasons.

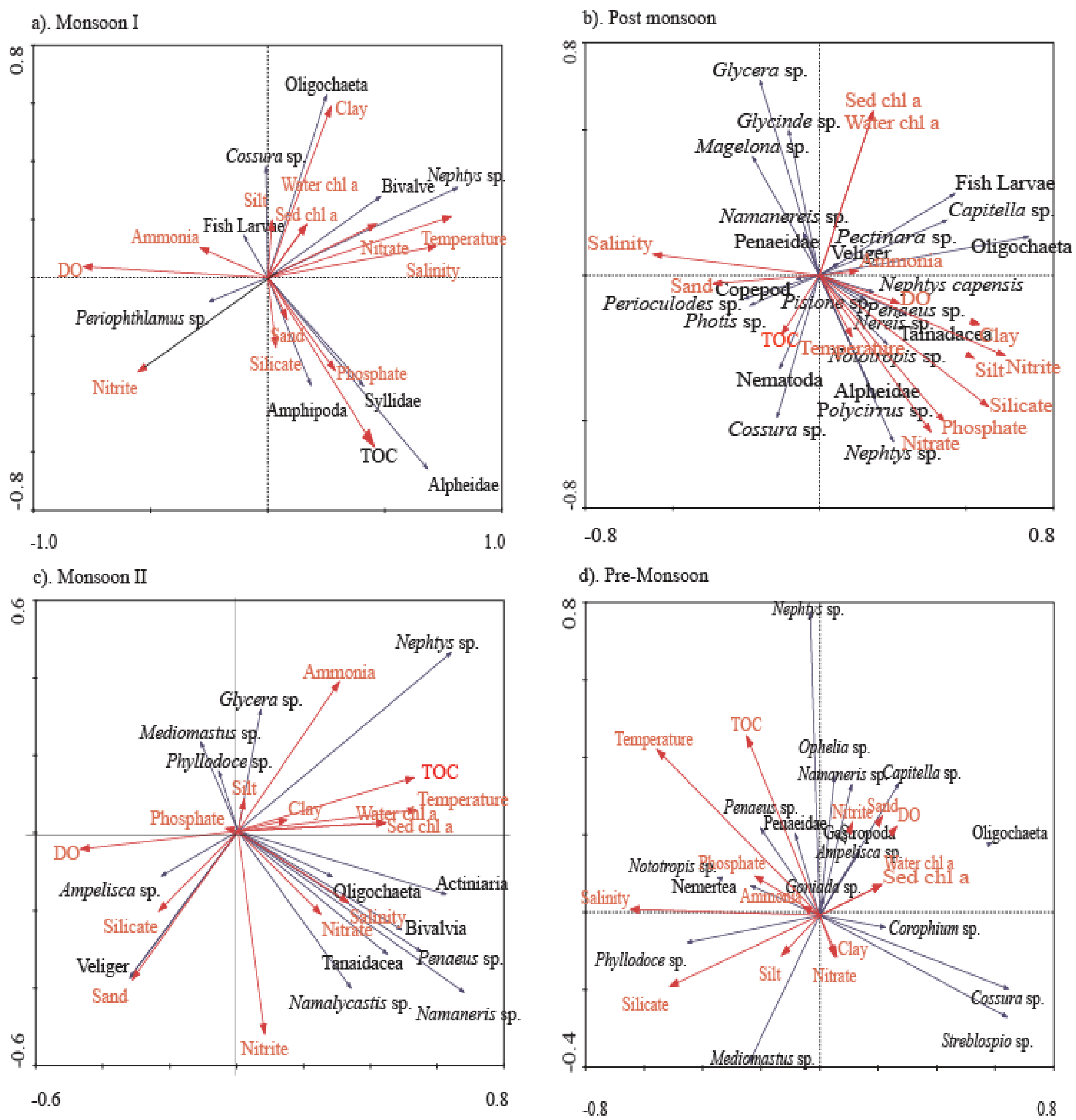


Figure 3.2.6: RDA plots illustrating the correlation between environmental parameters and species diversity during different seasons (a) Monsoon I (b) Postmonsoon (c) Monsoon II and (d) Pre-monsoon at Haldia port.

The correlation percentage between macrobenthos abundance and the environmental variables during MON I was 91.3%, POM and PreM it was 82.3% each and MON II it was 84.8%. The redundancy analysis during MON I (Figure 3.2.6a) indicated that silt, temperature, salinity and sediment organic carbon influenced the abundance of the organisms such as *Nephtys* sp., *Cossura* sp., Bivalves and Oligochaetes, whereas sand, the nutrients (silicate and phosphate) along with organic carbon positively influenced the abundance of amphipods, Alpheidae and Syllidae. *Periopthalmus* sp. was not influenced by these factors but influenced by nitrite concentration and low to medium

DO concentration. During POM (Figure 3.2.6b) season the abundance of Oligochaeta, Bivalve larvae, *Penaeus* sp. and *Capitella* sp. was influenced by silty-clay sediment, near bottom seawater and sediment chlorophyll *a*, along with ammonia concentrations and they could withstand low to medium DO concentrations. Salinity with medium to low percentage of sand and organic carbon supported the occurrence of *Glycera* sp., *Glycinde* sp., *Magelona* sp. and *Namaneris* sp. and these organisms are mostly motile and they require sandy sediment for their movement.

Sand and organic carbon highly influenced Copepods, *Perioculodes* sp., *Photis* sp., *Cossura* sp. and Nematoda with medium to low concentrations of DO and percentage of silt in the sediment. The polychaetes, *Nereis* sp., *Pollycirrus* sp., *Nototropis* sp., *Penaeus* sp. and Alpheidae also positively influenced by silty-clay sediment along with concentration of silicate, phosphate and chlorophyll *a* (Figure 3.2.6b). Monsoon II indicated that silty sediment with both near bottom seawater and sediment chlorophyll *a* along with organic carbon influenced the abundance of polychaetes, *Glycera* sp., *Nephtys* sp., and these parameters had low to medium influence on the occurrence of *Namalycastiss* sp., *Namaneris* sp., *Penaeus* sp., Tanaids and oligochaetes with salinity playing a most influential role in their abundance (Figure 3.2.6c). While the amphipod, *Ampelisca* sp. and the veliger larvae were supported by sandy sediment, high DO concentration and silicate. During PreM season (Figure 3.2.6d) oligochaete, gastropoda, *Namaneris* sp., *Nephtys* sp., *Capitella* sp., *Goniada* sp. and *Ampelisca* sp. were influenced by sandy sediment with adequate DO and chlorophyll *a* content. The polychaete, *Cossura* sp. and *Streblospio* sp., were not influenced by most of the environmental parameters and these can be considered as indicator organisms. *Nototropis* sp., *Penaeus* sp. and Nemertea were positively.

3.2.3 Discussion

Haldia port located on the Hooghly River has limited information available on the benthic ecosystem and macrobenthos diversity. Understanding macrobenthic organisms, their distribution, abundance and their relation to surrounding environment helps us understand that particular region and also establish a database for future studies (Warwick and Ruswahyuni, 1987). In a benthic environment changes in the physio-chemical properties are mostly related to the changes in the climate, anthropogenic activities and biological activities (Kumar and Khan, 2013). The present study at Haldia port describes the changes in the benthic environment, macrobenthic abundance and community structure along with the role of sediment characteristics in structuring the benthic biodiversity at this port. At Haldia port, temperature can be considered as one of the important factor affecting the benthic biodiversity owing to its wide seasonal variation and this has been observed in Hooghly estuary (Nath and Patra, 2015). Due to the changes in the salinity, the macrobenthic organisms reported in Haldia port are mostly brackish water and the abundance of macrobenthos was minimum compared to other ports studied. Surface water salinity in the Hooghly estuary varied from 0.05 during monsoon to 20.8 during non-monsoon season (Bose et al, 2014). Previous studies on soft bottom macrobenthos along the west coast of India, shows that recolonization in the benthic fauna increases when the salinity increased specifying higher salinity positively affect benthic organisms (Vizakat et al, 1991). The bottom water salinity in at the Haldia port ranged from 0.05 to 8, and was comparatively lower than reported in the previous studies. It has been reported that the fluctuations in salinity is a limiting factor as they influence the organism's distribution and reproduction (Fenchel, 1969; Gibson, 1982; Saravanakumar et al, 2008). Temperature and Salinity are the important factors determining the fluctuations in the dissolved oxygen concentrations in an estuary (Reid and Wood, 1976). In Haldia port fluctuations in salinity and temperature have shown changes in DO concentrations during different seasons. Dissolved oxygen is an important component for the macrobenthic organisms that are living in the aquatic ecosystems, for water quality index, trophodynamics and for the metabolic activities of the organisms (Hull et al, 2000). The dissolved oxygen during study was comparatively low during monsoon season and it was high during non-monsoon season (POM and PreM). It has been observed that during the months of November – February there is an increase in the DO due to less fresh water runoff, increase in the sunlight transparency leading to the increase in photosynthesis and production of phytoplankton (Mandal et al, 2012). At Haldia port DO and bottom water chlorophyll *a* was comparatively high during POM except MON I and this can be attributed to higher primary productivity during non-monsoon season. The scores of TRIX analysis at Haldia port was 2.7, indicating good quality of near bottom water leading towards low eutrophication rate (<4 good water quality) (Vollenweider et al, 1998), however, it varied with the seasons, and it was 1.9 during MON I, 1.6 during POM, 1.8 in MON II and 1.2 during PreM which indicated healthy bottom water conditions. Also, the near bottom water had low nutrients and continuous fluctuation in the DO and salinity and this may lead to low primary productivity and the organic carbon found in the sediments of Haldia port are mainly due to black carbon. It has been observed in the Haldia port that due to large amount of coal handling, the port had coal carbon in the sediments.

In the formation of a habitat for the macrobenthos community structure and their survival, sediment texture and its various properties such as sediment quality, the sediment organic carbon, permeability controlled by erosion, water content of the sediment and erosion plays an important role (Sanders, 1958; Ingole, 1998; Jayaraj et al, 2008; Sarkar, 2005). Haldia port which is are isolated from the Hooghly River with only an inlet connecting the port to the river, the disturbance to the sediment characteristics was minimum both spatially and temporally at the port. The sediment texture in the port was dominated by silt followed by sand and negligible percentage of clay, and this also coincides with the riverine sediment characteristics observed in the Hooghly River (Sasamal, 1986). The presence of higher percentage of silt found in this port maybe associated with the settlement of fine particles due to sedimentation and weak water movements due to weak physical forcing (Joy et al., 1990; Menon et al., 2000). High silt content can be resultant of the settlement of decomposable organic particles which influences the population of macrobenthos especially deposit feeders (Sanders, 1958, 1968; Sanders et al., 1962; Jayaraj et al., 2008), and this has been observed at Haldia port during the study. The overall average of sediment organic carbon at Haldia port was <3.5%, except at few stations it was slightly higher ranging from 5.7 % to 41.2% (Figure 3.2.3 a-d). Increase in the organic carbon among the stations may lead to the decrease in the abundance and biodiversity of benthic fauna and this may leads to the dominance of few indicator species which are tolerant to organic carbon rich sediment, however, this is a sign of environmental degradation (Pearson and Rosenberg, 1978; Martin et al, 2011; Desai, 2020). Fine sediment deposits contain decomposable organic compounds, these compounds are food for benthic fauna either directly or indirectly leading to increased metabolism in the organisms (Gray, 1981; Meksumpun and Meksumpun, 1999, Musale and Desai, 2011), as observed in Haldia port is dominated by fine silty sediment. Along with constant change in temperature, salinity, organic carbon and low near bottom water chlorophyll *a* lead to low abundance and diversity in Haldia port.

At Haldia port least abundance and low diversity of macrobenthos was observed and it was dominated by indicator organisms and salinity tolerant forms of Annelids, Crustaceans and Bivalve larva. The macrobenthic diversity in Haldia port varied seasonally and spatially among the stations. The seasonal changes in salinity, temperature, sediment characteristics, organic carbon and other associated stresses lead to the change in the diversity (Ansari, 2014). In this study the diversity pattern of macrobenthic organisms due to seasonal variation were correlated to salinity, temperature and organic carbon. The diversity and population distribution varied among the seasons in Haldia port, with POM being the most productive as observed in Cochin port (Noyel et al, 2020), followed by MON II, PreM and MI. This study indicates that the Haldia port is a stressful environment for the benthic fauna documented with low abundance and this observation is supported by Shannon index (H') and species richness (d) values which are 0.2–1.4 and for a healthy environment d value were observed in the range of 2.5 to 3.5 (Magurran, 1988). Among the MON seasons, the benthic population varied, and MON II indicated low abundance (Table 3.3.2c). This can be attributed to the changes in the bottom water nutrients and low chlorophyll *a* concentration along with change in the sediment characteristics during MON II season. In the present study POM had high abundance compared to PreM which had the lowest abundance, and the sediment characteristics, salinity and organic carbon were mostly similar however, due to increase in chlorophyll *a* and DO (Table 3.3.1 c and d) during POM the abundance may be high compared to other seasons. The most common macrobenthic organisms reported during MON I and II were *Alpheus* sp. and *Nephtys* sp. The snapping shrimp (*Alpheus* sp.) are mostly found in marine and estuarine environments (Soledade and Almeida 2013), and usually they are found associated with the polychaetes (Anker et al., 2007b, 2008a, 2008d). At Haldia port, this organism was observed during MON I and POM season and their abundance was high during POM season. The RDA analysis indicated that the organic carbon along with sandy substratum favoured higher abundance of *Alphes* sp. The polychaete, *Nephtys* sp. is affected by the sediment texture, as they are commonly found in sandy sediments (Lange et al., 2014). In the present study the abundance of *Nephtys* sp. was influenced by salinity and temperature along with silty-sand substratum. The stations were dominated by silt with low concentrations of sand, and *Cossura* sp. was observed during all the seasons except MON II. *Cossura* sp. were observed to be dominant deposit feeders in a silt dominant sediments (Musale et al, 2015), and this sub-surface deposit feeding polychaete and also considered as an indicator organism (Sivadas et al, 2010). As observed by Sanders, (1958) and Ingole et al, (1998) sediment texture is the most essential component of benthic fauns, as it provides a habitat along with food (Gray, 1981). *Namalycastis* sp. belonging to the subfamily of Namanereidinae is one of the few annelid groups that are well adapted to low salinity or fresh water conditions (Alves and Santos, 2016). In the present study *Namalycastis* sp. was observed during MON II, with low bottom water salinity with medium concentrations of DO in the sediment with higher percentage of sand. The polychaete, *Magelona* sp. was observed during the POM season with the concentration of high near bottom water and sediment chlorophyll a concentration and salinity (Figure 3.2.6), and these organisms show no selective feeding strategy and are surface deposit feeders sometimes switch the feeding mode to suspension feeding (Along, 1989). The amphipod, *Ampelisca* sp. was reported during MON II and this is common amphipod which can function as both suspension and deposit feeders with an opportunistic behaviour (Santos and Pires-Vanin, 2004; Paganelli et al. 2012). The occurrence of this species is mainly influenced by the concentration of DO and sandy-silt sediment and amphipods were observed only during MON seasons during the present study (Table 3.2.2 a and c). *Mediomastus* sp. is a silty-sand dwelling polychaetes that can survive in high organic matter, these organisms also show non-selective feeding mechanism that absorb food directly from the sediments (Hoey et al, 2004), in the present study even though they can survive in stress full environment they are very low in abundance. Oligochaetes are sedentary organisms which lack movement which stops them from escaping the habitat during environmental stress, this makes them useful as bio indicators (Joyce and Catherine, 2018). In Haldia port, Oligochaeta was observed in all the seasons but their abundance varied according to seasonal changes, they are most abundant in post monsoon season and least in monsoon season, this may be due to the decrease in chlorophyll *a* in monsoon. This present study due to constant fluctuations in salinity and temperature in bottom water along with low nutrients concentrations with high concentrations of sediment organic carbon showed lowest abundance and diversity in the Haldia port.

Chapter 3.3

Spatio-temporal variation in the macrobenthic community structure and the factors influencing the macrobenthic diversity in Kolkata port

3.3.1 Introduction

Kolkata port is the only freshwater major port in India, located 232 kms upstream from the sand heads, and can be considered having one of the longest navigational channel in the world. Kolkata port is 202 kms from the sea, and is considered as the ‘Gateway of eastern India’. Hooghly river is a part of the Ganges riverine system and it flows through a heavily industrialised locations and also considered as most polluted river. Tidal variation is important for the operations in Kolkata port as the port activities are based on the tides, and tidal amplitude during spring tide is 6.5 m and during neap it is 4.2 m (IMD). Sea water intrusion is restricted to 70 km from the mouth.

3.3.2 Results

3.3.2a Variations in the environmental parameters

The seasonal variations in the environmental parameters, near bottom seawater temperature and dissolved oxygen is presented in Figure 3.3.1. The average near bottom water temperature during MON season was 30.9 (±0.2) °C and it ranged from 18.6 (±0.3) °C to 21 (±0.1) °C during PreM I and II; during POM it was 24.5 to 26.3 (±0.4) °C (Figure 3.3.1a; Table 3.3.1a) and significantly varied between stations within the port (One-way ANOVA; F = 11384, df = 3, p = $3.0*10^{-106}$). The near bottom seawater temperature had a difference of 11 (±4.2) °C between MON and PreM seasons. The tidal amplitude at Kolkata port was 1.15 – 6.11 m. The DO concentration of the near bottom water ranged between 3.3 to 7.8 (±1.2) mg. L^{-1} during MON season and the average DO was high during PreM and POM seasons (Figure 3.3.1b, Table 3.3.1b) and it varied spatially in the port region (One-way ANOVA; F = 16.58, df = 3, p = $3.7*10^{-8}$). During PreM I and II, it was 5.6(±0.8) to 8.8(±1.0) mg. L^{-1} and 5.2(±1.2) to 6.8(±1.0) mg. L^{-1} respectively, while during POM the DO was 4.3(±2.05) to 9.9(±2.0) mg. L^{-1} respectively (Figure 3.3.1b; Table 3.3.1b), and it indicated seasonal variation. The salinity ranged from 0.17 to 0.35, and the higher salinity was observed in NSD dock and it varied among the stations (One-way ANOVA; $F = 2.44$, df = 3, p = 0.07), indicating near fresh water conditions. The concentration of nutrients in the near bottom water varied with seasons and the stations during the study (Appendix Figure 3.3.7).

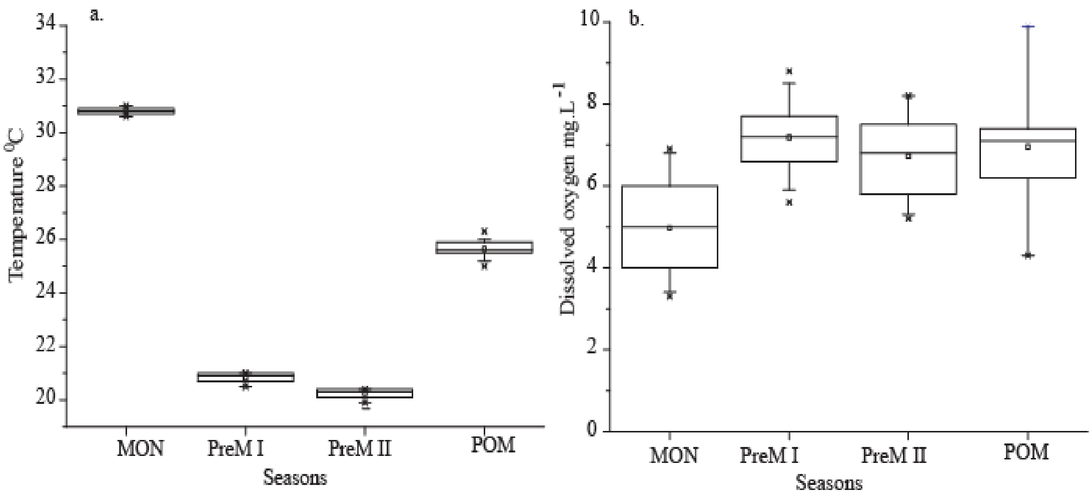


Figure 3.3.1: - Box-plot illustrating the seasonal variation in the a). Temperature and b). Dissolved oxygen during the different seasons at Kolkata port.

The maximum and minimum concentration of phosphate was observed during PreM II (0.2±1.7 µM) and POM (12.5±0.6 µM) and silicate concentration was minimum during MON (3.9±46.3 µM) and maximum during PreM II (477±38.9µM) season. The minimum concentration of ammonia, nitrite and nitrate were observed during PreM II (0.1±2.6), (0.2±1.1 µM) and PreM I (0.2±7.3µM) respectively and the maximum concentration was observed during PreM I (31.7±5.9µM), (9.8±3.0µM) and POM (205±68.1µM) respectively (Supplementary Figure 3.3.7). The multivariate index of tropic state (TRIX) was 2.37 on an average during the study period at Kolkata port, and it indicated good water quality which is highly eutrophic. The TRIX score ranged from 0.24 to 3.77 during all the seasons. The average TRIX scores during MON, PreM I and II and POM was 1.9, 1.6, 1.7 and 1.4 respectively.

3.3.2b Sediment parameters

Sediment composed of sand, silt and clay and their percentage composition varied spatio-temporally within the port. Figure 3.3.2).

Table 3.3.1: - a).Temperature, b). Dissolved oxygen and c). Chlorophyll *a* of bottom water at Kolkata port during different seasons (MON - Monsoon I, PreM I – Pre-monsoon I, Pre-M II–Pre- monsoon II and POM – Post monsoon).

	a. Temperature [°C]				b. D. O. [mg.L^{-1}]				c. Chlorophyll a [mg.m^{-3}]			
Stations	MON	Pre-M I	Pre-M II	POM	MON	Pre-M I	Pre-M II	POM	MON	Pre-M I	Pre-M II	POM
1	30.9	21.0	19.9	25.6	3.5	8.8	5.2	9.9	2.5	4.0	1.6	3.7
2	30.8	21.0	19.9	25.9	3.4	5.6	6.2	7.4	1.9	4.8	3.3	2.4
3	30.8	20.8	20.1	25.8	3.7	6.5	7.6	ND	3.2	6.2	1.2	3.0
4	30.8	20.8	20.1	25.4	3.3	6.7	6.8	ND	5.9	8.9	1.0	4.3
5	30.8	20.7	20.0	25.2	3.7	7.8	6.4	ND	2.8	9.1	1.0	4.2
6	30.8	20.8	20.2	25.6	4.1	6.9	8.2	ND	3.7	4.3	2.1	3.7
7	30.8	20.8	20.1	25.2	4.2	7.2	5.6	4.7	8.1	3.7	1.9	5.6
8	30.7	20.7	20.2	26.3	5.0	7.6	6.8	ND	5.3	4.8	3.5	4.5
9	30.7	20.5	20.3	25.0	4.4	6.6	5.8	ND	5.1	4.7	3.6	6.6
10	30.7	20.6	20.4	25.9	4.0	7.1	6.5	ND	6.7	4.7	4.6	4.5
11	30.6	20.6	20.4	26.0	5.2	7.8	5.3	ND	6.3	7.4	5.5	ND
12	30.6	20.5	20.4	26.0	4.3	7.6	5.8	4.3	6.4	10.2	4.9	3.1
13	ND	20.9	20.3	25.5	6.0	8.0	6.9	7.1	16.0	6.1	1.9	2.3
14	31.0	20.9	20.3	ND	6.6	8.5	8.2	9.1	13.5	4.8	0.9	1.0
15	31.0	20.9	20.3	25.6	6.8	5.9	5.6	ND	24.9	3.7	2.7	1.8
16	31.0	21.0	20.3	25.3	6.9	6.5	6.8	ND	21.1	3.4	0.9	1.7
17	30.8	21.0	20.4	25.6	6.5	7.0	8.2	ND	27.6	4.0	1.5	1.8
18	30.8	21.0	20.4	25.7	5.6	7.2	7.4	6.9	9.0	4.2		
19	30.7	21.0	20.4	25.8	6.2	7.5	8.2	ND	13.0	16.5	3.3	1.3
20	31.0	20.9	20.4	25.6	5.3	7.3	7.5	ND	21.2	9.3	1.6	1.6
21	31.0	21.0	20.4	25.5	6.0	6.2	6.8	6.2	17.5	16.3	1.1	ND
22	ND	21.0	20.4	25.9	4.6	7.7	6.2	ND	10.9	9.3	1.3	1.5

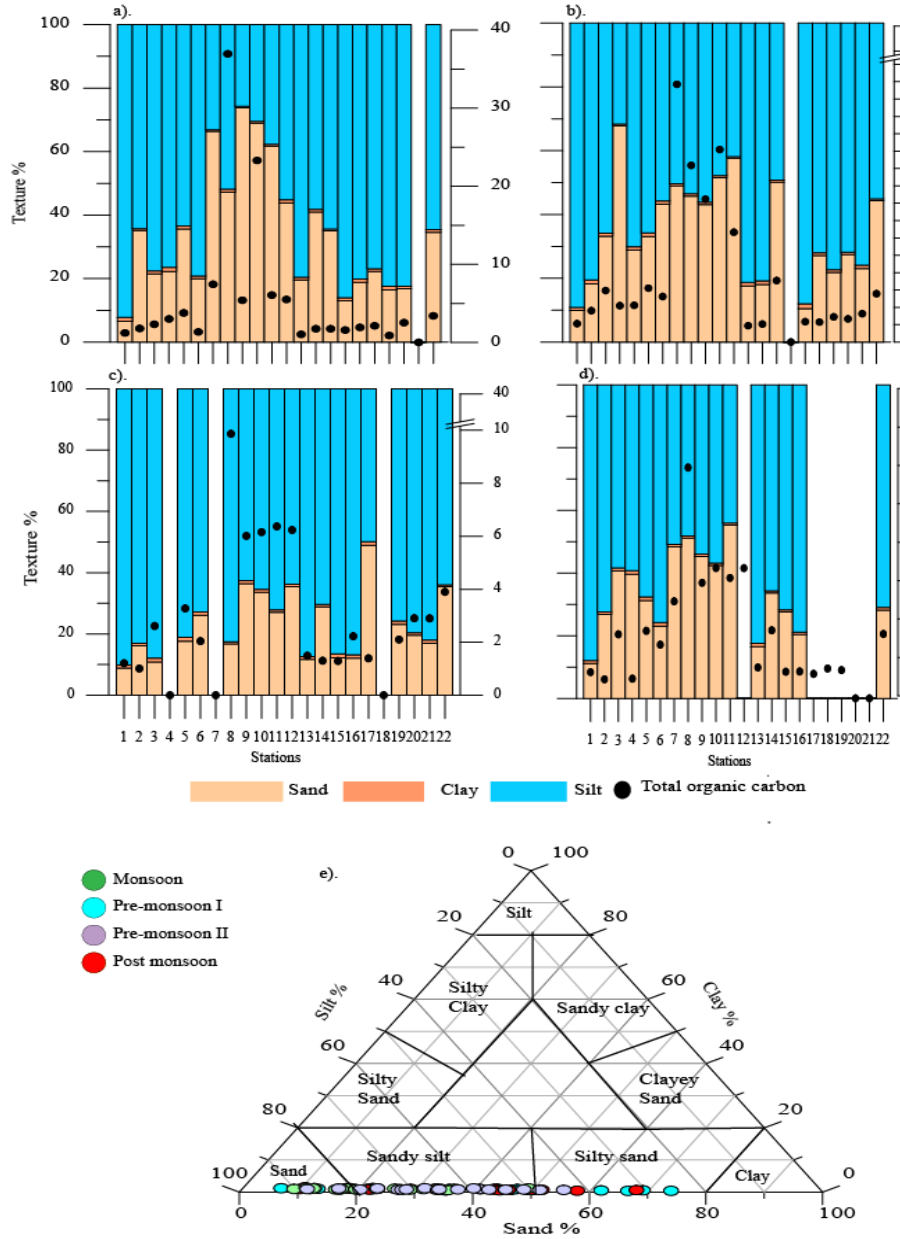


Figure 3.3.2: - Variation in the sediment texture and organic carbon during different seasons (a) Monsoon I (b) Pre-monsoon I (c) Pre-Monsoon II and (d) Post monsoon (e)Ternary plot indicating the changes in the sediment texture at Kolkata port.

In general, silt was the most dominant component 66.8 % (±17.5) followed by sand - 31.0 % (±16.3) and clay - 0.8 % (±0.2) during all the seasons at most of the stations (The percentage of silt in the sediment ranged between 25.7% at S09 to 92.2 % at S01 during monsoon (Figure 3.3.2) and it varied with the stations (One-way ANOVA; *F* = 1.4, df = 3, p = 0.22). Percentage of sand was comparatively less than silt ranging between 6.5% at S01 to 73.8% at S09 during MON. The average percentage of sand was 34%

during MON, PreM I and POM. The percentage composition of sand varied with the seasons (MON - 34.2(±19.8) %, PreM I and II - 34.3(±16.1) % and 23(±11) % and POM = 33.8(±12.9) %) (Figure 3.3.2) and it showed significant spatial variation (One-way ANOVA; F = 2.4, df = 3, p = 0.07). The percentage of clay in the sediment was the lowest and ranged between 0.2(±0.2) % to 1.5(±0.1) % during all the seasons (Figure 3.3.2) (One-way ANOVA; F = 2.4, df = 3, p = 0.07) indicating its negligible contribution to the sediment texture. The minimum and maximum percentage sediment organic carbon was observed at S19 (0.8%) and S08 (36.9%) during MON season, and the average organic carbon content 5.8(±8.7) % was higher during MON (Figure 3.3.2). During PreM I and II and POM the organic carbon content was 3.9(±0.9) %, 3.4(±1.0) % and 3.8(±1.1) % respectively (Figure 3.3.2) and it varied with the stations (One-way ANOVA; F = 0.6, df = 3, p = 0.6).

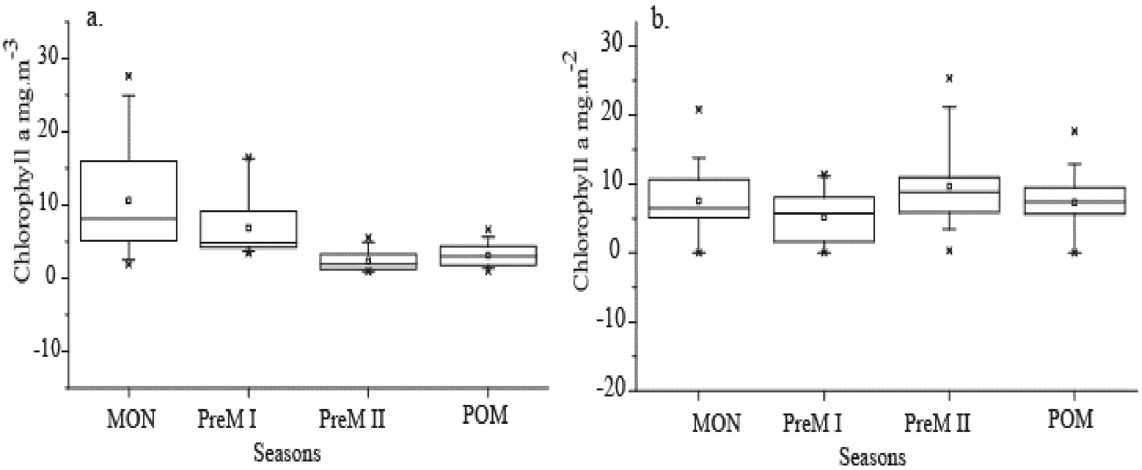


Figure 3.3.3: - Box plot indicating the seasonal changes in the Chlorophyll *a* (a). Bottom water and (b). Sediment content during different seasons.

The chlorophyll *a* concentrations in the near bottom water was higher during MON and in PreM seasons at S-17 (27.6 mg. m^{-3}), and S-19 (16.5 mg. m^{-3}) (Figure 3.3.3a; Table 3.3.1d), whereas the lower concentrations of chlorophyll *a* were observed during PreM II and POM seasons at S14and S16 (0.9 and 1.0 mg. m^{-3} respectively) (Figure 3.3.3a; Table 3.3.1c). The average chlorophyll *a* during MON was 10.6(±7.7) mg. m^{-3}, PreM I 6.8(±3.7) mg. m^{-3}, PreM II 2.4(±1.4) mg. m^{-3} and during POM it was 3.1(±1.5) mg. m^{-3} (Figure 3.3.3a) and it varied with stations (One-way ANOVA; F = 14.84, df = 3, p = $9.02*10^{-8}$) in the near bottom water. The sediment chlorophyll *a* showed a different trend when compared to near bottom water. During MON, PreM I and II, and POM it was 8.29 (±4.4) mg. m^{-2}, 6.2 (±3.1) mg. m^{-2}, 9.6 (±5.9) mg. m^{-2} and 8.0 (±3.8) mg. m^{-2} respectively (Figure 3.3.3b). During POM and PreM II the near bottom chlorophyll *a* concertation was lower compared sediment chlorophyll *a* concentration. The maximum and minimum sediment chlorophyll *a* was observed during PreM II (0.31 mg. m^{-2} and 25.30 mg. m^{-2} respectively) (Figure 3.3.1b) which significantly varied with the stations (One-way ANOVA; F = 1.8, df = 3, p = 0.15).

3.3.2c Seasonal variation in the macrobenthic community

The macrobenthos at Kolkata port during different seasons comprised of Annelida (Polychaeta and Oligochaeta). The Oligochaeta were the most common and abundant macrobenthos taxa during all the seasons. Among the 25 macrobenthic taxa, 19 were oligochaetes contributing more than 90% to the total abundance. Oligochaetes belonging to Naididae and Tubificidae were observed during all the seasons, and they have been identified as the indicator organisms for the river quality and pollution aspects. The abundance of macrobenthos varied with the seasons, and during MON it was 14930 no. m^{-2}, PreM I 4661 no. m^{-2}, PreM II 4010 no. m^{-2} and POM 4382 no. m^{-2} (Table 3.3.2) (One-way ANOVA; F = 11.11, df = 3, p = $3.23*10^{-6}$). During MON season the stations with maximum abundance were S11 (KPD Berth 19) – 1864 no. m^{-2}, S08 (KPD Berth 15) – 1726 no. m^{-2}, and S04 (KPD Berth 06) – 1525 no. m^{-2}, and the minimum abundance was observed at S02 (KPD Tidal basin-2) - 92 no. m^{-2} (Table 3.3.2a). Monsoon showed maximum diversity and abundance of macrobenthic organisms and it varied among the stations (One-way ANOVA; F = 2.4, df = 21, p = 0.002). The most abundant oligochaete was *Heliodrilus* sp. with an abundance of 5190 no. m^{-2} and they were reported at maximum stations except S01, S13, S16, S19 and S21, followed by *Aelosoma* sp., with an abundance of 2447 no. m^{-2}, *Branchiura* sp., 1678 no. m^{-2} and *Drawida* sp. 1355 no. m^{-2} (Table 3.3.2a). During MON season apart from Oligochaeta, the Polychaeta, *Nephtys* sp. 259 no. m^{-2} and *Nephtys oligobranchia* 46 no. m^{-2} were observed (Figure 3.3.4; Table 3.3.2a).

During PreM I, the maximum abundance was observed at S15 (NSD Berth 13) – 817 no. m^{-2}, followed by S07 (KPD berth 11) – 709 no. m^{-2}, and S01 (KPD tidal basin 1) - 463 no. m^{-2} (Table 3.3.2). During, PreM I, the most abundant macrobenthos was *Heliodrilus* sp. (693 no. m^{-2}) and was found at stations, S01, S02, S03, S06, S07, S08, S15, S21 and S22.

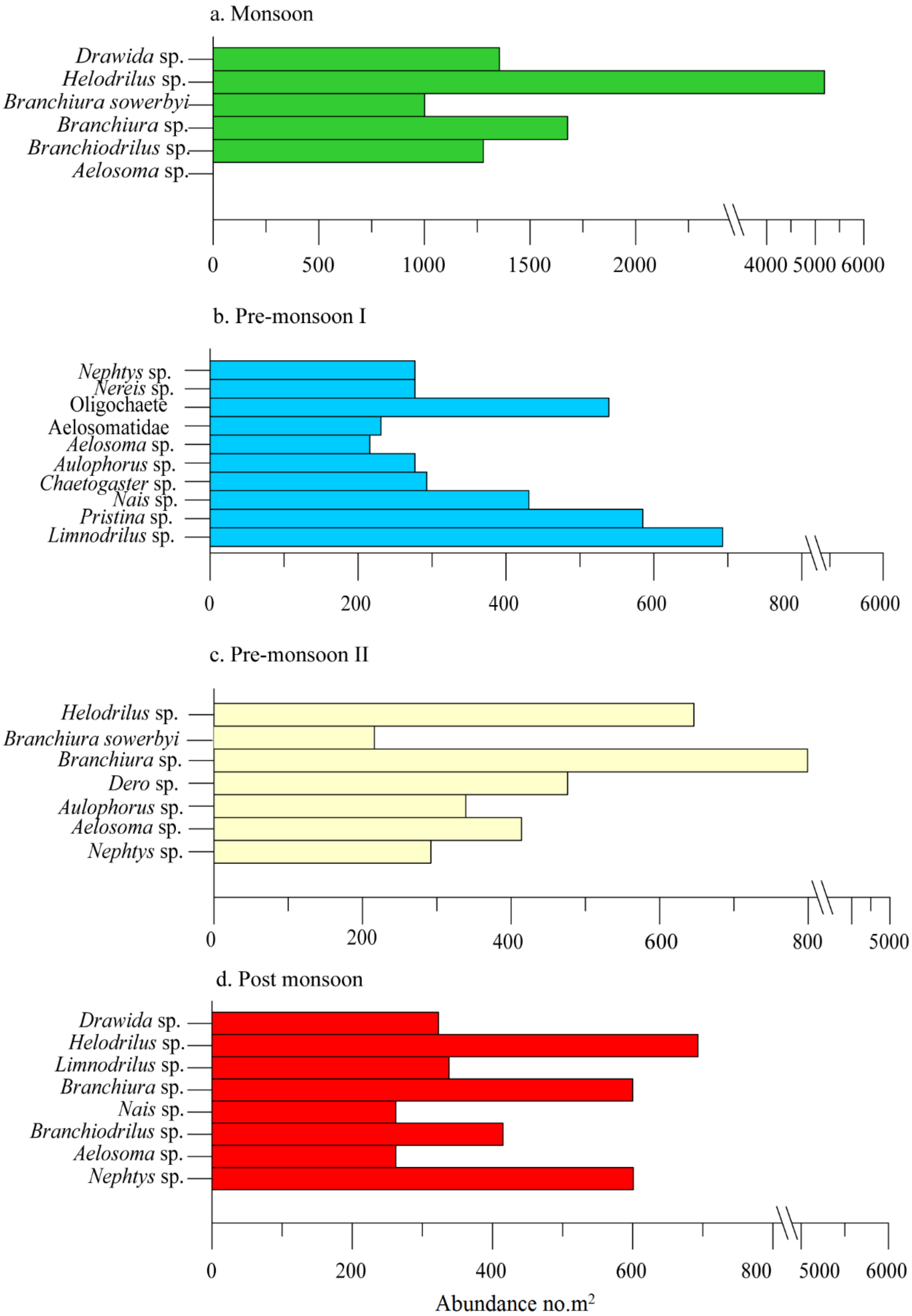


Figure 3.3.4: Bar-chart showing the variations in the dominant taxa during different seasons (a) Monsoon I (b) Pre-monsoon I (c) Pre-Monsoon II and (d) Post monsoon at Kolkata port.

Table 3.3.2. Variation in the abundance of macrobenthos in Kolkata port during different seasons.

Table 3.3.2a. Abundance (no.m^{-2}) of macrobenthos in Kolkata port during Monsoon season.

Fauna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Helodrilus sp.		31	231	1063	416	662	46	1140	108	447	262	77		231	123		123	15		169		46	5190
Aelosoma sp.	77		169	323	15	246		293		31	231	139		201	123		46	169			292	92	2447
Branchiura sp.											446	293			169	15		77	108		308	262	1678
Drawida sp.			231		169	370		108			108		77	185		77			15			15	1355
Branchiodrilus sp.					46			108		46	447	108	231	185	31							77	1279
Branchiura sowerbyi	15	46	108	139			231			31		46	139		77			15			108	46	1001
Chaetogaster sp.								77			262		123			77			185				724
Nephtys sp.	15	15									31	15	15	15	46			15	15		46	31	259
Capitella sp.												31		15			77	15				77	215
Nais sp.													77			108			15		15		215
Dero sp.													15			15		169					199
Aulophorus sp.													31			46			46				123
Stylaria sp.													15				15					62	92
Perionyx sp.											77												77
Nephtys oligobranchia													46										46
Limnodrilus sp.																			15				15
Eutyphoeus sp.													15										15

Table 3.3.2b. Abundance (no.m^{-2}) of macrobenthos in Kolkata port during Pre-monsoon I season.

Fauna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Helodrilus sp.	139	15	46			15	77	31							231						108	31	693
Branchiura sowerbyi	31		77				31				15	92			108				31		123	77	585
Aulophorus sp.	46	31		15			31		15		108	62			77		31			77		46	539
Branchiura *sp*.		62									15		77					169		108			431
Stylaria sp.	77						62							77								77	293
Nephtys sp.	31		15			15	77	31					77									31	277
Aelosoma sp.	31	46	31			15	108				15											31	277
Nais sp.	108	15												46	108								277
Branchiodrilus sp.		62				31							15	15	108								231
Chaetogaster sp.							139	46														31	216
Nephtys oligobranchia							46						15	15	46			62				15	199
Limnodrilus sp.								15	31						62				15			46	169
Eutyphoeus sp.							92																92
Capitella sp.																					77		77
Dero sp.		15							31						31								77
Pristina sp.							46		15						15								76
Drawida sp.								15							31						15		61
Pheretima sp.																					46		46
Dendroneries sp.																						15	15
Namalycastis sp.								15															15
Perionyx sp.												15											15

Table 3.3.2c. Abundance (no.m^{-2}) of macrobenthos in Kolkata port during Pre-monsoon II season.

Faunal Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Branchiura sp.	31		400			138				62			15				15				138		799
Helodrilus sp.	77		108													46					415		646
Dero sp.			138			77		15					15									231	476
Aelosoma sp.	46		123			31		15					46				15			15	123		414
Aulophorus sp.						31		92					31			62				46	77		339
Nephtys sp.			77					31					46								138		292
Branchiura sowerbyi			108														62				46		216
Nais sp.			169																	15			184
Pristina sp.																						169	169
Branchiodrilus sp.																		15			138		153
Nephtys oligobranchia			31										15								77	15	138
Chaetogaster sp.								31										15					46
Limnodrilus sp.																					46		46
Naididae										31													31
Pheretima sp.			31																				31
Namalycastis sp.													15								15		30

Table 3.3.2d. Abundance (no.m^{-2}) of macrobenthos in Kolkata port during Post monsoon season.

Faunal Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Helodrilus sp.			169		293		31					31	169										693
Nephtys sp.	31	108			62				62			46	31	154		15			92				601
Branchiura sp.	46			169			139	77			123							31				15	600
Branchiodrilus sp.	15		108	77	46		46					46	77										415
Limnodrilus sp.		15		92				62						15		31						123	338
Drawida sp.					123																15	185	323
Aelosoma sp.	139	77			31																15		262
Nais sp.					77				46										139				262
Stylaria sp.			31				15	108	15														169
Pristina sp.													77		15				46		15	15	168
Dero sp.			77				15														46		138
Nephtys oligobranchia		77							15										15				107
Capitella sp.	15						15					31			15						15		91
Aulophorus sp.	31						31						15										77
Branchiura sowerbyi		46						31															77
Nereis sp.														31									31
Dendroneries sp.																			15				15
Namalycastis sp.																			15				15

In PreM II, the maximum abundance of macrobenthos was observed at S21 (NSD ship breaking) - 1213 no. m^{-2}, S03 (KPD berth 3) - 1185 no. m^{-2} and S22 (NSD Dolphin mooring 2) - 415 no. m^{-2}. Macrobenthos were reported at stations - S02, S04, S05, S07, S09, S11, S12, S14, S15 and S19 (Figure 3.3.4). During PreM II, apart from Oligochaeta, Polychaeta belonging to family Nephytidae, *Nephtys* sp. (292 no. m^{-2}), *Nephtys oligobranchia* (138 no. m^{-2}) were observed. During this season the most abundant macrobenthos was *Branchiura sowerbyi* and its abundance was 799 no. m^{-2} followed by *Heliodrilus* sp. – 646 no. m^{-2} and *Aulophorus* sp. 339 no. m^{-2} (ANOVA; F = .6, df = 21, p = .84). During POM season higher abundance of macrobenthos was reported at S05 (KPD berth 7) – 632 no. m^{-2}, S03 - 385 no. m^{-2} and S13 (NSD berth 1&14) - 369 no. m^{-2} (Figure 3.3.4; Table 3.3.2d). The fresh water tolerant polychaetes belonging to family Nephtyidae and Capitellidae, *Capitella* sp. - 99 no. m^{-2}, *Nephtys* sp. - 601 no. m^{-2} and *Nephtys oligobranchia* - 107 no. m^{-2} were reported. The other forms observed during this season were *Branchiodrilus* sp. - 415 no. m^{-2}, *Branchiura* sp. - 600 no. m^{-2} and *Heliodrilus* sp. - 693 no. m^{-2} (Figure 3.3.4d) (ANOVA; F = .8, df = 21, p = .6). Except monsoon, during other seasons low abundance of macrobenthos was observed, and this can attributed to wide variation in the temperature during Pre- and Post-monsoon seasons.

3.3.2d Variations in the diversity of macrobenthos

Species diversity indices at all the stations were estimated based on Margalef species richness (d), Shannon-Weiner index (H′) and evenness (J′). The maximum number of species were encountered during MON season and the correspondence values of the Shannon–Weiner index (H′) during MON, PreM I, PreM II and POM were 1.9, 2.2, 2.2 and 1.9 respectively (Table 3.3.3). Monsoon showed maximum abundance (14930 no. m^{-2}) of macrobenthos compared to other three seasons namely PreM I, PreM II and POM with an abundance of 4661 no.m^{-2}, 4010 no.m^{-2} and 4382 no.m^{-2} respectively (Table 3.3.2). Station-wise similarity was interpreted at 50% level using Bray-Curtis similarity index, each seasons showing the similarity among the stations in groups. Monsoon season indicated five groups, which had maximum abundance compared to other seasons (Figure 3.3.5a). Group I with stations (S13, S16 and S19) located in Netaji Subhas dock had an average similarity of 42.8% and the macrofauna *Chaetogaster* sp., *Aulophorus* sp., *Nais* sp. and *Drawida* sp. contributed to the abundance at these stations.

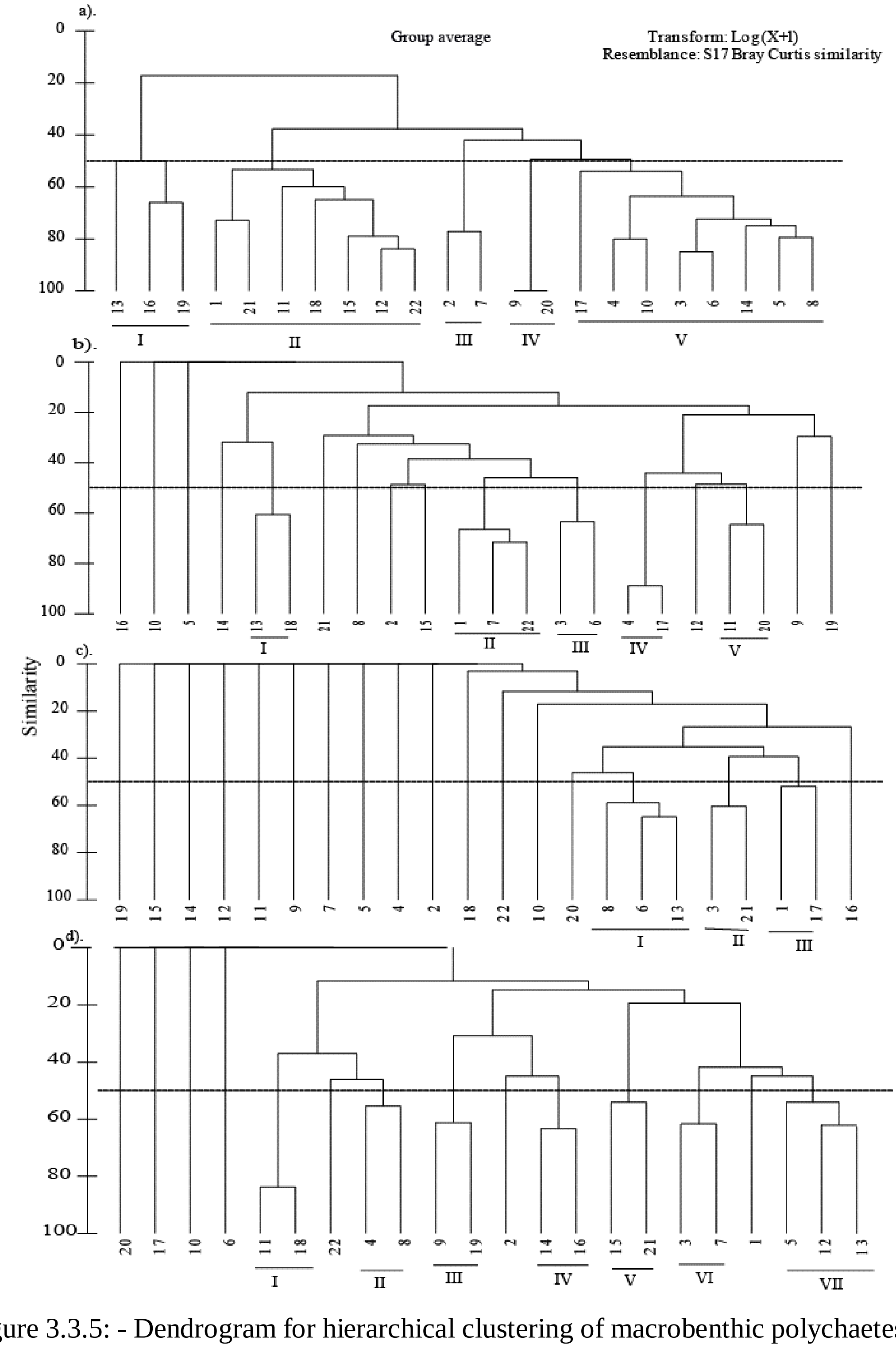


Figure 3.3.5: - Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons (a) Monsoon I (b) Pre-monsoon I (c) Pre-Monsoon II and (d) Post monsoon. Stations are grouped with respect to their similarity.

Group II (S01, S11, S12, S15 S18, S21 and S22) stations had an average similarity of 44.3% among the stations and the macrobenthic organisms found were *Aelosoma* sp., *Branchiura* sp., *Branchiura sowerbyi*, *Helodrilus* sp. and a polychaeta *Nephtys* sp. (Figure 3.3.5a). Group II (S02 and S07) and group IV (S09 and S 20) had two stations each with an average similarity of 41.7% and 78%, and the macrobenthos, *Branchiura* sp., and *Helodrilus* sp. were commonly observed at both these stations. In Group V, stations S03, S04, S05, S06, S08, S10, S14 and S17 were clustered together which are in general located in Kidderpore dock except S14 and S17, with a similarity of 41.7%.

The commonly observed macrofauna in this group were *Helodrilus* sp., *Aelosoma* sp. and *Drawida* sp. During PreM I season, stations were clustered in five groups and 11 stations did not cluster with other stations to form the group, and had second highest abundance compared to other seasons, and the stations among the two docks formed the groups. Group I (S13 and S18) located in Netaji Subhas dock had an average similarity of 44.3% and the contributing macrobenthos were *Branchiura* sp. and *Nephtys oligobranchia* respectively (Figure 3.3.5a). Group II (S01, S07and S22) stations had the average similarity of 49.9% among the stations with macrobenthos *Stylaria* sp., *Aulophorus* sp., *Branchiura sowerbyi*, *Helodrilus* sp., *Aelosoma* sp. and *Nephtys* sp. as the dominant organisms.

Group III (S03 and S06), group IV (S04 and S17) and Group V (S11 and S11 and S20) all had two stations grouped together with a similarity of 36.7%, 65.2% and 54.4% respectively, and the dominant and most common organisms observed among these stations were *Branchiura* sp., *Aelosoma* sp., *Aulophorus* sp. and *Helodrilus* sp. (Figure 3.3.5b). At the non-grouped stations are S05, S10 and S16 macrobenthic fauna were not reported (Table 3.3.2, Figure 3.3.5b). Pre-monsoon II season which had the least abundance of macrobenthos showed three groups in the clustering of stations (Figure 3.3.5c). Group I with stations (S06, S08 and S13) located in KPD dock had an average similarity of 38.8% and the contributing macrofauna were *Aulophorus* sp., *Aelosoma* sp., *Dero* sp. and *Nephtys* sp. Group II stations (S03 and S21) had the average similarity of 43.6% among the stations and the macrobenthic organisms common to these stations were *Aelosoma* sp., *Branchiura sowerbyi*, *Helodrilus* sp., *Branchiura* sp. and *Nephtys* sp. respectively. Group III (S01, S16 and S17) had low average similarity (19.8%), and the common organisms observed at these stations were *Branchiura* sp., *Aelosoma* sp. and *Helodrilus* sp. The non-clustered stations in this season are S02, S04, S05, S09, S11S12, S14 S15 and S19 are also without any macrobenthic fauna found during this period (Table 3.3.2c; Figure 3.3.5c).

During POM, similarity among the stations resulted in six groups. Group I (S11 and S18) and II (S04, S08 and S22) showed similarity of 40.2% and 33.9%. The taxa found among them were *Branchiura* sp. in group I and this species along with *Limnodrilus* sp., in group II. *Nephtys* sp., *Nephtys oligobranchia* and *Nais* sp. represented group III with an average similarity of 53.4%. In group IV, stations, S14 and S16 from NSD dock had a similarity of 24.3% and the macrobenthos *Nephtys* sp. and *Limnodrilus* sp. (Figure 3.3.5d) contributed to this group. Group V (S15 and S21), group VI (S03 and S07) and group VII (S05, S12 and S13) had an average similarity of 44.1%, 31.6% and 40.6% respectively. Except group V, the stations of group VI and VII are located in the KPD dock and had commonly occurring organisms such as *Branchiodrilus* sp., *Helodrilus* sp., *Dero* sp. and *Stylaria* sp. at group VI stations. In group VII, the contributing organisms are *Branchiodrilus* sp., *Helodrilus* sp. and *Nephtys* sp. The stations that are not grouped under the Bay-Curtis similarity are S06, S10, S17 and S20 and these stations are empty stations without any macrobenthos (Table 3.3.2d; Figure 3.3.5d).

The CCA analysis of the study showed that sediment characteristics along with organic carbon and dissolved oxygen play an important role in the community structure of macrobenthic organisms during different seasons. Length of gradient value >2 was observed during all the seasons (Figure 3.3.6). Monsoon season represented by higher abundance of macrobenthic fauna, and the environmental parameters such as near bottom water nutrients, chlorophyll *a*, dissolved oxygen and organic carbon influenced the species richness and their abundance (Figure 3.3.6a). The Annelids reported were mostly the indicator organisms of pollution owing to the anthropogenic activities occurring in this fresh water port. During MON season, *Branchiura* sp., *Helodrilus* sp., and *Aelosoma* sp. were positively influenced by sand, organic carbon and bottom water nutrients, and they could survive in low DO and chlorophyll *a* conditions. The macrobenthos such as *Chaetogaster* sp., *Eutyphoeus* sp., *Aulophorus* sp., *Nais* sp., *Dero* sp. and *Nephtys* sp. were supported by silty-clay sediment with medium to high amount of DO and chlorophyll *a* (Figure 3.3.6a).

Table 3.3.3. Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou's evenness (J′) and Shannon index (H), of macrobenthic polychaetes during different seasons at Kolkata port.

Monsoon						Pre monsoon I					Pre monsoon II					Post monsoon				
Sample	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)
1	3	100	.43	.72	.79	7	28	1.80	.99	1.94	3	12	.81	1.00	1.09	6	21	1.64	.99	1.77
2	3	100	.43	.92	1.01	7	24	1.89	.99	1.93			****	****	.00	5	20	1.34	.99	1.59
3	4	100	.65	.97	1.35	4	14	1.12	.99	1.37	9	42	2.15	.99	2.18	4	18	1.05	.99	1.38
4	3	100	.43	.73	.80	1	3	.00	****	.00			****	****	.00	3	14	.76	1.00	1.10
5	4	100	.65	.66	.91			****	****	.00			****	****	.00	6	26	1.53	.99	1.78
6	3	100	.43	.93	1.02	4	12	1.22	1.00	1.38	4	16	1.08	.99	1.38			****	****	.00
7	2	100	.22	.65	.45	10	42	2.41	1.00	2.30			****	****	.00	7	24	1.89	.99	1.92
8	5	100	.87	.66	1.06	6	19	1.70	.99	1.78	5	17	1.41	.99	1.59	4	17	1.07	1.00	1.38
9	1	100	.00	****	.00	4	12	1.19	1.00	1.38			****	****	.00	4	14	1.15	.99	1.37
10	4	100	.65	.51	.70			****	****	.00	2	8	.49	.99	.69			****	****	.00
11	8	100	1.52	.89	1.86	4	13	1.17	.98	1.36			****	****	.00	1	5	.00	****	.00
12	7	100	1.30	.83	1.61	3	11	.82	.98	1.08			****	****	.00	4	15	1.12	1.00	1.39
13	11	100	2.17	.84	2.01	4	14	1.13	.98	1.36	7	22	1.93	.99	1.94	5	20	1.33	.99	1.59
14	6	100	1.09	.84	1.51	4	14	1.15	.99	1.37			****	****	.00	3	11	.83	.97	1.07
15	6	100	1.09	.92	1.66	10	42	2.41	.99	2.29			****	****	.00	2	6	.58	1.00	.69
16	6	100	1.09	.89	1.59			****	****	.00	2	8	.48	1.00	.69	2	6	.55	.99	.69
17	4	100	.65	.85	1.19	1	3	.00	****	.00	3	10	.88	.98	1.08			****	****	.00
18	7	100	1.30	.75	1.47	2	9	.45	.99	.69	2	6	.58	1.00	.69	1	3	.00	****	.00
19	7	100	1.30	.75	1.45	2	6	.55	.99	.69			****	****	.00	6	22	1.63	.98	1.76
20	1	100	.00	****	.00	2	9	.45	1.00	.69	3	9	.89	.99	1.09			****	****	.00
21	5	100	.87	.78	1.26	5	20	1.33	.99	1.59	10	45	2.37	.99	2.29	5	15	1.48	.99	1.60
22	9	100	1.74	.87	1.90	10	36	2.52	1.00	2.29	3	13	.77	.96	1.06	4	16	1.09	.97	1.34

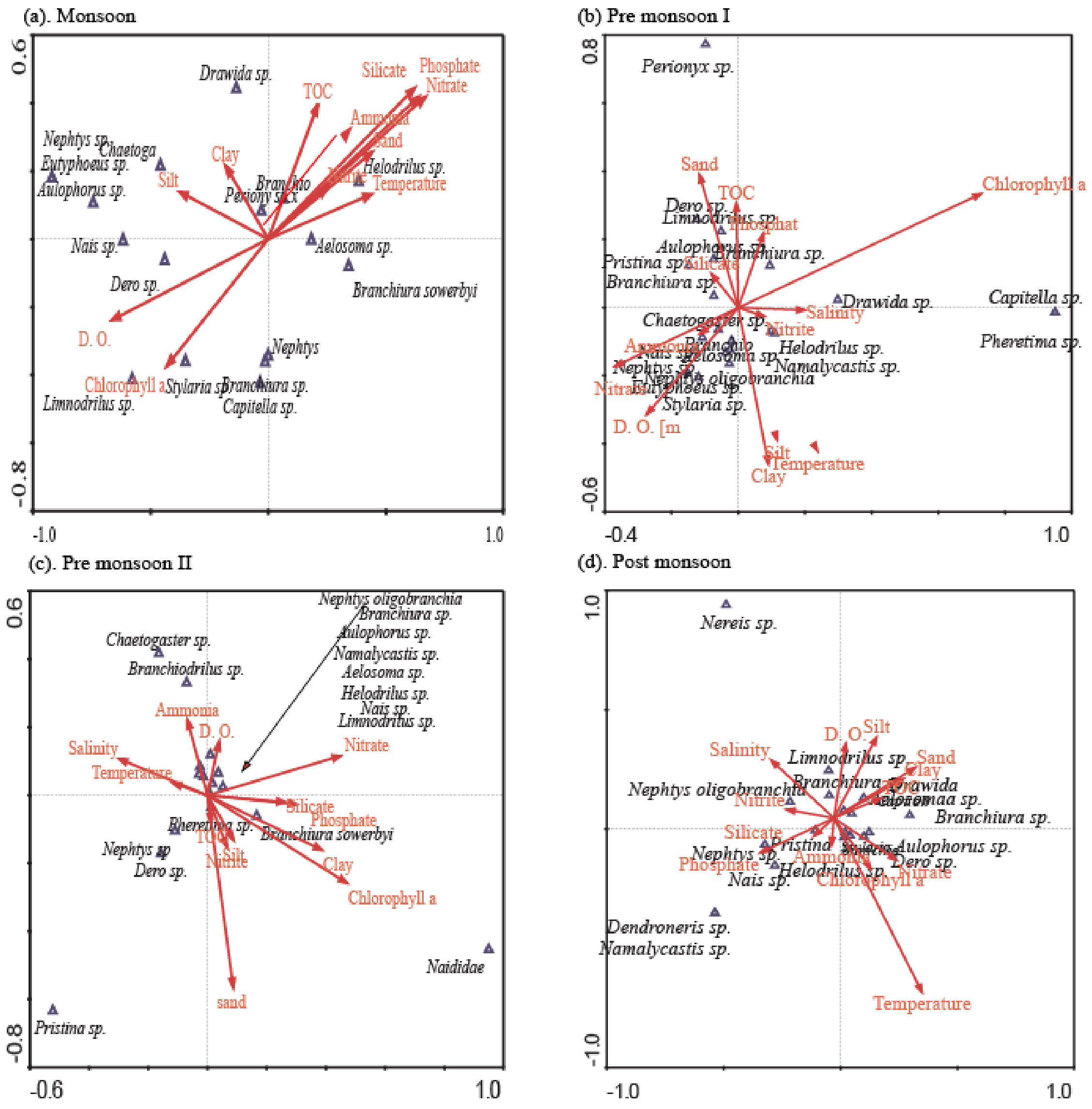


Figure 3.3.6: CCA plots to illustrate the correlation between environmental parameters and species diversity during different seasons (a) Monsoon I (b) Pre-monsoon I (c) Pre-Monsoon II and (d) Post monsoon) at Kolkata port.

During PreM I, sand, organic carbon, silicate in high concentrations along with low to medium concentrations of ammonia, nitrate and DO influenced the macrofauna, *Dero* sp., *Aulophorus* sp., *Limnodrilus* sp., *Branchiura* sp. and *Pristina* sp. respectively (Figure 3.3.6b). As observed during MON season, *Nephtys* sp., *Nephtys oligobranchia*, *Aelosoma* sp., *Chaetogaster* sp., *Nais* sp., and *Dendroneris* sp. survived in silty-clay (Figure 3.3.2e) sediments and DO along with low sediment organic carbon. During PreM II, *Nephtys* sp., *Dero* sp., *Pheretima* sp. were dominant and were positively influenced by silty-sand sediment (Figure 3.3.2e) with medium concentrations of nitrite and organic carbon, low concentrations of DO, ammonia and lower temperature. *Branchiura* sp., *Nais* sp., *Limnodrilu*s sp., *Aulophoru*s sp. and *Aelosoma* sp. require high temperature and DO with medium and low contents of organic carbon and nitrite (Figure 3.3.6c). During POM season, sandy-silt (Figure 3.3.2e) along with high DO and organic carbon is required for *Branchiura* sp., *Aelosoma* sp., *Drawida* sp., *Limnodrilus* sp., and *Aulophorus* sp. The macrobenthos such as *Nephtys* sp. and *Nais* sp., *Dendroneris* sp., and *Namalycastis* sp. require phosphate and ammonia along with low DO and silty-sand sediment (Figure 3.3.6d).

3.3.3 Discussion

Rich biodiversity in the tropical regions are vanishing due to over-exploitation and habitat destruction, and this is also observed in aquatic ecosystems due to the development that resulted in pollution of aquatic environment (Sanjeeva Raj, 1995). To understand the environment and to establish a database for the future studies, grasping the knowledge of aquatic organisms along with their distribution, community structure and the physio-chemical parameters of an environment is important (Warwick and Ruswahyuni, 1987). Benthic organisms which live within the sediment are an important component of the benthic habitat and of the aquatic ecosystem. Since these are sessile or sedentary in nature the impact of changing environment is mostly seen in these organisms. They are ubiquitous to all the aquatic ecosystem such as lakes, rivers and estuaries, coastal and deep ocean environments. Hooghly estuarine system is one of the largest estuarine ecosystems in the world that form 'River delta estuary' (Mandal et al, 2012) and Kolkata port is located on the banks of the Hooghly river. Water quality signifies the quality of water and its components along with the drainage and catchment basin (Lothspeich, 1980; Verdonschot, 1989). To understand the survival of a community, it is important to understand the organisms and the complex of various factors involving their survival in a habitat (Verdonschot, 1989). The present study at the Kolkata port is to understand the macrobenthos abundance, their community structure along with the changes in different environmental and sediment characteristics indicated that the distribution and community structure of macrobenthic organisms is highly influenced by these factors. At this port the bottom water temperature is considered as one of the limiting factors (Barnes 1980; Nicolaidou et al. 1988; Lamptey and Aramah, 2008), since there is a wide variation in the temperature at Kolkata port, which is up to 10°C during the winter months of November to February, and this affects the abundance in macrobenthic organisms. The Kolkata port exhibited fresh water characteristics, and the average bottom water temperature during the MON season was 30.8 °C and during other seasons (POM, PreM I and PreM II) the average temperature was 20 to 24°C, and this impacted the occurrence of macrobenthic organisms. In Kolkata port the abundance of the macrobenthic fauna reduced comparatively during winter months (Post monsoon and early pre-monsoon seasons) but during the optimal temperature of 30°C during monsoon season the abundance was high. Cold temperatures on the surface and sub-surface sediments leads to the death or reduction in the abundance in the benthic deposit feeders (Pearson and Rosenberg, 1978), and at Kolkata port benthic deposit feeders (Oligochaetes) dominated the sediment column followed by fresh water tolerant carnivorous polychaetes (Nereididae and Nephtyidae) (Table 3.3.2). During monsoon season the diversity and abundance was high and during non-monsoon months the abundance of macrobenthos was low (Table 3.3.2). As suggested by Reid and Wood, (1976) one of the determining factor in variations in dissolved oxygen is the temperature and dissolved oxygen is an important component for the macrobenthic organisms that are living in the aquatic ecosystems, as they alter the water quality index, trophodynamics and the metabolic activities of the organisms (Hull et al, 2000). In Kolkata port, DO was comparatively low during monsoon and it was high during non-monsoon seasons. Oligochaetes are sedentary organisms those lack movement and this halts them from escaping the habitat during environmental stress, and this makes them useful as bio indicators (Odigie and Osimen, 2019). Due to their less motility and are mostly deposit feeders these organisms are already observed in high organic carbon sediments and they can be used as indicator organisms for organic pollution (Rashid and Pandit, 2014). Due to increase in sunlight transparency leading to primary productivity leads to increase in DO as observed by Mandal et al, (2012) along the creeks of Hooghly estuary, this was observed during MON season at Kolkata port. The TRIX analysis of Kolkata port was 2.4 indicating good quality of water (<4 good quality) (Vollenweider et al, 1998) and healthy bottom water conditions. The TRIX score during MON was 2.3, PreM I, II was 2.9, 2.4 and POM was 3.29 respectively.

Kolkata port is connected to the Hooghly River with an inlet connecting them, and the disturbance to the sediment characteristics was minimum both spatially and temporally. Distribution of macrobenthic organisms and their community structure depends mostly on benthic environment and highly controlled by the sediment characteristics, its quality, penetrability, erosion control and the water content present in the sediment (Sanders, 1958; Ingole, 1998; Jayaraj et al, 2008; Musale et al, 2015). Sasamal, (1986) observed that sediment texture in the Hooghly river are mostly dominated by silt followed by sand and clay was negligible, and this also coincides with the sediment characteristics observed in the Kolkata port during the study. High silt content found in these ports may be associated with the settlement of fine particles due to sedimentation and weak water movements (Joy et al., 1990; Menon et al., 2000). Even though silt was dominant followed by sand, variations in their percentage among the stations led to settlement of specific macrobenthic communities spatially within the port. High silt content is mainly resulted due to the settlement of decomposable organic particles which influence the population of macrobenthos especially the deposit feeders (Sanders, 1958, 1968; Sanders et al., 1962; Jayaraj et al., 2008), and this was very well observed at Kolkata port. The dominance of silt was due to the sedimentation process of fine silt particles settling at the bottom due to low water movement (Joy et al., 1990). The overall average of organic carbon at Kolkata port was high (<6%) and in most of the stations it was above 10%. The increase in the organic carbon may be a resultant of the input of riverine runoff, sediment texture, high deposition rate of organic material and primary productivity leading to environmental deterioration and reduction in the diversity of macrobenthos (Muraleedharan and Ramachandran, 2002; Martin et al., 2011). Increase in the organic carbon among the stations may lead to the decrease in the abundance and biodiversity of benthic fauna and this may lead to the dominance of indicator species, and this is also a sign of environmental degradation (Pearson and Rosenberg, 1978; Martin et al., 2011; Desai et al 2020). Organic carbon distribution among the stations within port was different, and this may be due to its dependence on sediment grain size as finer grain size sediments possess higher organic carbon (Valdés et al., 2005; Rodríguez-Barroso et al., 2010; Paneer Selvam et al., 2012; Velayudham et al. 2020) and this was observed at the Kolkata port, increase in the percentage of silt resulting in higher organic carbon content. Previous studies on the Hooghly River by Sasamal, 1986 also reported high organic matter (4.6 to 7.1 mg. g^{-1}). Due to the increase of organic carbon in the sediments may lead to organic carbon related stress in the Kolkata port stations (Figure 3.3.4).

The macrobenthic organisms at Kolkata port varied in their abundance and species diversity along with the variations in the environmental parameters and the community was dominated by fresh water dwelling oligochaetes and fresh water tolerant polychaetes belonging to the family Nereidae and Nephytidae, indicating that the sediment at the Kolkata port supported the oligochaetes and few fresh water tolerant polychaetes. The most commonly found families were Tubificidae, which are aquatic sludge worms known for being environmental indicators related to organic pollution, and low oxygen levels (Plisko, 2013; Odigie and Osimen, 2018). Family Naididae, which live among the benthic macrophytes (Odigie and Osimen, 2018). Aelosomatidae, which are viewed as important forms in the benthic ecology as they accelerate nitrogen loss in the sandy riverine sediments (Odigie and Osimen, 2018). During the study seasonal variation in the diversity of macrobenthos was minimum, however, there was drastic seasonal variation in their abundance. During MON season, with an increase in temperature the abundance and diversity of macrobenthos peaked at Kolkata port, however, during POM and PreM the reduction in the temperature by nearly 10°C lead to substantial decrease in the abundance. *Helodrilus* sp. is observed during all the seasons and it is one of the most dominant taxon found at Kolkata port, they are reported at the stations with high percentage of sediment organic carbon and bottom water nutrients. As observed by Angyal et al, (2014), these organisms live in banks of the streams and caves, due to their quick maturity to adulthood and short life cycle, however studies on these organisms are limited. Daniel et al (1975), has reported that *Helodrilus* sp. is one of the commonly found taxon in Hooghly River. The taxa which were commonly observed were *Branchiura sowerbyi*, one of the most abundant fresh water oligochaeta reported all over the world except Antarctica (Caroll and Dorris, 1972; Milbrink, 1980; Bazzanti, 1983), and these organisms have been observed in lower temperature without reproductive functions at low temperatures and also survive in oxygen deficient conditions. In the present study, *Branchiura* sp. is observed during all the seasons and wide variations in the physio-chemical and organic carbon. The other commonly found macrobenthos was *Limnodrilus* sp. and these are reported mainly in heavily polluted waters, along with high organic effluents and unchecked by predators leading to their increase in abundance (Aston, 1973). In the present study *Limnodrilus* sp. is associated with high concentration of chlorophyll *a*, OC and dissolved oxygen with silty sand sediment. This species is a soft substrate dwelling worm and they bury their anterior appendage and rest their body in water, and are reported along with *Branchiura sowerbyi*, *Aulodrilus* sp., *Branchiodrilus* sp. and *Dero* sp. (Naidu, 1962). *Nais* sp. and *Aelosoma* sp. prefer silty sediments rich in organic matter which is ideal for the survival of these organisms (Mir and Yousuf, 2003). During monsoon season these two groups can survive with low concentration of chlorophyll a and DO with moderate temperature and in low temperature (winter months) they were observed along with high concentrations of Chlorophyll a and DO (Figure 3.3.6). The macrobenthic community is often influenced by substrate type, organic matter, aquatic plants and the calcium concentration in the sediment (Qadri and Yousuf, 2004). *Dero* sp. reported by Joyce and Catherine, (2018) has observed that these organisms live in silty and clayey sediment with abundant organic carbon since they are deposit feeders, and this coincides with the current study. Among the fresh water polychaetes, Pramanik et al. (2009) has recorded *Nephtys oligobranchia* from Bangladesh, in Indian water of Ganges, and Mishra, 1999 had reported from West Bengal. The *Dendroneris* sp. has been reported from the wetlands, rivers and estuaries of West Bengal (Chandra and Chakraborty, 2008; Das et al, 2009; Khan, 2003; Misra 1999; Mitra and Misra, 2010, Nesemann et al, 2007; Paul and Nandi, 2003) and they are fresh water tolerant organisms. The TRIX score indicated that the bottom water quality is good, however, owing to low temperature during winter months along with high organic carbon content the diversity of macrobenthos at Kolkata port is restricted to oligochaetes, which are indicator species for anthropogenic activities. Studies carried out in Hooghly river reported various macrobenthic taxa belonging to Molluscs (Majhi et al. 2018), Nematoda, Polychaeta, Harpacticoida, Ostracoda, Turbellaria (Ansari, 1982). The present study shows that due to various anthropogenic and natural factors the sediments of Kolkata port is restricted to only Annelids leading to low diversity.

Chapter 3.4.

Spatio-temporal variation in the macrobenthic community structure and the factors influencing the macrobenthic diversity in Paradip port.

3.4.1 Introduction

Paradip port is a major port along the east coast of India in the state of Odisha. The port is influenced by the south–west monsoon (June–September) and receives 75–80% of rainfall during these months, and remaining during the northeast monsoon (October–December). On the east coast, this port manages a large amount of trade of the country. Even though this is a natural deep water port, artificial bunds (breakwaters) were built to reduce the severe wave intensity in the port; thus it resembles an artificial lagoon. The breakwaters are: (1) south break- water with a length of 1217 m and (2) north breakwater with a length of 538 m. It is a major port that handles various cargo such as crude oil, petroleum, oil and lubricants (POL), iron ore, thermal coal, chrome ore, coking coal, manganese and other ores, fertilizer raw materials and containers, etc. Observations were carried out on four occasions covering different seasons.

3.4.2 Results

3.4.2a Environmental Parameters

Variations in environmental parameters such as temperature, salinity and dissolved oxygen, are presented in Figure 3.4.1. The average near bottom seawater temperature during MON I and MON II was 28.9(±0.09) C and 29.7 (±0.45) ˚C, and overall range during POM and PreM were 26.2(±0.6) ˚C and 27.7(±0.1) ˚C respectively. The salinity of near bottom seawater during MON I and II was 26.5(±0.7) and 30.2(±1.4), during POM 32.1(±0.5) and 33.9(±0.04) during PreM (Figure 3.4.1). The DO of near bottom water during POM was 4.5 (±0.9) mg. l^{-1} and 3.9(±0.3) mg. l^{-1} during PreM season, in MON I and II it was 4.5(±0.9) mg. l^{-1} and 4.0(±0.6) mg. l^{-1} respectively (Figure 3.4.1). The concentration of bottom water nutrients varied with the seasons and stations during the study (Appendix Figure 3.4.1). The tidal range was 0.2 to 3.5 m and the maximum wave height was 5.3 m. The multivariate index of tropic state (TRIX) is analysed for the bottom water during the study and the overall average was 1.8 (±0.8) indicating very good water quality. TRIX scores showed that the range varied from 0.07 to 3.39 during all the seasons.

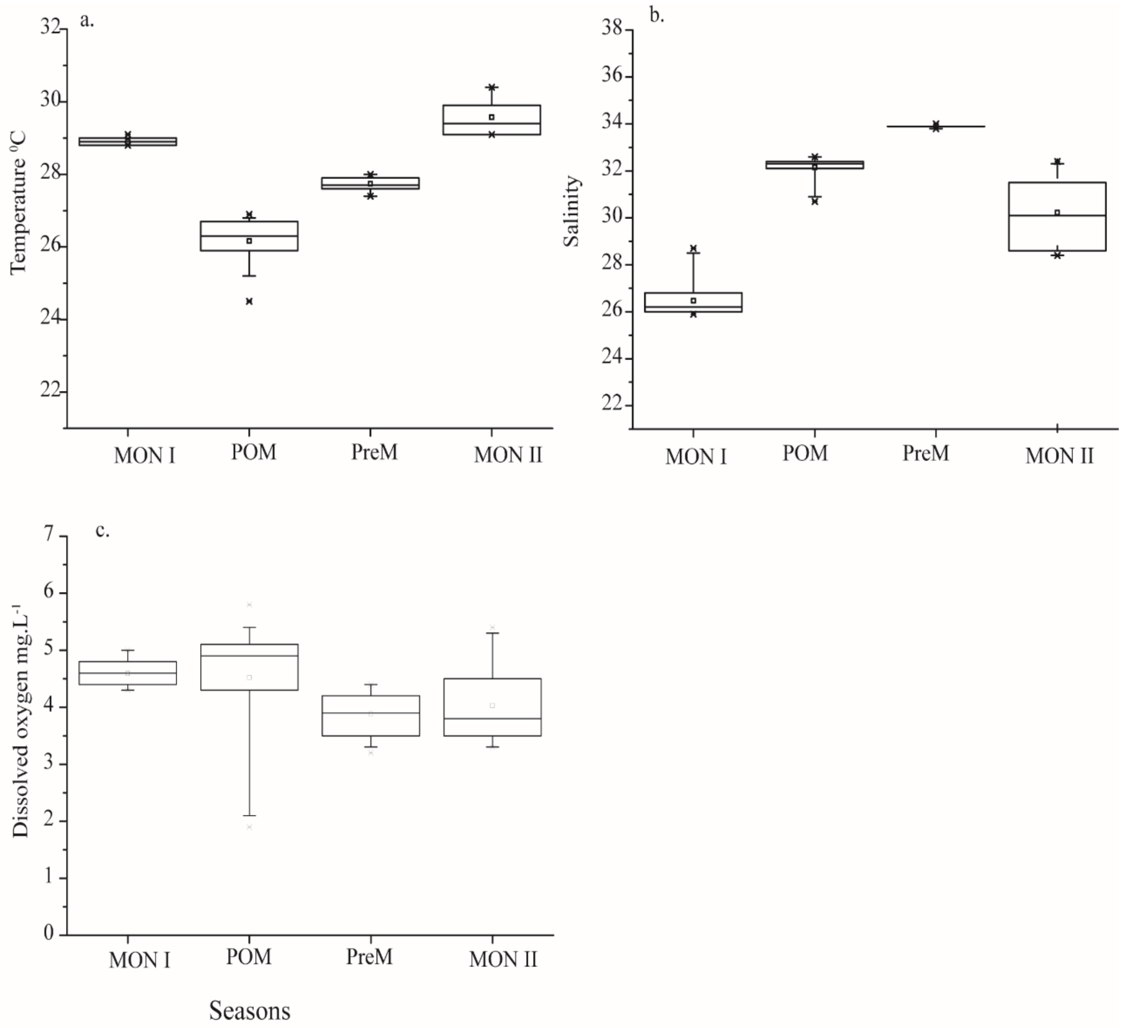


Figure 3.4.1: Box-plot to illustrate the seasonal changes in (a) Temperature, (b) Salinity and (c) Dissolved oxygen during the different seasons at Paradip port (MON I- Monsoon I, POM-Post monsoon, PreM- Pre-monsoon and MON II- Monsoon II).

3.4.2b Sediment parameters

Sediment texture was analysed for the composition of sand, silt and clay and they varied spatio-temporally within the port (Figure 3.4.2). Overall, silt was the most dominant component 59(±26.8) % followed by sand - 37.3(±26.3) % and Clay - 2.8(±9.5) % during all the seasons at most of the stations. The percentage of sand in the sediment ranged between 3.4% at S-11 during MON II to 94% at S-02 during MON II (Figure 3.4.2).

Table 3.4.1: - Temperature, Salinity and Dissolved oxygen of near bottom water of Paradip port during different seasons. (MON I. Monsoon, POM. Post monsoon, PreM. Pre-monsoon, MON II – Post Monsoon II).

	Temperature [°C]				Salinity [PSU]				D.O. [mg.m^3]			
ST	MON I	POM	PreM	MONII	MONI	POM	PreM	MONII	MONI	POM	PreM	MONII
1	28.9	26.0	27.9	30.4	25.9	30.7	33.8	28.4	5.0	5.0	4.4	5.2
2	28.9	26.1	27.7	30.4	26.0	30.9	33.8	28.6	5.0	3.7	4.4	5.3
3	28.9	26.1	27.8	30.2	26.0	31.2	33.8	28.4	4.8	4.3	4.4	5.4
4	28.9	25.2	27.4	29.2	26.9	32.4	33.9	29.8	4.6	4.6	4.2	4.0
5	28.9	24.5	27.6	29.1	26.8	32.4	33.9	30.1	4.4	4.0	3.5	3.8
6	29.0	26.4	27.8	29.1	26.0	32.5	33.9	30.6	4.3	1.9	4.2	3.6
7	28.8	26.4	27.8	29.4	26.1	32.3	33.9	30.1	4.4	5.2	4.2	3.6
8	28.9	26.1	27.9	29.4	26.0	32.1	34.0	29.3	4.6	5.3	4.3	3.7
9	28.9	26.2	27.9	29.4	26.0	32.3	33.9	29.7	4.4	5.1	4.2	3.9
10	28.8	26.6	27.7	29.1	26.0	32.4	33.9	32.4	4.4	2.1	3.5	3.3
11	28.8	25.9	27.6	29.1	26.8	32.4	33.9	32.1	4.7	4.4	3.4	3.4
12	29.0	25.4	27.6	29.6	28.7	32.6	33.9	28.4	4.9	5.8	4.0	4.3
13	28.8	25.8	27.4	29.1	28.5	32.6	33.9	32.3	4.8	3.4	4.2	3.8
14	28.8	25.5	27.9	29.1	26.9	32.2	33.9	32.2	4.6	4.4	3.9	3.3
15	29.0	26.7	28.0	29.4	26.4	32.5	33.8	31.4	4.3	4.8	3.9	3.4
16	29.0	26.8	27.7	29.6	26.3	32.3	33.9	31.6	4.4	4.9	3.2	3.3
17	29.1	26.7	28.0	29.4	26.4	32.3	33.9	31.5	4.5	4.8	3.6	3.5
18	28.8	26.7	27.7	29.6	26.1	32.1	33.9	31.4	4.6	5.1	3.8	3.5
19	28.8	26.9	27.6	30.3	26.0	32.6	33.9	29.9	4.9	5.1	3.8	4.8
20	28.8	26.7	27.9	29.9	26.0	31.9	33.9	28.6	4.3	5.4	3.4	4.2
21	28.9	26.6	27.7	29.9	26.3	32.1	33.9	29.7	4.6	5.1	3.6	4.5
22	29.0	26.3	27.6	29.9	26.2	32.4	33.9	28.4	4.5	5.0	3.3	4.8

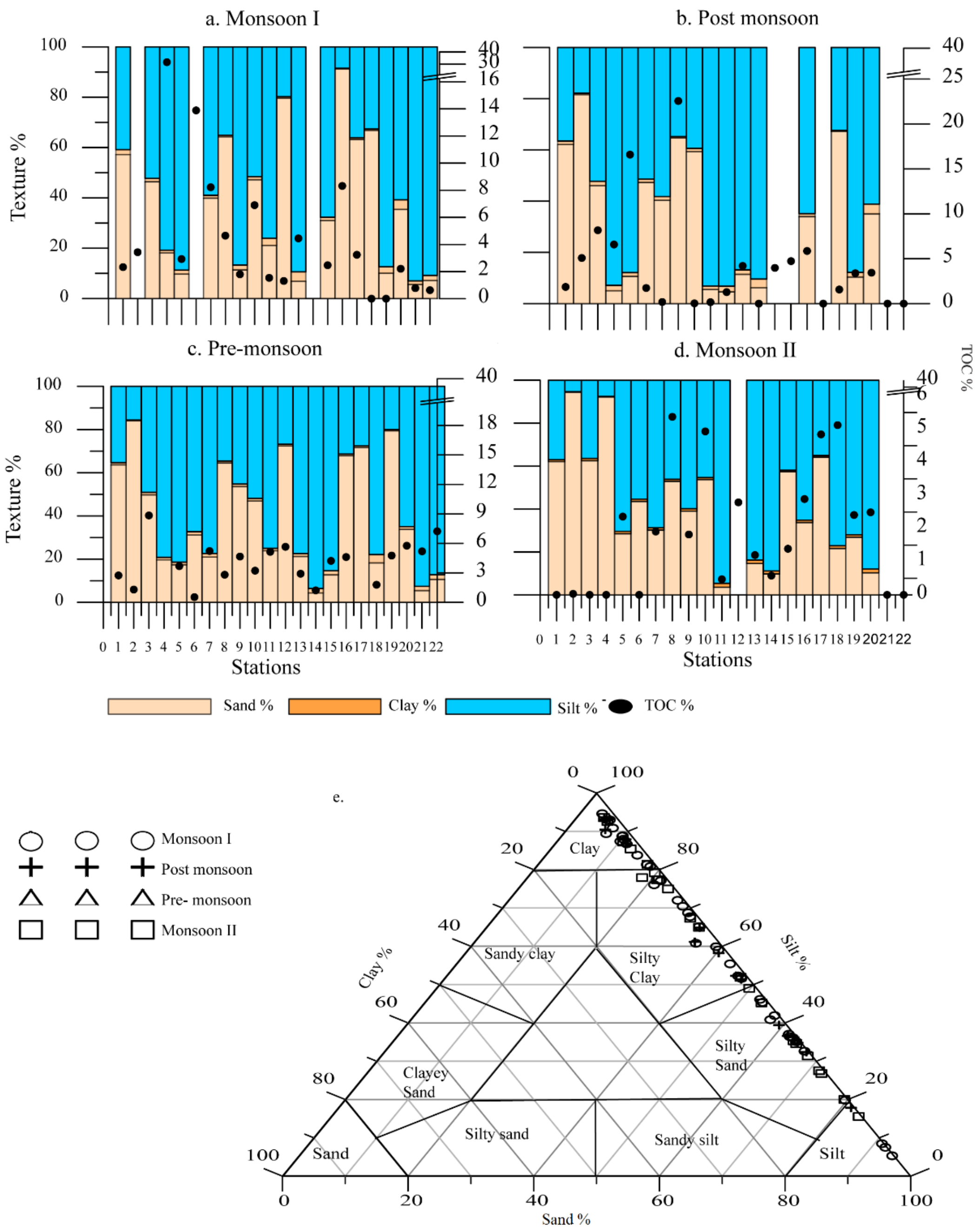


Figure 3.4.2: - Bar chart indicating seasonal changes in the sediment characteristics during different seasons (a. Monsoon I, b. Post monsoon, c. Pre-monsoon, d. Monsoon II) and e. Ternary plot.

Percentage of sand was comparatively high during PreM season with overall percentage of 40(±26.1) %. The range of silt was from 5.3% to 94.6% and was dominant during POM (Figure 3.4.2) and indicated less variations during other seasons [MON I 60.9(±26.4) %, MON II 52.7(±29.9) %, POM 63.6(±25.6) % and 58.9(±25.6) % during PreM respectively] (Figure 3.4.2). The percentage of clay was least and ranged between

0.3% at S-16 during MON I to 3.8% at S20 during POM (Figure 3.4.2). The sediment organic carbon ranged from 0.5% at S06 to 31.6% at S04. The OC was maximum during MON I (Figure 3.4.2) and during MON II organic carbon was minimum, 5.6(±7.4) % and 1.8(±1.8) % respectively. During POM and PreM the average organic carbon content was 4.1% and 3.7(±2.3) % respectively (Figure 3.4.2). The sediment chlorophyll *a* during MON I, PreM, MON I and MON II was 0.22(±0.1) mg. m^{-2}, 2.9(±1.2) mg. m^{-2}, 1.6(±0.7) mg. m^{-2} and 1.4(±0.8) mg. m^{-2} respectively (Figure 3.4.3). The maximum sediment chlorophyll *a* was observed during POM at S-13 (5.0 mg. m^{-2}) and minimum during MON I at S-16 (0.04 mg. m^{-2}) (Figure 3.4.3). POM showed maximum chlorophyll *a* in the sediment.

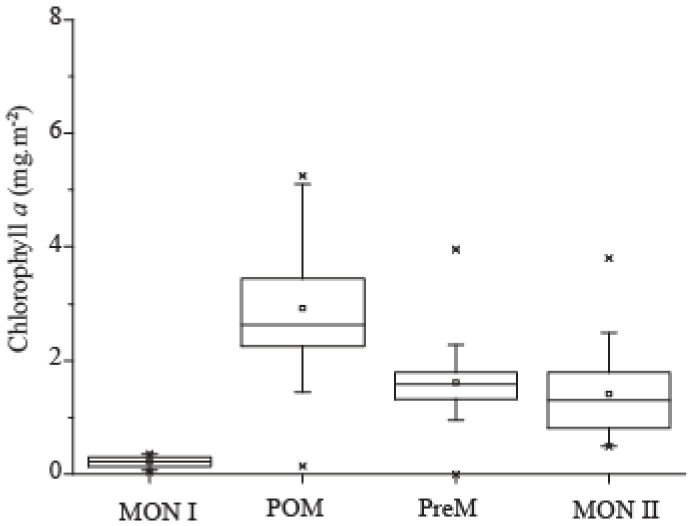


Figure 3.4.3: - Box-plot indicating the seasonal variation in sediment chlorophyll *a* during different seasons (MON I- Monsoon I, POM – Post monsoon, PreM- Pre-monsoon and MON II- Monsoon II).

3.4.2c Seasonal variation in the macrobenthic community

Macrobenthic organisms in Paradip port comprised of Annelida (polychaeta and Oligochaeta), Arthropoda (Pantopoda, amphipods, and isopods), Mollusca (bivalves) and Echinoderms (Sea anemones and brittle stars). Among these groups polychaetes were the most common and abundant organisms during all the seasons. Among the 30 macrobenthic taxa, 20 were polychaetes contributing more than 70% to the total macrobenthos abundance. Polychaetes belonging to *Capitellidae* and *Cossuridae* were observed during all the seasons.

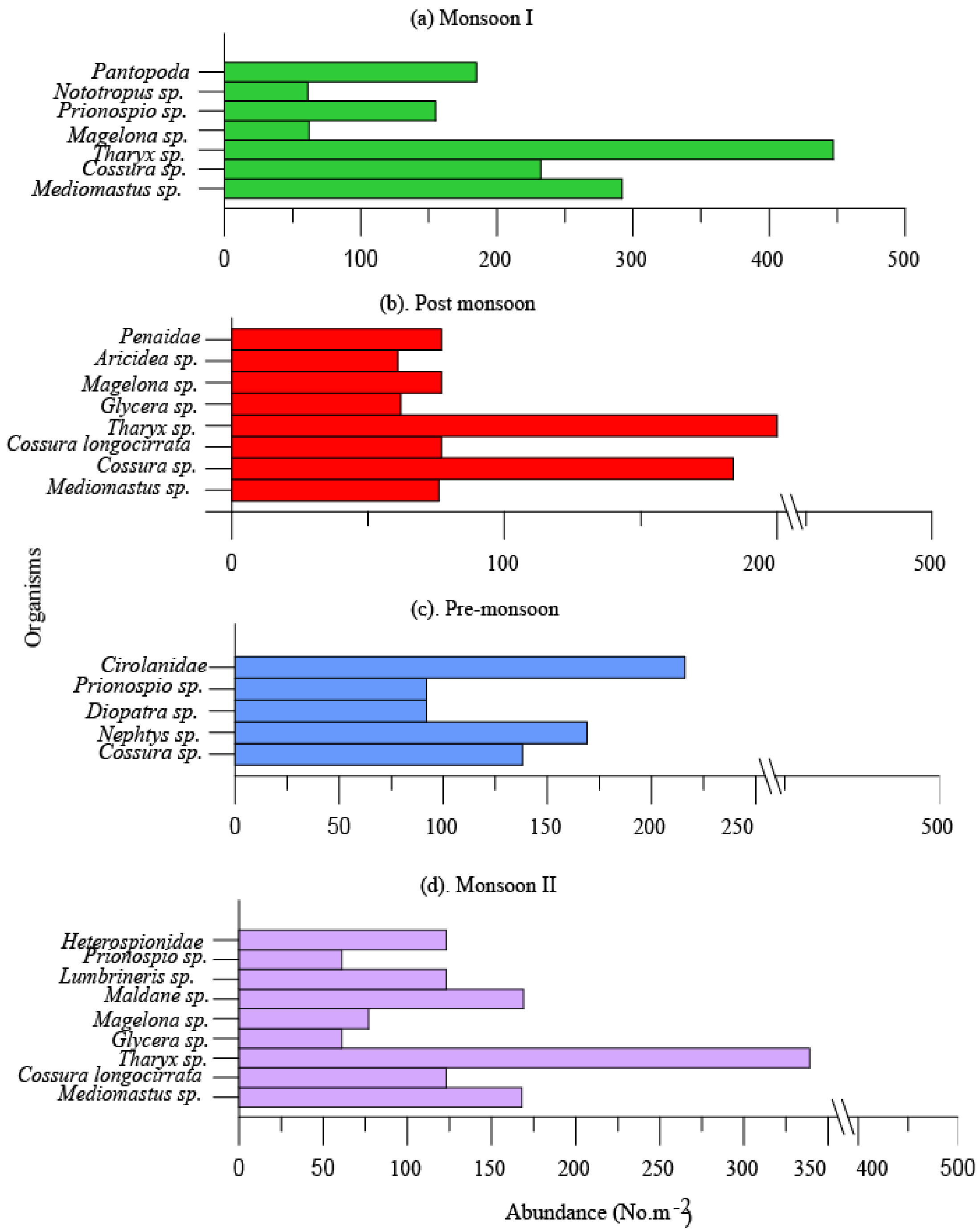


Figure 3.4.4: Bar-chart showing the variations in the dominant taxa during different seasons (a) Monsoon I, (b) Post monsoon, (c) Pre-monsoon and (d) Monsoon II at Paradip port.

The maximum abundance of macrobenthos was observed during MON II (2059 no. m^{-2}), followed by MON I (1581 no. m^{-2}), POM (983 no. m^{-2}) and PreM season (875 no. m^{-2}) (Table 3.4.2).The stations with maximum abundance varied with the seasons and during MON I -S06-323 no. m^{-2} and S11- 446 no. m^{-2}, POM S04 - 122 no. m^{-2}, PreMS18-216 no. m^{-2} and during MON II at S12- 324 no. m^{-2} respectively (Table 3.4.2).

During MON I, the maximum abundance of macrobenthic polychaete was contributed by the Cirratulidae, *Tharyx sp.* (447 no. m^{-2}), followed by *Mediomastus sp*. (292 no. m^{-2}) and *Cossura sp.* (232 no. m^{-2}) and order Pantopoda (185 no. m^{-2}) dominated the overall abundance (Figure 3.4.4). The *Prionospio* sp. was 155 no. m^{-2}. *Tharyx sp.* contributed 21% to the total abundance followed by *Mediomastus* sp. (14.1%) and *Cossura sp*. (11.2%). Among the non-polychaetes, Pantopods contributed about 9%, *Nototropus sp*. and Isophilidae contributed 2.9% and 2.2% respectively. The stations S11, S06 and S08 showed higher abundance of macrobenthos, and Pantopoda were reported only at S11. At stations S02, S12, S18, S21 and S22, macrobenthos were not reported. Compared to MON I, POM season had lower abundance and diversity dominated by *Tharyx sp*. (S01, S04, S12, S17 and S22) and *Cossura sp*. with abundance of 200 no. m^{-2} and 184 no. m^{-2}. Sedentary polychaetes *Mediomastus sp*. (S01, S05, S15 and S21) and *Magelona sp*. (S20, S21 and S22) contributed 7% to the total abundance followed by *Aricidea sp*. (contributed 6%). PreM had the least abundance and diversity compared to other seasons, the most abundant group was Cirolanidae (215 no. m^{-2}) at S18. Among the polychaetes, *Nephtys sp*. was high in abundance (169 no. m^{-2}) and reported at S04, S07, S10, S12, S14 and S17, followed by *Cossura sp*. (138 no. m^{-2}) reported at S04, S11, S14, S17 and S20 (Figure 3.4.5).

Monsoon seasons were more productive in terms of occurrence of macrobenthos as compared to non-monsoon seasons at this port. The polychaete, *Tharyx* sp. was most abundant (339 no. m^{-2}) during MON II and was observed at stations S10, S11, S12, S15, S16 and S17, followed by *Mediomastus* sp. (168 no. m^{-2}) and *Maldane* sp. 169 no. m^{-2} (Figure 4d). The other common Polychaetes were *Cossura longicerrata* 123 no. m^{-2}, *Lumbrineries* sp. 123 no. m^{-2}, *Prionsopio* sp. 61 no. m^{-2}, *Melinna* sp. 46 no. m^{-2}, *Megalona* sp. 77 no. m^{-2}, *Glycera* sp. 61 no. m^{-2} and *Paraonis* sp., 61 no. m^{-2} respectively (Figure 3.4.4d).

Table 3.4.2. Variation in the abundance of macrobenthos in Paradip port during different seasons.

Table 3.4.2a. Abundance (no.m^{-2}) of macrobenthic organisms in Paradip port during Monsoon I.

Monsoon I																							
Organisms/Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	Total
Hesione sp.											31												31
Mediomastus sp.				31	77	92		15			46								31				292
Cossura sp.	139							31			62												232
Kirkegaardia sp.			31																				31
Tharyx sp.						231	108	62	46														447
Glycera sp.								31															31
Goniada sp.				46																			46
Magelona sp.					62																		62
Maldane sp.										31									15				46
Lumbrineris sp.			15																				15
Diopatra sp.											31												31
Aricidea sp.								15					15										30
Paraonois sp.								15			15								31				61
Eteone sp.													15										15
Ancistrosyllis sp.								15															15
Prionospio sp.			62					31	31											31			155
Streblospio sp.					15																		15
Isophilidae																46							46
Nototropus sp.									15		15					31							61
Order Pantopoda											185												185
Isopoda											46												46

Table 3.4.2b. Abundance (no.m^{-2}) of macrobenthic organisms in Paradip port during Post monsoon.

Post monsoon																							
Organisms	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Mediomastus sp.	15				15										31					15			76
Cossura sp.				31	15				31		15	31		31	15		15						184
Cossura longocirrata														46							31		77
Tharyx sp.	31			46								31				15	46					31	200
Glycera sp.		31																		31			62
Magelona sp.																				15	31	31	77
Nephtys sp.																15						31	46
Aricidae sp.		46		15																			61
Prionospio sp.			31																				31
Pantopoda																				31			31
Penaidae									46										31				77

Table 3.4.2c. Abundance (no.m^{-2}) of macrobenthic organisms in Paradip port during Pre-monsoon

Pre-monsoon																							
stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Cossura sp.				31							15			46			15			31			138
Tharyx sp.																	46						46
Magelona sp.				46																			46
Nephtys sp.				31			15			31		46		15			31						169
Diopatra sp.	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77	0	92
Prionospio sp.										15	15						31						61
Cirolanidae																		215					215

Table 3.4.2d. Abundance (no.m^{-2}) of macrobenthic organisms in Paradip port during Monsoon II.

Monsoon II																							
Organisms	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Sipuncula				31																			31
Melinna sp.		46																					46
Mediomastus sp.	31		15		15		31	46					15					15					168
Cossura longocirrata				31						15				15				62					123
Tharyx sp.									31		46	139			31	15	77						339
Glycera sp.		46											15										61
Magelona sp.					31									46									77
Maldane sp.					108		15					31				15							169
Lumbrineris sp.		31			62					15					15	0							123
Eunice sp.							46																46
Paraonis sp.	15											31											46
Prionospio sp.		31			15										15								61
Heterospionidae												123											123
Acantharia											31												31

Macrobenthos diversity

Species diversity index at all the stations was estimated based on Margalef species richness (d), Shannon-Weiner index (H′) and evenness (J′). The maximum number of species were encountered during MON I, and the correspondence values of the Shannon–Weiner index (H′) during MON I and MON II were 1.9 and 1.5 followed by PreM (1.3) and POM (1.3) respectively.

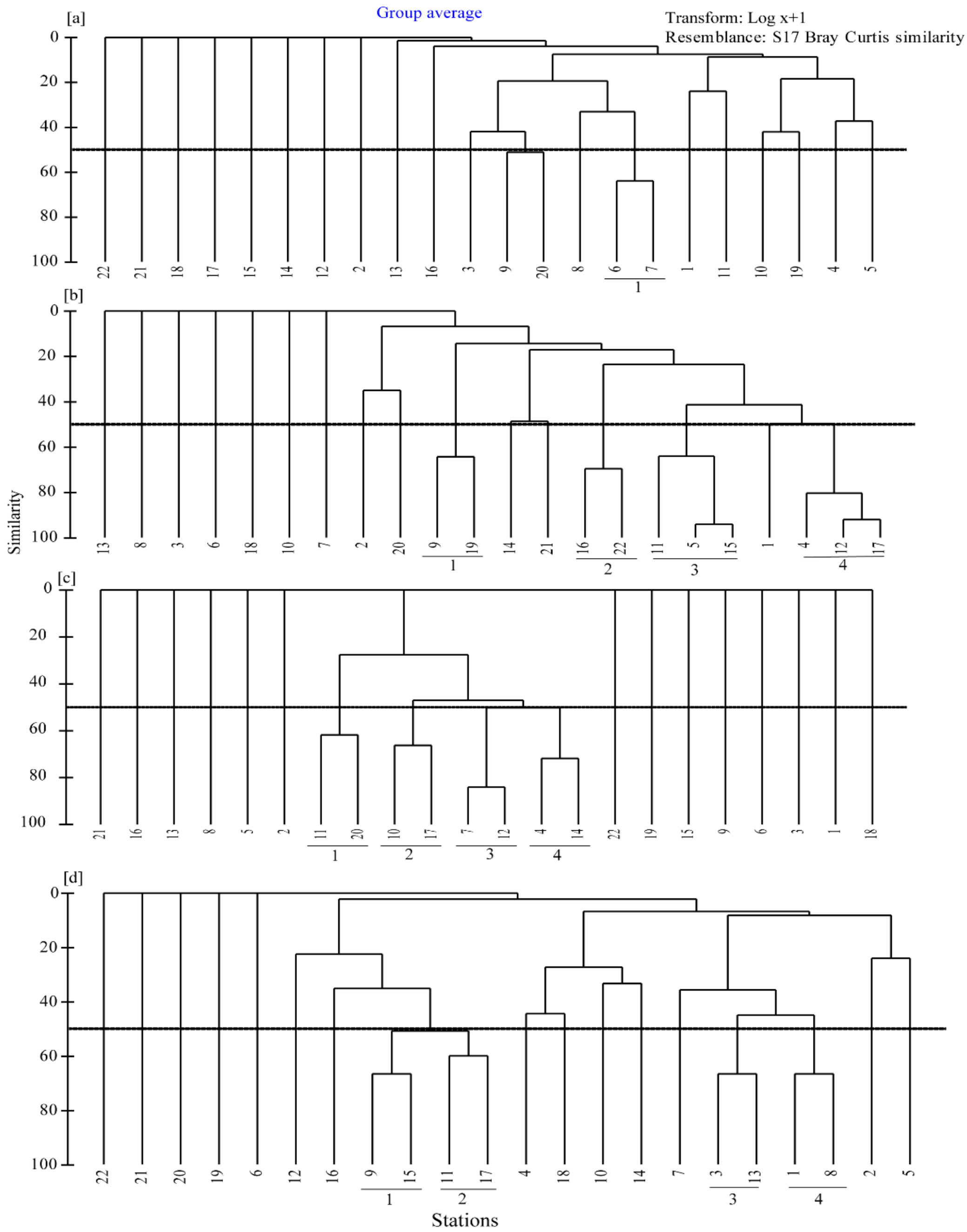


Figure 3.4.5: - Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons (a) Monsoon I (b) Post monsoon (c) Pre-monsoon (d) Monsoon II.

Table 3.4.3. Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou's evenness (J′), Shannon index (H) of macrobenthic polychaetes during different seasons at Paradip port.

a.Monsoon I						**b. Post Monsoon**					**c.Pre-monsoon**					**d. Monsoon II**				
St	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)
1	1	139	0	****	0	2	46	0.2612	0.9109	0.6314	0	0	****	****	0	2	6	0.5454	0.9919	0.6875
2	0	0	****	****	0	2	77	0.2302	0.9724	0.6741	0	0	****	****	0	4	15	1.118	0.9989	1.385
3	3	108	0.4272	0.8657	0.9511	1	31	0	****	0	0	0	****	****	0	1	3	0	****	0
4	2	77	0.2302	0.9724	0.6741	3	92	0.4423	0.9183	1.009	3	108	0.4273	0.9821	1.079	2	7	0.517	1	0.6931
5	3	154	0.3971	0.8554	0.9397	2	30	0.294	1	0.6931	0	0	****	****	0	5	18	1.387	0.9866	1.588
6	2	323	0.1731	0.8619	0.5975	0	0	****	****	0	0	0	****	****	0	0	0	****	****	0
7	1	108	0	****	0	0	0	****	****	0	1	15	0	****	0	3	10	0.8644	0.9922	1.09
8	8	215	1.303	0.9326	1.939	0	0	****	****	0	0	0	****	****	0	1	4	0	****	0
9	3	92	0.4423	0.9183	1.009	2	77	0.2302	0.9724	0.6741	0	0	****	****	0	1	3	0	****	0
10	1	31	0	****	0	0	0	****	****	0	2	77	0.2302	0.971	0.673	2	6	0.5808	1	0.6931
11	8	431	1.154	0.8329	1.732	1	15	0	****	0	2	31	0.2918	1	0.6931	2	7	0.5026	0.9979	0.6917
12	0	0	****	****	0	2	62	0.2423	1	0.6931	1	46	0	****	0	4	17	1.066	0.9894	1.372
13	2	30	0.294	1	0.6931	0	0	****	****	0	0	0	****	****	0	2	6	0.5808	1	0.6931
14	0	0	****	****	0	2	77	0.2302	0.9724	0.6741	2	62	0.2427	0.8113	0.5623	2	7	0.5277	0.9817	0.6805
15	0	0	****	****	0	2	46	0.2612	0.9109	0.6314	0	0	****	****	0	3	9	0.9078	0.9952	1.093
16	2	77	0.2302	0.9724	0.6741	2	30	0.294	1	0.6931	0	0	****	****	0	2	6	0.5808	1	0.6931
17	0	0	****	****	0	2	61	0.2433	0.8047	0.5578	4	123	0.6232	0.9528	1.321	1	4	0	****	0
18	0	0	****	****	0	0	0	****	****	0	1	216	0	****	0	2	7	0.5164	0.9729	0.6744
19	3	77	0.4604	0.9569	1.051	1	31	0	****	0	0	0	****	****	0	0	0	****	****	0
20	1	31	0	****	0	4	92	0.6635	0.9554	1.325	1	31	0	****	0	0	0	****	****	0
21	0	0	****	****	0	2	62	0.2423	1	0.6931	0	0	****	****	0	0	0	****	****	0

Post monsoon showed low species diversity and abundance compared to other three seasons (Table 3.4.3). Bray–Curtis similarity index was applied for grouping the stations according to the abundance of macrobenthos. At 50% similarity level, MON I and MON II showed two and three groups respectively, and monsoon season showed higher diversity and abundance compared to other seasons (Table 3.4.2). Monsoon season showed maximum diversity of macrobenthos with high temperature and low salinity in near bottom water compared to other seasons (Figures 3.4.1 and Table 3.4.2). MON I showed more diversity and least similarity among the stations (Table 3.4.2), and the group I stations were dominated by *Prionospio* sp. (contribution to abundance – 7.5 %). In group II, *Tharyx sp.* was abundant with 21.7% and the other abundant species were *Mediomastus sp*. and *Cossura sp*. contributing 14.1% and 11.2% respectively. During POM season, the similarity of organisms and their average abundance in group I, II, III and IV were dominated by *Tharyx* sp. (20%), *Cossura* sp. (18.4%), *Mediomastus* sp. (7.6%), *Nephtys* sp. (4.6%), and *Magelona sp*. (7.7%) (Figure 3.4.5). During PreM season the average similarity among group I, II and III was 36.6%, 61.5% and 50.0% respectively (Table 3.4.2). During MON II, three groups were observed, with group I (stations S09, S11, S15 and S17), group II (stations S03 and S13) and group III (stations S01 and S08) with similarity of 66.6, 66.6 and 54.9% respectively (Figure 3.4.5).

CCA and Redundancy analysis (Figure 3.4.6) of the study indicated sediment characteristics and organic carbon play an important role in influencing the community structure of benthic organisms at different stations during different seasons. Length of the gradient value >2 was shown during MON I and II seasons and during POM and PreM it was <2. The correlation percentage between macrobenthic abundance and the environmental variables during MON I and II was 81.4% and 96.7%, and during POM and PreM they were 92.6% and 82.8% respectively. The canonical correspondence analysis during MON I (Figure 3.4.6) indicated that sand, temperature and organic carbon influenced the abundance of the organisms such as *Prionospio* sp.*, Lumbrineris* sp. *Kirkegaardia* sp.. The parameters such as silt, organic nitrogen and D.O. positively influenced *Goniada* sp.*, Magelona* sp.*, Cossura* sp. *and Streblospio* sp. The polychaetes, *Mediomastus* sp.*,* and *Eteone* sp. were not influenced by the environmental variables. During POM season, *Tharyx* sp., Penaidae and Aricidea were positively influenced by Silt, DO, and salinity and they could survive on low chlorophyll *a*, clay, phosphate and ammonia. *Mediomastus* sp.*, Magelona* sp.*, Glycera* sp. *and* Pantopoda survive well in clayey sediment and in low DO, salinity and silt (Figure 3.4.6).

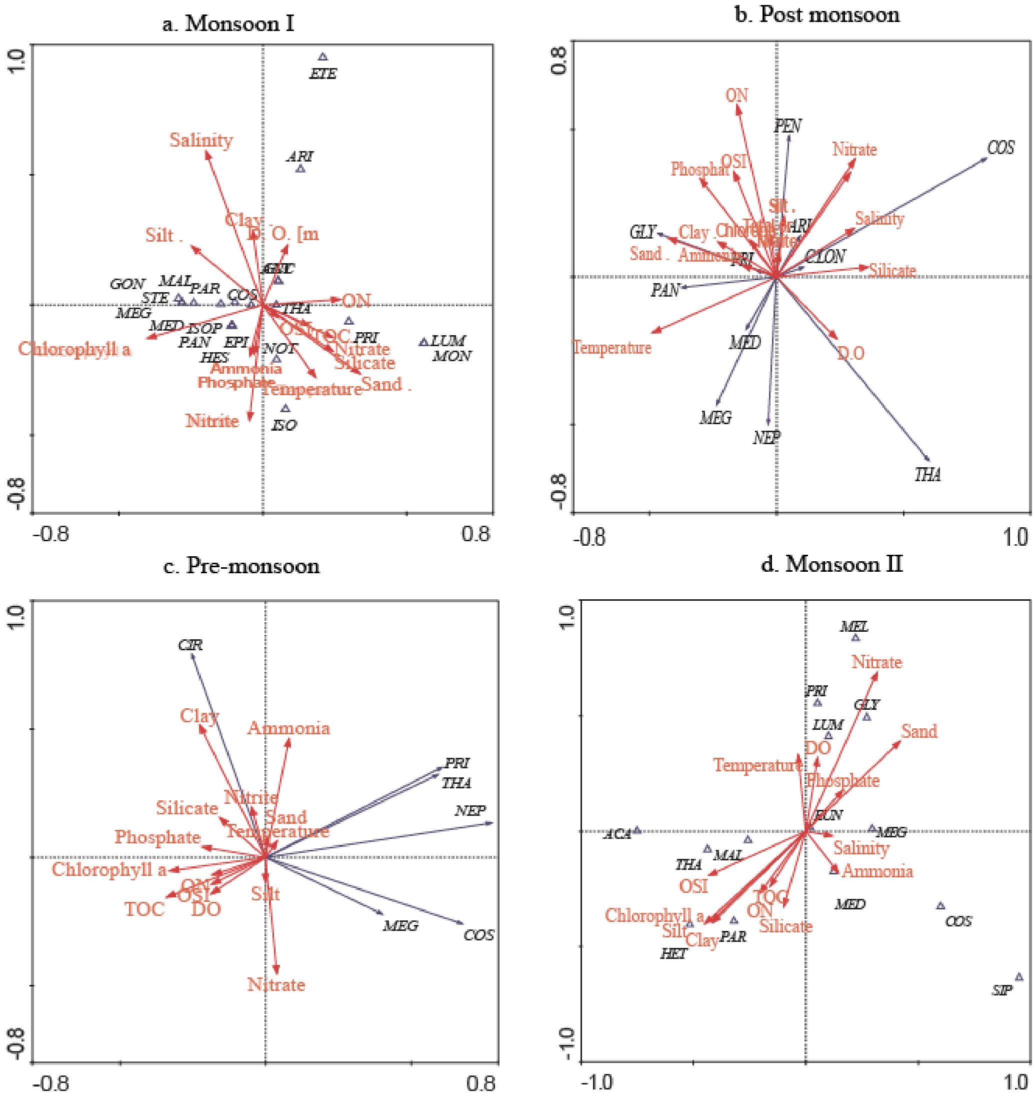


Figure 3.4.6. CCA and RDA plots of different seasons [(a) Monsoon I (b) Post monsoon (c) Pre-monsoon (d) Monsoon II at Paradip port to illustrate the correlation between environmental parameters and species diversity. (ANC - *Ancistrosyllis* sp., ARI - *Aricide*a sp., COS - *Cossura* sp., C.LON – *Cossura longocirrata*, ETE- *Eteone* sp., EUN - *Eunice* sp., EPI - *Diopatra* sp., GLY - *Glycera* sp., GON - *Goniada* sp., HES - *Hesione* sp., LUM - *Lumbrineris* sp., MAL - *Maldane* sp., MED - *Mediomastus* sp., MEG - *Magelona* sp., MEL - *Melinna* sp., MON - *Kirkegaardia* sp., NEP - *Nephtys* sp., NOT - *Nototropus* sp., PAR - *Paraonis* sp., PRI - *Prionospio* sp., STR - *Streblospio* sp., THA - *Tharyx* sp., ACA - Acantharia, CIR - Cirolanidae , HET - Longosomatidae, ISO - Iospilidae, ISOP - Isopoda, PAN - Pantopoda, PEN - Penaeidae and SIP – Sipuncula)(ON-Organic Nitrogen (%), OSI- Organic sediment index (%), DO - Dissolved oxygen - mg. l^{-1}, TOC - Total organic Carbon (%)).

The redundancy plot (Figure 3.4.6) of PreM showed that sand and temperature positively influenced *Tharyx* sp., *Prionospio* sp., *Nephtys* sp., and negatively influenced by organic carbon, organic nitrogen, silt and chlorophyll a. Cirolanidae is thrives well in clay and nutrients. *Magelona* sp. and *Cossura* sp. is high in organic carbon and nitrogen rich silty or sandy sediments. The CCA plot of MON II showed silt, chlorophyll *a*, organic nitrogen and silicate led to the higher abundance in *Tharyx* sp., *Maldane* sp., *Paraonis* sp., Heterospionidae and Acantharia, while errantia polychaetes *Glycera* sp., *Lumbrineris* sp., *Melinna* sp. were well suited in sandy sediment with high temperature and DO (Figure 3.4.6).

3.4.3 Discussion

Studies on the biodiversity of benthic organisms from the tropical regions are limited when compared to higher altitudes (Along, 1989) and the same is true for Paradip port situated on the east coast of India (Sharma et al, 2016). The study of macrobenthic organisms is important to understand and establish a database for the region to improve our understanding on distribution, abundance, diversity and other characteristics of macrobenthic organisms in the marine environment (Warwick and Ruswahyuni, 1987), as they play an important role in the food web dynamics and ecological functioning of the benthic ecosystems. The changes occurring in these parameters can lead to disturbance in the benthic faunal diversity and abundance. In the present study, macrobenthic community structure and abundance varied with the seasons, associated with changes in salinity (lower in monsoon and higher in non- monsoon seasons), temperature, DO and sediment characteristics. The sediment quality was the most important parameter for seasonal and spatial distribution and diversity of benthic organisms. The various properties related to sediment quality are permeability, penetrability that is controlled by erosion, resuspension and water content in the sediments (Sarkar et al, 2005). The sediment quality in Paradip port indicated that there were limited changes in the spatio-temporal variation in the sediment texture which was mostly dominated by silt followed by sand with minimum contribution of clay. The TRIX analysis for bottom water indicated that the near-bottom water quality was good and rich in organic matter, indicating healthy bottom water conditions (Jayaraj et al, 2008). There was a wide range in salinity (25–34) during the non-monsoon and monsoon seasons, resulting in the euryhaline species belonging to genus Cossuridae and Cirratulidae to adapt and survive during monsoon and stenohaline organisms such as isopods and crustaceans (Penaeidae) during the non-monsoon seasons. The near bottom sea-water nutrients were higher during pre-monsoon (summer) than in the other seasons due to gradual increase in temperature (Faragallah et al, 2009). The present study area also showed increased nutrient levels during PreM compared to MON and POM seasons.

The organic carbon enrichment was high in Paradip port especially during MON I and POM and it was low during PreM and MON II, and such an increase in organic carbon in the sediments leads to hypoxic conditions as well as a decrease the abundance and diversity of benthic organisms (Pearson and Rosenberg, 1978). The stations with high organic content in the study area were either dominated by the indicator species or had lower abundance of macrobenthos. The distribution of organic carbon also varied in the surface sediments at different stations along with changes in the percentage of sand-silt content, as organic carbon content was high in silt dominated areas. The finer silt particles accumulated higher organic carbon content due to the lack of disturbance in the sediments. There was a dominance of subsurface dwelling polychaetes, which are considered as biological indicators of high organic matter in the sediments. This high organic carbon content may be due to plant material and faeces that settle down, and such organic carbon is removed from the water column and at the sediment–water interface by the benthic fauna. The deposited organic material either becomes part of particulate organic matter, which is taken as food by the benthic fauna or directly ingested by deposit feeders (Snelgrove, 1997). The temporal changes in salinity, sediment size gradient and other environmental stresses associated with organic carbon enrichment lead to the succession of different species as pointed out by Ansari et al, (2014). The present study also showed changes in the diversity pattern of macrobenthos due to seasonal variation along with increased organic carbon input. The most common organisms reported were *Tharyx* sp., *Prionospio* sp., *Cossura* sp. and *Magelona* sp. in Paradip port, and these are called opportunistic species and are well-known pollution indicators (Sivadas et al, 2010). These organisms are mostly found in stations with high organic carbon in the sediments, indicating that they may be surface or subsurface deposit feeders (Rosenberg, 1995). An earlier study indicated higher abundance of *Prionospio* sp. in a semi-polluted (moderate organic carbon) region of the Visakhapatnam harbour (Musale et al, 2015). It has been reported that *Prionospio* sp. and few other species burrow in sand and are capable of constructing tubes in which they hide and which also protects them from predators, indicating their subsurface deposit-feeding habit (Mortiz, 2012). With regard to properties of sediment dynamics, it has been suggested that high silt-clay fraction in the sediments contain more food particles which are commonly composed of decomposable organic constituents and sustain deposit-feeding benthic organisms

(Musale et al, 2015; Jayaraj et al, 2008; Sanders, 1958; Sanders, 1960). Organisms belonging to *Cossura* sp. are mostly burrowers in the soft sediment dominated by high silt.

Higher abundance of deposit feeders belonging to genus *Cossura* was reported in a high silt area at Visakhapatnam port (Musale et al, 2015). *Prionospio* sp. has been reported as an indicator of organic enrichment in subtidal areas, which is an inhabitant of the subsurface region of the sediments (Elias et al, 2005). An earlier study has reported that subsurface deposit-feeding polychaetes such as *Mediomastus* sp., *Tharyx* sp. and *Cossura* sp. are capable of feeding on freshly settled organic carbon and also on aged organic carbon in the sediments (Long, 1995) indicating towards their adaptation to a variety of benthic habitat. The *Magelona* sp. is a subsurface deposit feeder and its feeding activity usually occurs below the surface (Jumars et al, 2015). Spatial variation in the benthic community is observed mostly in the estuaries and bays, under extreme or abnormal circumstances of organic matter overloading in the coastal waters leading to disturbance in the faunal community (Mendez, 2013). They are also mostly deposit feeders and are present in sandy-silt sediments with high total organic carbon, as observed in *Mediomastus* sp. (Jumars et al, 2015).

Similar conditions were observed in the Paradip port and *Mediomastus* sp. which is one of the most abundant sedentary polychaete present in the fine-grained sandy habitats dominated by silt with high organic matter. The individuals of *Mediomastus* sp. were present during all the seasons. These are non-selective feeders as they engulf food directly from the sediments (Van Hoey et al, 2004) and this may be related to less disturbance in the sediments as they are observed during all the seasons. *Cossura* sp. is a stress-tolerant macrobenthic polychaete which is a suspension feeder and prefers sandy and fine silty sediments. It is a burrower which prefers soft sediments with high silt, as reported earlier (Jayaraj et al, 2008). The other dominant polychaete, *Nephtys* sp. found during all the seasons is an active predator that prefers fine sandy sediments, and studies have reported higher abundance of these organisms in fine sandy sediments (Van Hoey et al, 2004; Jayaraj et al, 2008). The hypoxia and pollution-tolerant polychaetes *Tharyx* sp. and *Prionospio* sp., which are deposit feeders were observed during all the seasons, thus indicating the health of the benthic ecosystem. Even though *Tharyx* sp. is a selective feeder which inhabits the mud-coloured tubes, they are found in highly polluted areas (Fauchald and Jumars, 1979). During monsoon season, the observed high organic carbon content can be attributed to collapse and sinking of phytoplankton from the surface waters (Sivadas et al, 2013). The presence of Spionidae, *Prionospio* sp. and Cossuridae, *Cossur*a sp. in the sediments shows sediment instability and disturbed environment, and both these species are deposit feeders which feed on fresh surface organic matter (Muniz and Pires, 2010; Dolbeth et al, 2007). The diversity of macrobenthos is limited in Paradip port, as high organic matter content promoted the abundance of tolerant species and lowered the abundance of sensitive species (Pearson and Rosenberg, 1978), and this led to reduction in their diversity and abundance. There is also another possibility of macrobenthic assemblages in high organic carbon sediments, where black carbon contributes more to organic carbon content present in the sediments (Middelburg et al, 1999). The presence of indicator species of pollution, viz. *Prionospio* sp., *Streblospio* sp., *Mediomastus* sp. and *Tharyx* sp. in this study indicates that they thrive in low oxygen and high organic load (Khan et al, 2004).

The polychaete, *Lumbrineris* sp. are carnivores or carrion feeders and they prey on other polychaetes, Nemertea, Crustacea and Bivalvia (Fauchald and Jumars, 1979). It is possible that disturbance in the surface sediments during monsoon season may lead to the exposure of burrowing organisms and this may be the reason for observing *Lumbrineris* sp. during the monsoon season. The *Magelona* sp. is also found during all the seasons. Studies on *Magelona* indicated that they are non-selective surface deposit feeders and also alter their feeding mode to suspension feeding (Fauchald and Jumars, 1979). In respect to their non-selective feeding behaviour and the presence of sufficient organic matter in the study area, *Magelona* sp. can thrive during all the seasons despite variations in its abundance. There is a difference in species abundance and diversity in accordance to the seasonal changes in Paradip port, with higher abundance during the monsoon season (Along, 1989). The life cycle of a tropical macrobenthic organism integrates with the monsoon and this results in seasonal differences in occurrence and abundance of such organisms. A previous study on Indian ports showed reduction in the macrobenthic species composition, density and biomass due to dredging and anthropogenic activities, as observed in Cochin port (Rehitha et al, 2017). In Visakhapatnam port, a coastal ecosystem, the macrobenthic community composition varied due to various levels of pollutant accumulation in the sediments spatially showing the difference in benthic community in the port ecosystem (Musale et al, 2015). The loss of macrobenthic communities and their rapid recovery in these stations are due to the migration of these fauna from the nearby sediment patches that are not leading to reclamation of macrobenthos under suitable conditions, as observed in Cleveland Bay (Cruz and Collins, 2004).

Present study shows higher organic carbon in the study area leading to the depletion in diversity and also survival of pollution tolerant species albeit their count. Industrial growth that focusses on oil refining, aluminium and petrochemical industries generate hydrocarbon related effluents, these effluents leads to changes in macrobenthic community structure, species number and decrease in overall diversity (Sridhar and Bhaskaran, 2015). The present study shows that the Paradip port environment is influenced by the seasonal variation mostly brought in by the monsoons and the anthropogenic activities, however, healthy bottom water quality and high amount of organic load accumulated in the sediment leads to the survival and proliferation of indicator macrobenthos species.

Chapter 3.5.

Spatio-temporal variation in the macrobenthic community structure and the factors influencing the macrobenthic diversity in Zuari, a tropical monsoonal estuary

3.5.1 Introduction

Zuari estuary, a part of Mondovi-Zuari estuarine system, is the complex estuarine ecosystem in the state of Goa. This estuary is connected to the Arabian sea. This estuary experiences three major seasons, PreM (February-May), Monsoon (June-September) and POM (October – January). Zuari estuary has a catchment area of 550Km^2 and the rainfall it receives was about 491 x 10^6 m^3.

3.5.2 Results

3.5.2a. Environmental parameters

Variations in the environmental parameters such as temperature, salinity, dissolved oxygen, and chlorophyll *a* are presented in Figure 3.5.1. The average near bottom water temperature was 29.08(±1.4) ºC at Dona Paula, 28.9(±1.6) ºC at Chicalim, 29.0(±1.7) ºC at Cortalim, 29.3(±1.8) ºC at Loutolim, 29.3(±1.9) ºC at Borim, 29.1(±1.9) ºC at Shiroda, and 28.7(±1.8) ºC at Kushavati (Figure 3.5.1a). The monthly variation in the bottom water temperature was observed among the stations during the post monsoon months (November and December) of 2013, monsoon months (July, August and September) of 2014 and pre-monsoon months (February and March) of 2015 with an average temperature of 27.6±1.3 ºC (Table 3.5.1). The salinity of near bottom water in Dona Paula - 33.8(±1.1), Chicalim - 26.9(±8.3), Cortalim - 24.7(±10.2), Loutolim - 18.2(±11.0), Borim - 11.8(±8.7), Shiroda - 7.5 (±6.3) and Kushavati - 2.4(±2.7) (Figure 3.5.1b) during the study, indicating a decrease in the salinity from estuarine mouth to the upstream of the estuary. The maximum near bottom seawater salinity was observed at Dona Paula, and the salinity significantly varied within the stations (ANOVA; F = 33.95, df = 6, $p = 2.5*10^{-23}$) during the study. Among the stations there was a gradual decrease in the salinity from Dona Paula (32 - 34), downstream to Kushavati (0.04 to 5), the upstream station (Table 3.5.1). Monthly variations were observed in the salinity at all the stations. A considerable drop in the bottom water salinity was observed from Chicalim to Kushavati during the monsoon months (July, August and September) was 7.1± (8.4) as a result of fresh water inflow arsing as a result of the southwest monsoon. At Dona Paula station (estuarine mouth) due to rough weather, water samples were not collected during the monsoon months.

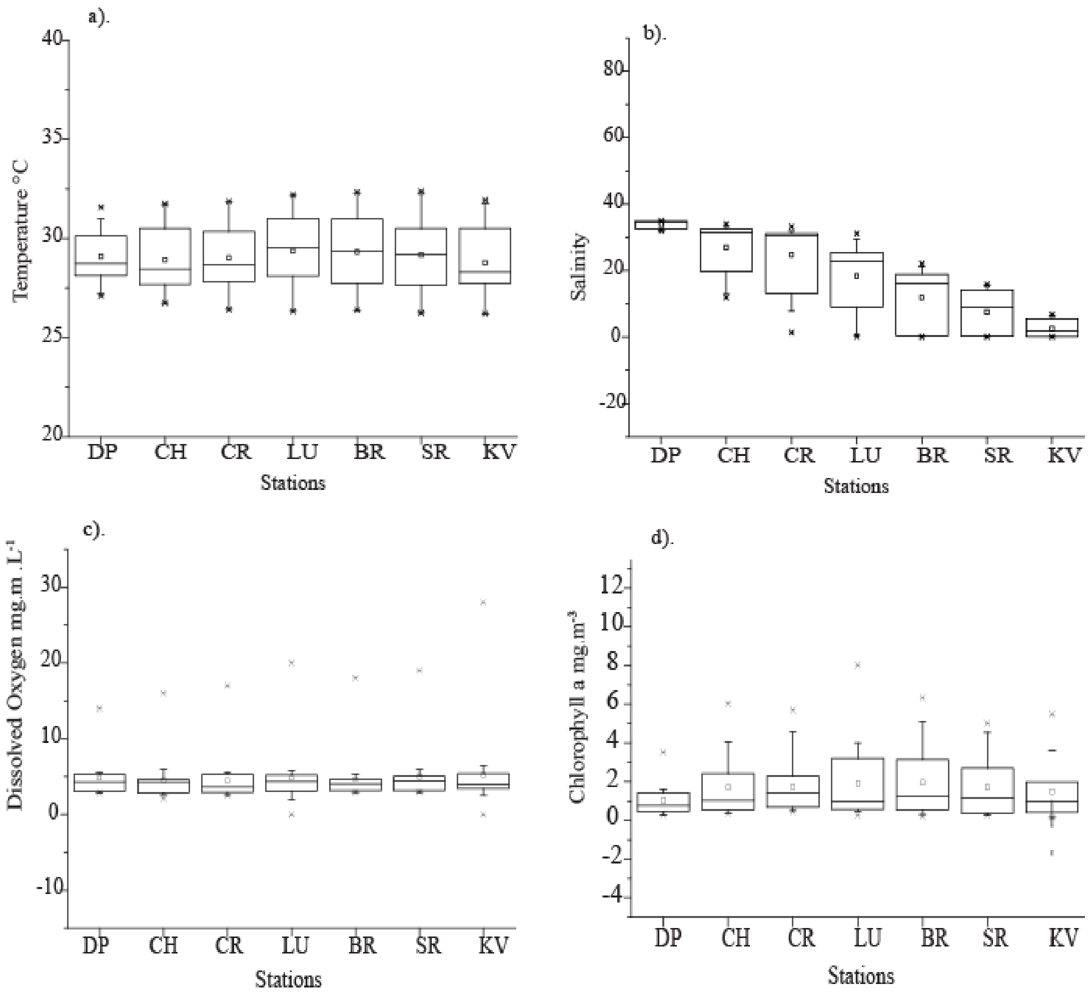


Figure 3.5.1: - Box-plot illustrating the spatial variation in the (a) Temperature, (b) Salinity (c) Dissolved oxygen and (d) Chlorophyll *a* at Zuari estuary (DP- Dona Paula, CH- Chicalim, CR- Cortalim, LU- Loutolim, BR- Borim, SR- Shiroda, KV- Kushavati).

The average dissolved oxygen concentration of near bottom water at Dona Paula was 4.8(±1.0) mg. l^{-1}, at Chicalim 4.5(±1.3) mg. l^{-1}, at Cortalim 4.4(±1.1) mg.l^{-1}, at Loutolim 4.8(±1.4) mg.l^{-1}, at Borim 4.6(±0.7) mg.l^{-1}, at Shiroda 5.0(±1.0) mg.l^{-1} and at Kushavati it was 5.2(±1.5) mg.l^{-1} (Figure 3.5.1) during the study. The DO concentrations were slightly higher at the upstream stations compared to the downstream station and it significantly varied with the stations (ANOVA; F = 0.08, df = 6, p = 0.9). The variation in the DO was higher during post-monsoon and monsoon months with an average DO of

3.8±1.0 mg. l^{-1} (Table 3.5.1). The concentration of DO during monsoon and post monsoon months was lower (3.9±1.1 mg. l^{-1}) compared to pre-monsoon months (4.2±1.0 mg .l^{-1}). The chlorophyll *a* concentration was low in near bottom water at Dona Paula (1.0±0.8 mg.m^{-3}) and Chicalim (1.7 ±1.3 mg. m^{-3}), when compared to other stations. (Cortalim 4.4±1.1 mg. m^{-3}, Loutolim 4.8±1.4 mg. m^{-3}, Borim 4.6±0.7 mg.m^{-3}, Shiroda 5.0±1.0 mg. m^{-3} and Kushavati 5.2±1.5 mg. m^{-3}) (Figure 3.5.1d), and it significantly varied among the stations (ANOVA; F = 0.60, df = 6, p = 0.72). Monthly variations in chlorophyll *a* indicated that it was maximum during pre-monsoon months (April and May, 2014) and (April and June 2015) with an average concentration of 3.41 mg. m^{-3} (Table 3.5.1). Higher concentration of chlorophyll *a* in the near bottom water was observed at upstream stations (Shiroda and Kushavati), in particular during pre-monsoon and early monsoon months (Table 3.5.1). The suspended particulate matter (SPM) varied with stations (ANOVA; F = 5.8, df = 6, p = 0.00002), and the maximum SPM was observed at Cortalim 149.8(±91.3) mg. m^{-3} followed by Dona Paula 137.2(±98.2) mg. m^{-3}, Chicalim 130.0(±55.0) mg. m^{-3}, Loutolim 98.1(±46.3) mg.m^{-3}, Borim 82.0(±56.3) mg.m^{-3}, Shiroda 65.1(±38.4) mg.m^{-3} and it was minimum at Kushavati 58.2(±36.1) mg.m^{-3}, which is an upstream station during the study (Table 3.5.1). SPM varied seasonally in the Zuari estuary during PreM season and the overall SPM was 95.2 mg. m^{-3}, during MON it was 65.1 mg. m^{-3}, whereas it was comparatively higher during POM - 153.1 mg. m^{-3} (Table 3.5.1). The concentrations of near bottom water nutrients were presented as an Appendix Figure 3.5.1. The concentrations of ammonia (NH_4) was high during pre-monsoon month, April 2014 (114.8±27.8 µM) and the overall concentration was 18.3±22.9 µM (Appendix Figure No 3.5.1 and Appendix Table 3.5.1) (ANOVA; F = 0.1, df = 6, p = 0.98). The average PO_4 concentrations recorded in the bottom waters during the sampling period was 2.9(±3.4) µM (Appendix Figure 3.5.1 and Table 3.5.1b) (ANOVA; F = 0.52, df = 6, p = 0.78). The concentration of SiO_4 was high towards the upstream stations (Shiroda and Kushavati) and it ranged from 3.81(±21.3) to 107.89(±26.3) µM and the overall average was 29.4(±23.8) µM (Appendix Figure and Table 3.5.1) (ANOVA; F = 4.3, df = 6, p = 0.0004).

Table 3.5.1. Variations in the near bottom water parameters at Zuari estuary during different months. (DP- Dona Paula, CH- Chicalim, CR- Cortalim, LU- Loutolim, BR- Borim, SR- Shiroda, KV- Kushavati).

Temperature °C								Salinity							Dissolved oxygen $mg.l^{-1}$						
Months	DP	CH	CR	LU	BR	SR	KV	DP	CH	CR	LU	BR	SR	KV	DP	CH	CR	LU	BR	SR	KV
November-13	-	26.7	26.4	26.3	26.4	26.3	26.2	34.4	33.4	31.6	25.3	14.3	5.7	0.9	3.0	2.1	4.9	4.3	3.7	3.8	4.1
December- 13	-	27.7	27.8	28.1	27.8	27.7	27.8	34.5	32.4	30.4	25.0	18.9	13.1	5.2	5.1	4.6	5.4	4.7	5.3	4.8	3.5
January-14	28.5	30.5	30.5	31.0	30.0	30.5	30.5	34.3	34.0	33.2	31.1	17.5	14.1	5.5	5.3	6.0	2.9	3.6	4.9	5.3	
March-14	28.1	29.0	29.5	30.1	30.1	29.7	28.4	34.9	30.9	31.0	22.5	15.5	8.5	2.5	5.5	6.9	5.4	5.4	4.1	5.0	5.9
April-14	30.1	30.4	30.4	31.0	31.0	30.0	30.4	34.6	32.0	31.2	22.8	16.1	9.1	1.8	5.5	4.3	3.1	3.8	4.7	3.5	4.1
May-14	31.5	31.7	31.9	32.2	32.2	32.1	31.8	35.0	32.3	31.4	22.6	16.9	10.6	3.0	5.1	4.8	5.4	4.5	4.7	5.1	3.4
June-14	-	30.5	30.1	30.6	31.0	30.9	30.6	-	27.1	30.1	25.0	20.5	15.8	6.3		4.3	3.8	5.2	4.0	4.8	3.7
July-14	-	26.7	26.4	26.3	26.4	26.3	26.2	-	13.8	1.3	0.2	0.1	0.1	0.0		6.0	5.3	5.8	4.5	6.0	5.4
August-14	-	27.7	27.8	28.1	27.8	27.7	27.8	-	11.9	7.8	0.5	0.1	0.1	0.0		4.4	5.6	5.2	3.3	5.0	3.8
September-14	-	27.3	27.4	27.3	27.1	27.1	26.6	-	19.8	11.0	9.1	0.1	0.0	0.0		2.8	3.3	5.4	2.9	5.7	6.4
November-14	29.1	29.2	29.3	29.7	29.7	29.2	28.3	32.8	30.8	29.0	22.1	12.3	3.6	0.3	4.3	4.3	2.5		3.8	3.2	5.0
February-14	27.9	28.1	28.3	28.7	28.9	28.5	27.7	32.6	31.5	30.8	26.8	21.2	15.7	6.8	3.8	3.1	3.4	5.7	3.0	4.3	4.0
March-15	27.1	27.1	27.4	28.1	28.3	28.3	27.8	32.4	31.3	30.0	25.4	19.4	14.4	5.8	5.5	4.3	3.0	4.0	4.5	3.4	5.4
April-15	30.9	31.7	31.8	32.2	32.3	32.3	31.8	34.7	33.1	31.8	29.4	22.1	15.3	6.3	2.8	3.2	2.6	2.0	4.1	4.4	6.3
June-15	30.8	31.3	31.6	31.9	32.3	32.4	31.9	34.9	32.2	31.0	27.2	17.1	9.0	0.0	3.5	2.9	3.6	2.9	3.0	3.1	3.5
July-15	28.7	28.4	28.5	28.6	28.7	28.5	27.7	32.1	12.8	13.2	0.5	0.3	0.2	0.1	3.7	2.9	2.5	3.1	3.4	3.0	2.5
August-15	28.7	28.5	28.5	28.6	28.7	28.5	27.7	32.1	12.8	13.2	0.5	0.3	0.2	0.1	2.9	2.5	2.7	3.1	3.1	3.0	2.7
September 15	27.1	28.1	28.7	29.5	29.3	29.2	28.8	34.9	32.5	27.5	13.2	0.7	0.1	0.0	3.1	3.2	3.6	3.4	2.9	3.0	3.0
Min	27.1	26.7	26.4	26.3	26.4	26.3	26.2	32.1	11.9	1.3	0.2	0.1	0.0	0.0	2.8	2.1	2.5	2.0	2.9	3.0	2.5
Max	31.6	31.7	31.9	32.2	32.3	32.4	31.9	35.0	34.0	33.2	31.1	22.1	15.8	6.8	5.5	6.9	5.6	5.8	5.3	6.0	6.4
Std. deviation	1.6	1.8	1.9	2.0	2.0	2.1	2.0	1.2	8.8	11.2	11.7	9.0	6.5	2.8	1.1	1.5	1.2	1.2	0.8	1.1	1.3

Table 3.5.1. (contd...)

	Chlorophyll a mg.m³							Suspended particulate matter mg.m³						
Months	DP	CH	CR	LU	BR	SR	KV	DP	CH	CR	LU	BR	SR	KV
November-13	0.8	2.4	2.2	1.0	3.3	2.7	2.0	137.6	173.6	158.4	179.5	164.6	154.6	87.2
December- 13	1.6	1.7	2.1	2.9	3.1	4.5	1.8	102.0	119.3	189.3	96.0	65.4	77.2	87.2
January-14	1.2	0.7	1.0	1.0	0.8	1.1	1.0	114.0	121.0	165.0	110.0	74.0	65.0	87.0
March-14	0.4	0.6	0.7	0.3	0.4	0.5	0.7	124.0	104.0	98.0	104.0	78.0	68.0	74.0
April-14	3.5	3.3	2.8	3.4	3.1	4.1	5.5	138.4	135.2	134.8	114.8	105.6	92.8	50.8
May-14	1.4	4.0	4.6	2.0	2.0	2.2	3.6	123.4	127.2	258.8	45.8	49.0	46.8	55.2
June-14		1.7	1.7	3.3	6.3	5.0	3.1		98.0	101.0	87.0	68.0	58.0	47.0
July-14		0.5	0.7	0.7	0.9	0.3	0.1		65.0	87.0	85.0	67.0	48.0	67.0
August-14		1.0	1.4	1.4	1.2	1.1	0.5		68.0	87.0	89.0	58.0	48.0	54.0
September-14		0.5	0.7	0.5	0.3	0.4	0.4		84.9	87.6	86.6	85.3	89.6	86.3
November-14	0.5	0.5	0.5	0.4	0.7	0.7	1.5	463.0	307.0	452.0	202.0	224.0	41.0	13.0
February-14	0.5	0.7	0.7	0.5	0.2	0.4	0.4	114.0	187.0	196.0	147.0	188.0	141.0	158.0
March-15	1.1	2.4	2.3	3.2	1.5	0.7	1.0	147.0	110.0	147.0	98.0	74.0	65.0	38.0
April-15	0.7	6.0	5.7	8.0	3.8	1.8	2.5	45.6	129.2	128.0	60.8	30.4	52.0	17.2
June-15	1.6	3.2	2.3	4.0	5.1	3.3	2.0	128.0	153.0	128.0	134.0	67.0	83.0	35.0
July-15	0.3	0.4	0.8	0.6	0.5	0.3	0.2	137.0	122.0	25.0	24.0	17.0	13.0	55.0
August-15	0.3	0.4	0.8	0.6	0.5	0.3	0.2	77.4	88.9	124.2	36.0	20.0	13.8	3.0
September-15	0.6	0.6	0.5	0.6	1.2	1.4	0.6	70.0	147.3	129.7	67.1	40.0	16.0	32.0
Min	0.3	0.4	0.5	0.3	0.2	0.3	0.1	45.6	65.0	25.0	24.0	17.0	13.0	3.0
Max	3.5	6.0	5.7	8.0	6.3	5.0	5.5	463.0	307.0	452.0	202.0	224.0	154.6	158.0
Std. deviation	1.0	1.8	1.7	2.3	2.0	1.7	1.7	98.3	55.0	91.3	46.3	56.4	38.4	36.1

The concentration of nitrite ranged from 0.02(±1.4) µM at Kushavati (September 2015) to 5.5(±1.3) µM at Dona Paula during June 2015, indicating its variation between the stations and the overall average was 1.4(±1.2) µM (Appendix Figure and Table 3.5.1d) (ANOVA; $F = 0.8$, df = 6, p = 0.54). The NO_3 concentrations were high (up to 147.0 µM) during the month of June 2015, the range was from 0.08(±38.2) µM in March 2015 to 147.05 (±38.2) µM, and the overall average did not vary much among the stations with an average nitrate concentrations of 9.7 µM respectively (Appendix Figure and Table 3.5.1e) (ANOVA; $F = 0.75$, df = 6, p = 0.6).

3.5.2b. Sediment parameters

The sediment texture composed of sand, silt and clay as their major components and their composition varied with stations and seasons (Figure 3.5.2). The percentage of sand was maximum 66.0(±19.39) % followed by silt 29.6(±18.6) % and clay 1.0(±3.2) % and this was true for most of the stations (Figure 3.5.2). The percentage of sand ranged between 61.1 to 97.5% at Dona Paula, 48.7 to 91% Chicalim, 2.76 to 82.4% at Cortalim, 26.8 to 88.9% at Loutolim, 38.7 to 92.0% at Borim, 26.1 to 96% at Shiroda and 49.6 to 94.4% at Kushavati (Figure 3.5.2a to g), indicating higher percantage of sand through out the estuary. The percentage of silt was comparatively low when compared to sand. However, its percentage indicated considerable variation at different stations, as it ranged from 2.3 to 38.1% at Dona Paula, 8.6 to 50.8% at Chicalim, 17.0 to 96.9% at Cortalim, 10.7 to 72.2% at Loutolim, 7.4 to 60.2% at Borim, 3.7 at 73.4% Shiroda and 5.4 to 47.8% at Kushavati (Figure 3.5.2a to g). The maximum amount of silt was observed in Cortalim and Loutolim which are the mid estuarine stations. Sand and silt dominated these stations and the changes in the texture is observed with the in changes in the seasons. Monthly variation in sediment composition were observed during the study, at Cortalim during the PreM ’14 silt was high compared to the other months. In May ’15 the silt content went up to 96.9% in Cortalim. In Dona Paula and Kushavati, the concentration of sand were particularly high compared to other stations, with an average of 85% and 75.1% respectively. The percentage of clay was minimum in the sediment and ranged between 0.1% to 31.4% (Figure 3.5.2a to g). The ternary plot indicated that the sediment texture of Zuari estuary is mostly sandy-silt and silty-sand with with meagre representation of clay (Figure 3.5.2h). The sediment total organic carbon ranged between 0.2 to 2.9% during the study indicating moderate sediment organic carbon. The OC ranged from 0.3 to 0.9% at Dona Paula, 0.2 to 2.0% at Chicalim, 1.1 to 2.0% at Cortalim, 0.9 to 2.9% at

Loutolim, 0.6 to 1.5% at Borim, 0.3 to 1.0% at Shiroda and Kusavati0.2 to 2.2% at Kushavati respectively (Figure 3.5.2 a to g), and it was observed that the range of organic carbon was narrow at the mid-estuarine stations. The sediment organic carbon was minimum at Dona Paula station.

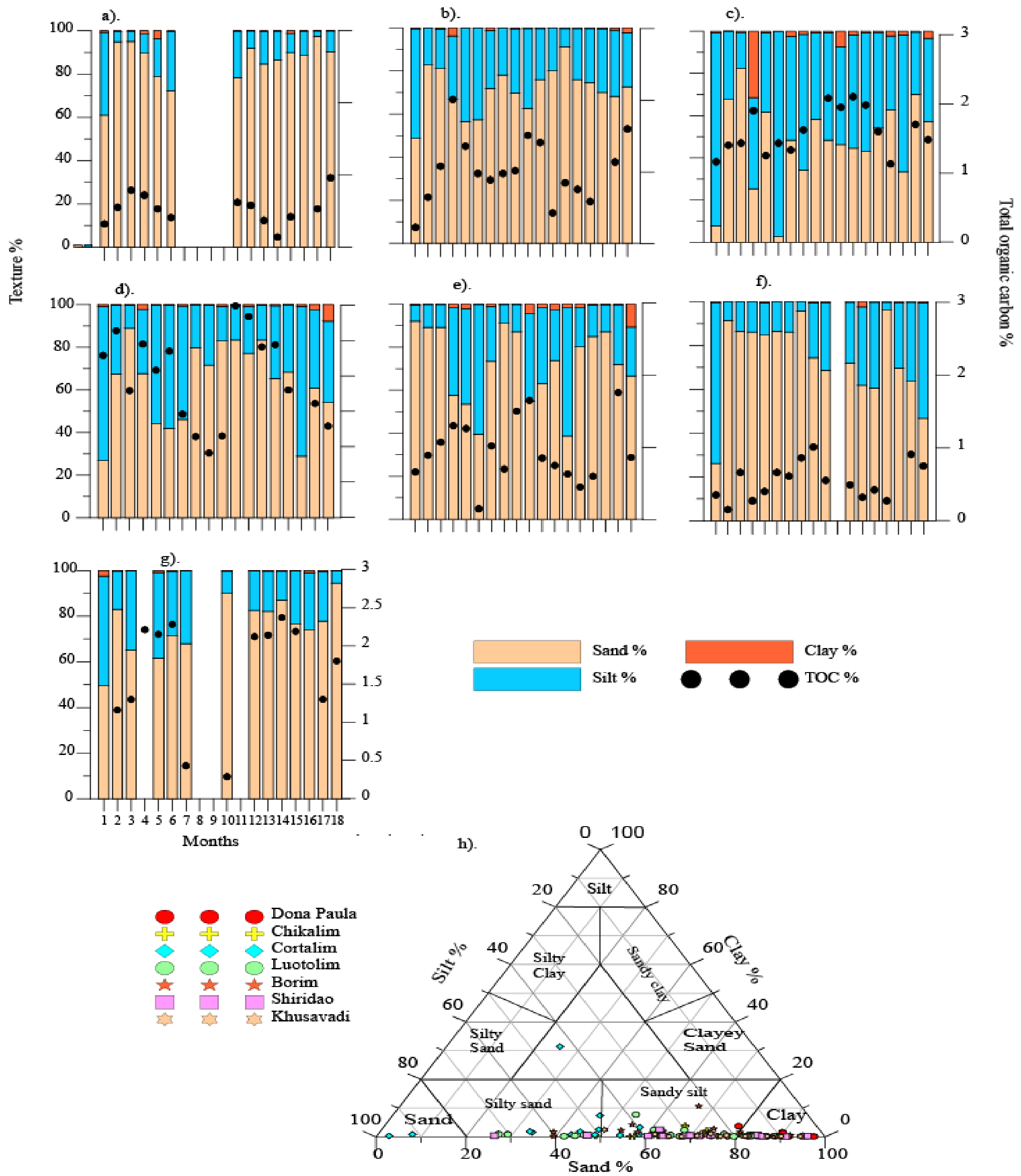


Figure 3.5.2: Monthly variations in the sediment texture and total organic carbon at different stations (a - Dona Paula, b - Chicalim, c - Cortalim, d - Loutolim, e - Borim, f - Shiroda and g - Kusavathi) and h). Ternary plot depicting the variations in the sediments texture.

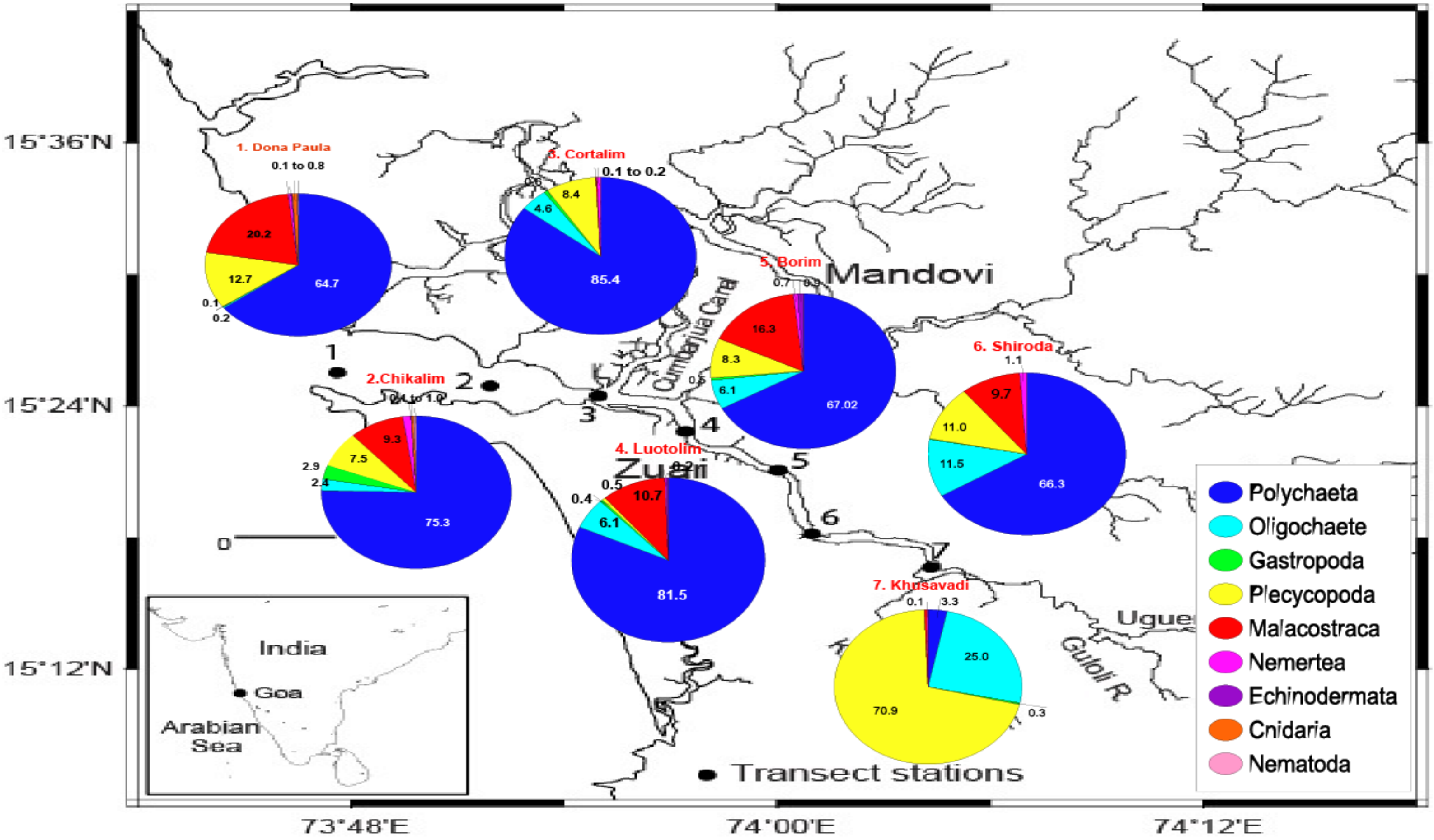
3.5.2c Seasonal variations in the abundance of macrobenthos at different sampling stations

The macrobenthos at Zuari estuary indicated a significant spatial variation in the abundance and diversity which is mainly comprised of Annelida (polychaeta and Oligochaeta), Arthropoda (crustaceans, amphipods, tanaids and isopods), Mollusca (bivalves and gastropods), Hydrozoa, Anthozoa, and Nematoda. The polychaetes were the most common and highly abundant organisms during all the months in most of the stations, except Kushavati. Among the 85 macrobenthic taxa, 50 taxa were polychaetes contributing more than 67% to the total abundance of macrobenthos during the study. The other forms which contributed to the total macrobenthos were Oligochaeta (5.9%), Nemertea (0.6%), Gastropoda (0.5%), Bivalvia (12.4 %), and 1% each contributed by Hydrozoa, Anthozoa, and Nematoda (Figure 3.5.3; Table 3.5.2). The stations were divided into three segments based on their locations and salinity gradients as A). Estuarine mouth (Dona Paula and Chicalim), B). Mid-estuary (Cortalim, Loutolim and Borim) and C). Upstream (Shiroda and Kushavati). The months were divided into three groups as Monsoon - MON (June, July, August and September), Post monsoon - PM (October, November, December and January) and Pre-monsoon - PreM months (February, March, April and May).

Seasonal variations in the macrobenthos at Dona Paula

The macrobenthos abundance at Dona Paula indicated monthly variations in the diversity, and abundance and a total of 59 taxa were observed at this station during the study. The total faunal taxa observed during POM, PreM and MON months were 40, 38 and 37 respectively. The maximum abundance was observed during POM months of November and December 2013 followed by November 2014 (Figure 3.5.4a: Table 3.5.2a). During PreM season the higher abundance on macrobenthos was observed during March 2014 and it was low during March 2015. During the MON season, the abundance was low compared to the non-monsoon season, and the abundance was maximum during June 2014 (343 no.m^{-2}) and minimum (64 no.m^{-2}) during July 2014 (Figure 3.5.4b). The abundance of macrobenthos during the POM months of November, December 2013 and January 2014 was 6064 no.m^{-2}, 4512 no.m^{-2} and 3571 respectively (Figure3.5.4b;Table3.5.2a).

Figure 3.5.3: - Variation in the major taxonomic groups observed at different stations of Zuari estuary during the study



The dominant taxa observed during November 2013 were bivalves (1386 no.m^{-2}), *Prionospio* sp. (1325 no.m^{-2}), *Mediomastus* sp. 1217 no.m^{-2}, and *Pseudopolydo*ra sp. (370 no.m^{-2}) and during December, the bivalves were maximum (1125 no.m^{-2}) followed by *Prionospio* sp. (724 no.m$^{-2)}$, *Mediomastus* sp. (524 no.m^{-2}) and the amphipod, *Ampelisca* sp. (478 no.m^{-2}) (Figure 3.5.4b; Table 3.5.2a). In January 2014, the amphipod *Ampelisca* sp. (832 no.m^{-2}) was dominant followed by Tanaidacea (647 no.m^{-2}), *Prionospio* sp. (355 no.m^{-2}) and *Mediomastus* sp. (355 no.m^{-2}) (Figure 3.5.4b) indicating a shift in the dominant taxa with change in the season at Dona Paula.

A gradual decrease in the total abundance of macrobenthos was observed from November 2014 to January 2015 and a shift in the occurrence of dominant species. During PreM month of March (2014) the total abundance was 2938 no.m^{-2}, and the arthropods were dominant. *Ampelisca* sp. (755 no.m^{-2}), Tanaidacea (586 no.m^{-2}), *Prionospio* sp. (432 no.m^{-2}) and *Nephtys* sp. (262 no.m^{-2}) (Figure 3.5.4c; Table 3.5.2a) and this increase in the abundance of microbenthic arthropods is being continued from the POM months as observed during January 2014. In the months of April and May, the total abundance was 1778 no.m^{-2} and 1549 no.m^{-2}, and the dominant taxa during April were *Prionospio* sp. (786 no.m^{-2}), *Naineris* sp. (124 no.m^{-2}) and *Eunice* sp. (216 no.m^{-2}) and in May, the abundant taxa were *Prionospio* sp. (478 no.m^{-2}), *Mediomastus* sp. (308 no.m^{-2}) and *Cossura* sp. (293 no.m^{-2}). During PreM (2014), the polychaetes showed fluctuations in their abundance, whereas *Ampelisca* and Tanaids were dominant in March while they disappeared during April and their abundance was during late PreM season. Polychaetes such as *Naineris* sp. and *Eunice* sp. were present only during one mid pre-monsoon month (April 2014) and they were absent during other months (Figure 3.5.4c). During MON season, in the month of June, July, August and September (2014) the total abundance was significantly low when compared to POM months and the abundance was 343 no.m^{-2}, 64 no.m^{-2}, 204 no.m^{-2} and 233 no.m^{-2} respectively (Table 3.5.2a). The dominant taxa observed during these months were *Glycera* sp. (77 no.m^{-2}) in June and they were absent during late MON months, *Tharyx filibranchia* (47 no.m^{-2}) in August'14, *Mediomastus* sp. (77 no.m^{-2}) and *Aricidea* sp. (62 no.m^{-2}) in September'14 respectively (Figure 3.5.4d).

The dominant taxa observed during the POM and PreM months of 2014, were either absent or their abundance was significantly low during the MON months indicating a change in the community structure with seasons. During POM (November, 2014) month the diversity increased due to gradual increase in the salinity, and the total abundance was 3585 no.m^{-2} and it was higher compared to the total abundance observed during November, 2013 (1520 no.m^{-2}) indicating an inter-annual variation in the abundance of macrobenthos (Figure 3.5.4A; Table 3.5.2a). The dominant taxa observed during November, 2014 were *Prionospio* sp. (1309 no.m^{-2}) followed by *Pseudopolydora* sp. (524 no.m^{-2}), and *Magelona* sp. (278 no.m^{-2}) (Table 3.5.2a). A comparison between POM of season 2014 and 2015 November month, the polychaete, *Prionospio* sp. was most dominant and the abundance of bivalve was considerably low in November 2015. The amphipod, *Ampelisca* sp. was not reported in November 2015, indicating a change in the community of dominant groups. In the PreM months of February, March and April (2015), the total abundance observed was 1520 no.m^{-2}, 683 no.m^{-2} and 1114 no.m^{-2} respectively and the dominant taxa were *Prionospio* sp. (447 no.m^{-2}), *Mediomastus* sp. (324 no.m^{-2}) and *Nephtys* sp. (154 no.m^{-2}) in the month of February, whereas, bivalvea (216 no.m^{-2}), *Prionospio* sp. (170 no.m^{-2}), *Mediomastus* sp. (139 no.m^{-2}) were dominant during March and in April the polychaete, *Prionospio* sp. (478 no.m^{-2}) was dominant followed by *Nephtys* sp. (124 no.m^{-2}) and *Cossura* sp. (170 no.m^{-2}) (Figure 3.5.4c; Table 3.5.2a). During PreM 2015 variation in the community structure of macrobenthos was observed from early to late pre-monsoon months. When compared to March 2014 the total abundance of the dominant taxa decreased during March 2015 and the dominant taxa, *Ampelisca* and Tanaidacea were greatly reduced. The overall abundance and diversity of dominant groups was higher during PreM 2014 compared to PreM 2015 (Table 3.5.2a).

Compared to MON of 2014, the abundance during MON of 2015 was almost similar, except during September 2015. The total abundance was 236 no.m^{-2} (June), 315 no.m^{-2} (July), 204 no.m^{-2} (August) and 1238 no.m^{-2} (September) respectively (Figure 3.5.4d; Table 3.5.2a) (during which monsoon, 2015). The dominant taxa observed during September'15 were *Mediomastus* sp. 324 no.m^{-2}, followed by *Cossura* sp. 293 no.m^{-2} and *Prionospio* sp. (201 no.m^{-2}) (Table 3.5.2a). In comparison to the MON months of 2014 and 2015, early and mid-monsoon months showed similarity in the abundance of macrobenthos, whereas, September (2015), showed increase in the diversity and abundance of macrobenthos (Table 3.5.2). During MON 2015, the opportunistic taxa such as *Prionospio* sp., *Mediomastus* sp., and *Cossura* sp. were greatly reduced in their count, and they were reported during mid and late MON months**.**

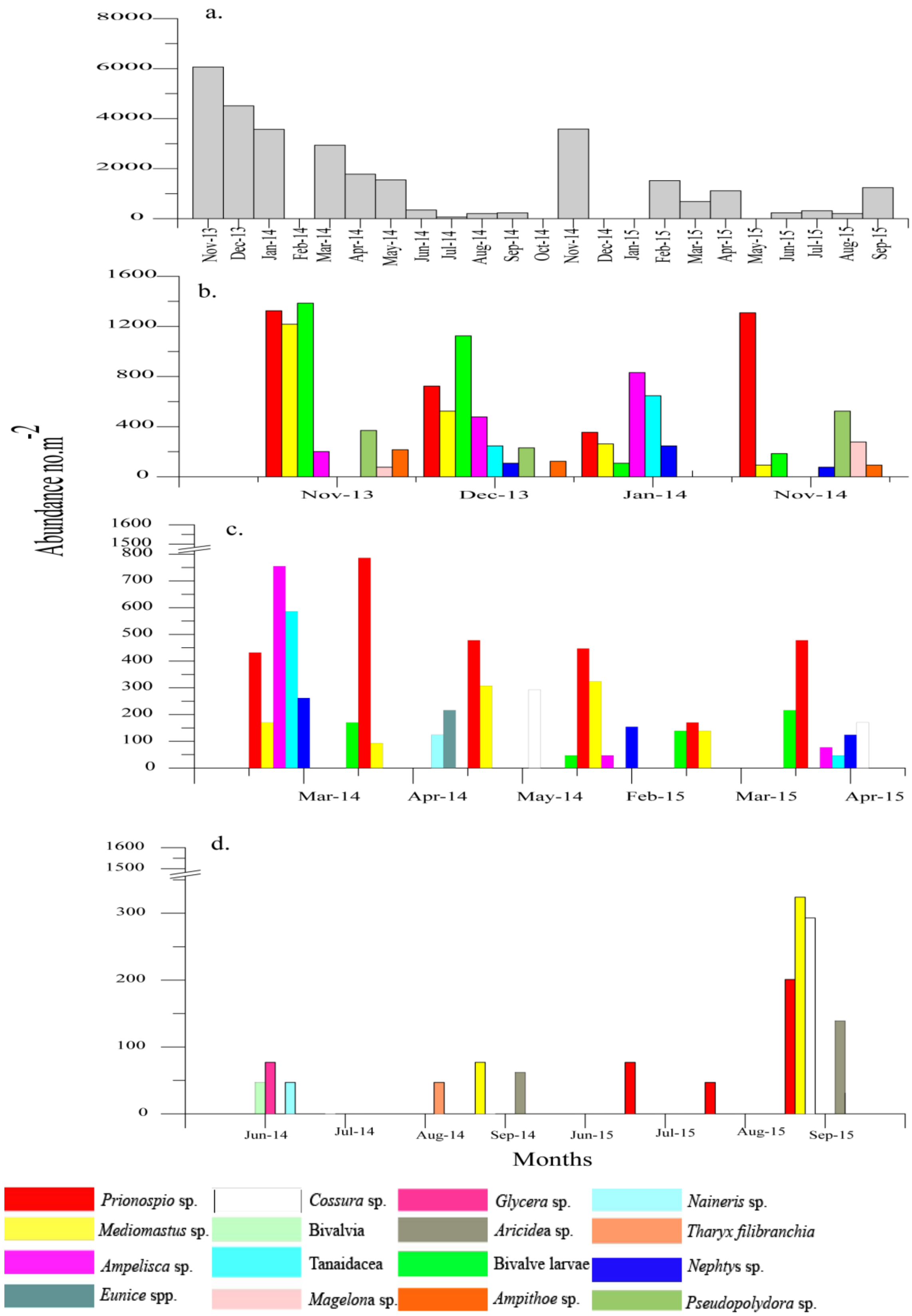


Figure 3.5.4. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Dona Paula station.

Table 3.5.2a. Abundance of macrobenthos (no.m^{-2}) observed at Dona Paula station during different months. (1)-Nov'13, (2)- Dec'13, (3)-Jan'14, (4)-Mar'14, (5)-Apr'14, (6)-May'14, 7()-Jun'14, (8)-Jul'14, (9)-Aug'14, (10)-Sep'14, (11)-Nov'14, (12)-Feb'15, (13)-Mar'15, (14)-Apr'15, (15)-Jun'15, (16)-Jul'15, (17) Aug'15 and(18). Sep'15).

Fauna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Prionospia sp.	1325	724	355	432	786	478	16	16			1309	447	170	478	16	77	47	201	6877
Mediomastus sp.	1217	524	262	170	93	308				77	93	324	139	16		31	16	324	3594
Bivalve larvae	1386	1125	108	170		47					185	139	216	31	62				3469
Ampelisca sp.	201	478	832	755		16				31		47	16	77	16	16			2485
Tanaidacea		247	647	586		16			16	16	16	16		47		16			1623
Nephtys sp.	62	108	247	262		16					77	154	16	124	16		31	108	1221
Pseudopolydora sp.	370	231	47	16							524	16		16					1220
Cossura sp.	47					293		16		31	16	16		170		16	31	293	929
Magelona sp.	77	62	47	77							278	93	47		47				728
Cumacea	170	154	77	16		16					139	16					31		619
Sternaspis sp.	62	47	139	62									47	77	47			16	497
Ampithoe sp.	216	124									93					16			449
Bivalvia				16			47		31		247	16						16	373
Glycera sp.	16	170	47				77					47				16			373
Gammarus sp.	77	47	139	77															340
Aricidea sp.	16	16								62	47			31			16	139	327
Anthuridae		47	124	47	16	16	16					47							313
Pectinaria sp.	231	62																	293
Kirkegaardia spp.	16	16	16	31		16					139			31		16			281
Naineris sp.	16		31		124		47		31									31	280
Phyllodoce spp.		16	31			170										16		16	249
Eunice spp.					216				31										247
Hesione sp.					170				16									31	217
Tharyx sp.	31			31	93							16				16	16		203

(Table 3.5.2a Contd…)

Fauna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Goniada sp.	77	31	31	16		16					16	16							203
Paraonis sp.	16		93	31							31	16							187
Poecilochaetus sp.		47	124	16															187
Notomastus sp.					124	31	31												186
Ancistrosyllis sp.	16		31									62	16	16	16			16	173
Nemertea	62		16	31	31						16							16	172
Segocephalus sp.	77	47							16										140
Hydrozoa	31										108								139
Anthozoa	108			16															124
Dendroneries sp.	31		16					16			47								110
Capitella sp.	16	16						16	16		16					16			96
Lumbrineris sp.		16	16	16		47													95
Maldanella sp.	16	47	16			16													95
Isopoda	31	31	16	16															94
Melinna sp.	31		47	16															94
Oligochaete											31					16		31	78
Syllis sp.					47												16		63
Ophiuroidea		16	16				31												63
Phylo sp.					31		31												62
Harmothoe sp.					16					16	16								48
Heteromastus sp.											47								47
Tharyx filibranchia									47										47
Glycinde sp.											47								47
Polydora sp.																47			47
Epidiopatra sp.		16		16															32
Nematoda							16				16								32
Chone sp.													16		16				32

(Table 3.5.2a Contd…)

Fauna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Nereis sp.											31								31
Gastropoda						31													31
Micronereis sp.							31												31
Decapod larvae		31																	31
Squilla sp.					31														31
Isolda sp.		16																	16
Chaetopteridae												16							16
Scoloplos sp.	16																		16
Pilargis sp.						16													16
Arthropoda				16															16
Amphipoda												16							16
Total	6064	4512	3571	2938	1778	1549	343	64	204	233	3585	1520	683	1114	236	315	204	1238	30151

Seasonal variations in the macrobenthos at Chicalim

Macrofauna at Chicalim indicated monthly variation with constant change in their diversity and abundance. The total number of taxa observed during POM, PreM and MON months were 38, 42 and 26 respectively. The total abundance was maximum during POM'13 (December) and in 2014 it was during January 2014 (2243 no.m^{-2}) and the abundance was minimum during November 2015 (729 no.m^{-2}) (Figure 3.5.5a). In PreM months of 2014 and 2015, the maximum and minimum abundance was observed during April 2015 (2238 no.m^{-2}) and May 2014 (558 no.m^{-2}). During MON the maximum abundance was observed during September 2014 (1006 no.m^{-2}) and it was minimum August 2015 and during this month macrobenthos were not encountered during the sampling (Figure3.5.5a). The abundance of macrobenthos during the POM months of November, December 2013 and January 2014 was (1488 no.m^{-2}), (1653 no.m^{-2}) and (2243 no.m^{-2}) respectively. The dominant fauna observed during November 2013 were bivalves (416 no.m^{-2}), *Gammarus* sp. (370 no.m^{-2}), *Prionospio* sp. (216 no.m^{-2}) and *Glycera* sp. (108 no.m^{-2}) (Figure 3.5.5b; Table 3.5.2b).

In the month of December, bivalve were dominant with a total abundance of 293 no.m^{-2}, followed by *Cossura* sp., *Polydora* sp. and *Streblospio* sp. each had 231 no.m^{-2} and *Prionospio* sp. (108 no.m^{-2}) (Figure 3.5.5b; Table 3.5.2b). In January 2014, there was an increase in total abundance (2243no. m^{-2}), and the dominant macrobenthos were *Prionospio* sp. (601 no.m^{-2}) followed by *Cossura* sp. and *Mediomastus* sp., each with an abundance of 231 no.m^{-2}, and *Nephtys* sp. (185 no.m^{-2}) (Figure 3.5.5b; Table 3.5.2b). During POM, November and December 2013 and January 2014, polychaetes such as *Prionospio* sp., *Cossura* sp. and *Mediomastus* sp. showed gradual increase in their abundance while, bivalves and amphipod *Gammarus* sp. population decreased. In November 2013, the abundance was dominated by bivalves, whereas in January 2014, the abundance of *Prionospio* sp. was maximum. During POM season, except bivalves, all other dominant taxa indicated an increase in their population. During PreM month of March (2014) (Total abundance 1672 no.m^{-2}), polychaetes *Prionospio* sp. (262 no.m^{-2}), C*ossura* sp. (231 no.m^{-2}), *Mediomastus* sp. and *Nephtys* sp. each (201 no.m^{-2}) were dominant (Figure 3.5.4B; Table 3.5.2b). In April and May 2014, the total abundance was 900 no.m^{-2} and 558 no.m^{-2} respectively, and *Eunice indica*, *Naineris sp*. with an abundance of 170 no.m^{-2} each were dominant followed by Anthuridae and Nemertea 124 no.m^{-2} each respectively (Figure 3.5.5c; Table 3.5.2b). During the month of May (PreM), the macrobenthic fauna decreased and the dominant taxa were C*ossura* sp. (185 no.m^{-2}), *Mediomastus* sp. (108 no.m^{-2}) and bivalves (108 no.m^{-2}) (figure 3.5.5c). In PreM 2014, the macrobenthic population showed variations in the dominant taxa; in March *Prionospio*, *Cossura*, bivalves and *Nephtys* were dominant, however, these were not encountered during April and again reported in May 2014, however, their count was low. In April 2014, motile benthos such as *Naineris* sp, *Eunice indica* and Anthuridae along with Nemertea worms were observed, which were absent during early and late PreM months. During MON, in the month of June, July, August and September (2014) the total abundance was 267 no.m^{-2}, 139 no.m^{-2}, 79 no.m^{-2} and 16 no.m^{-2} respectively indicating a low abundance of macrobenthos compared to other seasons. The dominant groups observed during April 2014 (PreM), were reported again during the MON month of July, albeit their abundance was low. During POM, in November, 2014 an increase in the abundance was observed which can be attributed to fresh recruitment owing to stabilised conditions and increase in the salinity, and the total abundance was 729 no.m^{-2}.The dominant taxa were *Prionospio* sp. 124 no.m^{-2} and *Lucifer* sp. 108 no.m^{-2}, (Table 3.5.2b). In comparison to the November 2013 and 2014, November'13 showed higher abundance and diversity. During February, March and April (2015) which are the PreM months, the total abundance was comparatively higher, and it was 1760 no.m^{-2}, 1826 no.m^{-2} and 2238 no.m^{-2} respectively. The dominant taxa were *Prionospio* sp. (539 no.m^{-2}), *Mediomastus* sp. (524 no.m^{-2}) and C*ossura* sp. (247 no.m^{-2}) in February 2015, in March 2015 they were *Prionospio* sp. (493 no.m^{-2}), *Mediomastus* sp. 432 no.m^{-2}, *Nephtys* sp. (124 no.m^{-2}) and *Cossura* sp. (108 no.m^{-2}) (Figure 3.5.5c). In April 2015, *Cossura* sp. (1094 no.m^{-2}) was the most dominant taxa followed by *Mediomastus* sp. (385 no.m^{-2}), *Prionospio* sp. (293 no.m^{-2}) and *Nephtys* sp. (108 no.m^{-2}) (Table 3.5.2b). In comparison to PreM 2014 and 2015, during PreM'15 the dominant taxa were in higher abundance.

Compared to the MON season of 2014, the abundance during 2015 was almost similar except during June and September 2015, and the total abundance was 503 no.m^{-2} (June 2014), 48 no.m^{-2} (July 2014), -NIL- (August 2014) and 1006 no.m^{-2} (September 2014) respectively (Figure 3.5.5d; Table 3.5.2b). The dominant taxa were *Nephtys* sp. (108 no.m^{-2}) and *Prionospio* sp. (47 no.m^{-2}), while in September 2015, the dominant taxa observed during other seasons (PreM and POM) such as *Prionospio* sp. (124 no.m^{-2}), *Mediomastus* sp. (231 no.m^{-2}), *Cossura* sp. (108 no.m^{-2}) and *Nephtys* sp. (77 no.m^{-2}) were observed. *Nephtys* sp. was reported in during early MON months (June

2015), however, they were absent during mid-monsoon months (July and August) and reappeared during the late MON month (September 2015) (Table 3.5.2b).

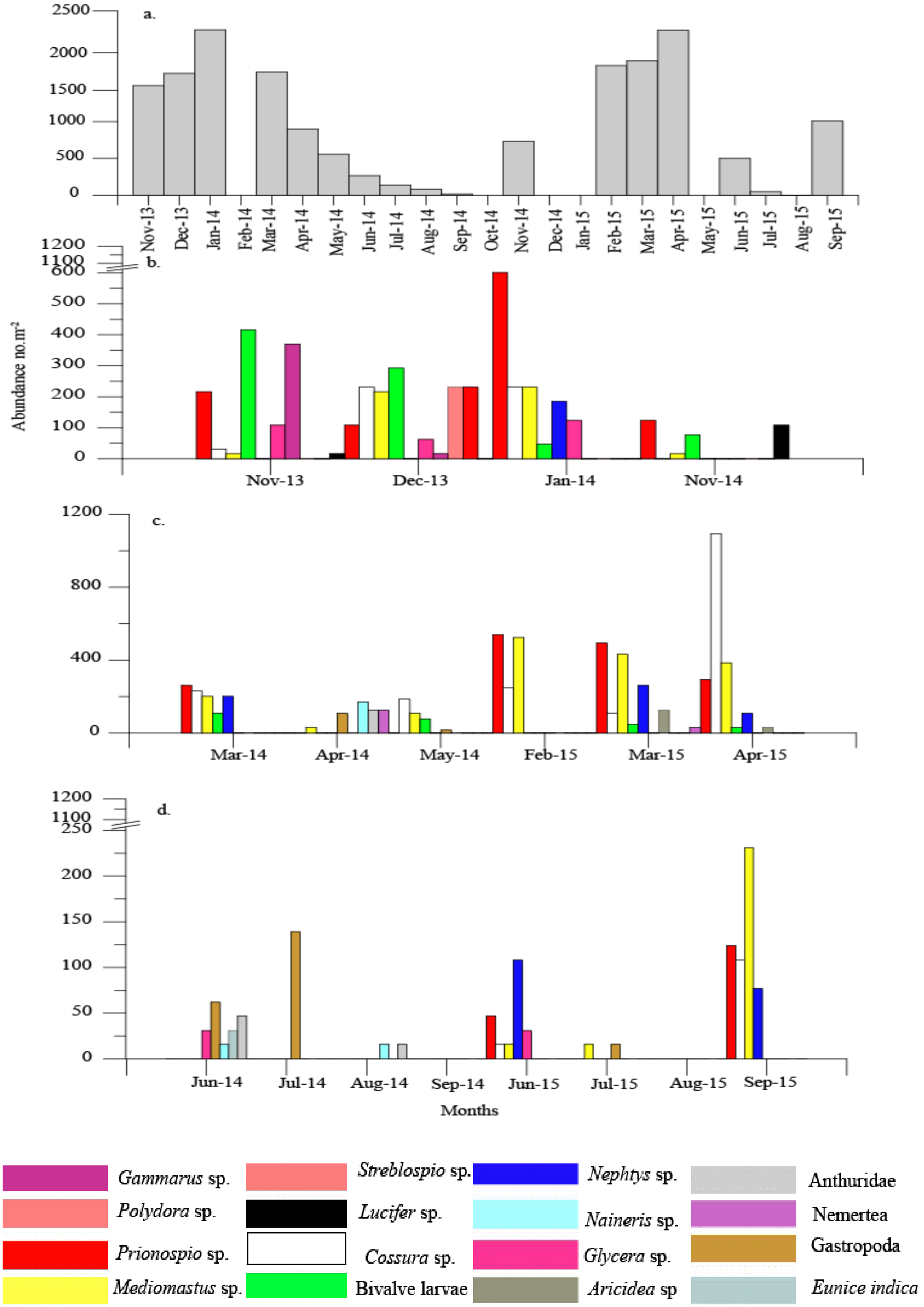


Figure 3.5.5. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Chicalim station.

Table 3.5.2b. Abundance of macrobenthos (no.m^{-2}) observed at Chicalim station during different months. (1)-Nov’13, (2)- Dec’13, (3)-Jan’14, (4)-Mar’14, (5)-Apr’14, (6)-May’14, 7()-Jun’14, (8)-Jul’14, (9)-Aug’14, (10)-Sep’14, (11)-Nov’14, (12)-Feb’15, (13)-Mar’15, (14)-Apr’15, (15)-Jun’15, (16)-Jul’15, (17)-Aug’15 and (18). Sep’15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Prionospia sp.	216	108	601	262							124	539	493	293	47			124	2807
Cossura sp.	31	231	231	231		185						247	108	1094	16			108	2482
Mediomastus sp.	16	216	231	201	31	108					16	524	432	385	16	16		231	2423
Bivalve larvae	416	293	47	108		77					77		47	31	47				1143
Nephtys sp.			185	201									262	108	108			77	941
Glycera sp.	108	62	124	31		16	31					154	31		31				588
Gastropoda	47	77	47		108	16	62	139								16			512
Oligochaete			185	93										16				124	418
Gammarus sp.	370	16										16						16	418
Aricidea sp.	16		170										124	31	16	16			373
Tharyx sp.			31	77	16							201							325
Polydora sp.		231												77					308
Order Cumacea	16			31		77						16	16		16			77	249
Ampelisca sp.	47	31	31	16									62	31	16				234
Streblospio sp.		231																	231
Nemertea		31			124								31		31			16	233
Kirkegaardia spp.		16	124			16							16	31	16				219
Sternaspis sp.				77									47	47	47				218
Goniada sp.			16	16		16							77	62	16				203
Naineris sp.					170		16		16										202

(Table 3.5.2b Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Eunice indica					170		31												201
Family Anthuridae					124		47		16										187
Lucifer sp.	16										108		16		16				156
Bivalvia				62	47							31						16	156
Paraonis sp.	31	31				31							16	16	16				141
Isolda sp.		16	77										16		16				125
Dendroneries sp.																		124	124
Capitella sp.	31		16							16	31	16							110
Glycinde sp.				16							93								109
Order Isopoda	16			77								16							109
Notomastus sp.	16			31	31		16												94
Magelona sp.	31	16									47								94
Scoloplos sp.											93								93
Lumbrineris sp.						16							16		16			31	79
Tanaidacea	16																	62	78
Class Hydrozoa											77								77
Nematoda			16	31							16								63
Eunice spp.			16	16					31										63
Pseudopolydora sp.	16	16	16																48
Decapod larvae			16								31								47
Family Penaeidae			31								16								47
Ampithoe sp.	16	31																	47
Heteromastus sp.													16		16				32
Dorvillea sp.					16		16												32

(Table 3.5.2b Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Epidiopatra sp.			16	16															32
Hesione sp.					31														31
Pilargis sp.				31															31
Tharyx filibranchia									16										16
Nereis sp.				16															16
Phylo sp.							16												16
Family Palymridae				16															16
Phyllodoce spp.				16															16
Ancistrosyllis sp.														16					16
Scolelepis sp.					16														16
Syllis sp.							16												16
Segocephalus sp.	16																		16
Melinna sp.			16																16
Squilla sp.					16														16
Class Ophiuroidea							16												16
Total	1488	1653	2243	1672	900	558	267	139	79	16	729	1760	1826	2238	503	48		1006	17125

Seasonal variations in the macrobenthos at Cortalim

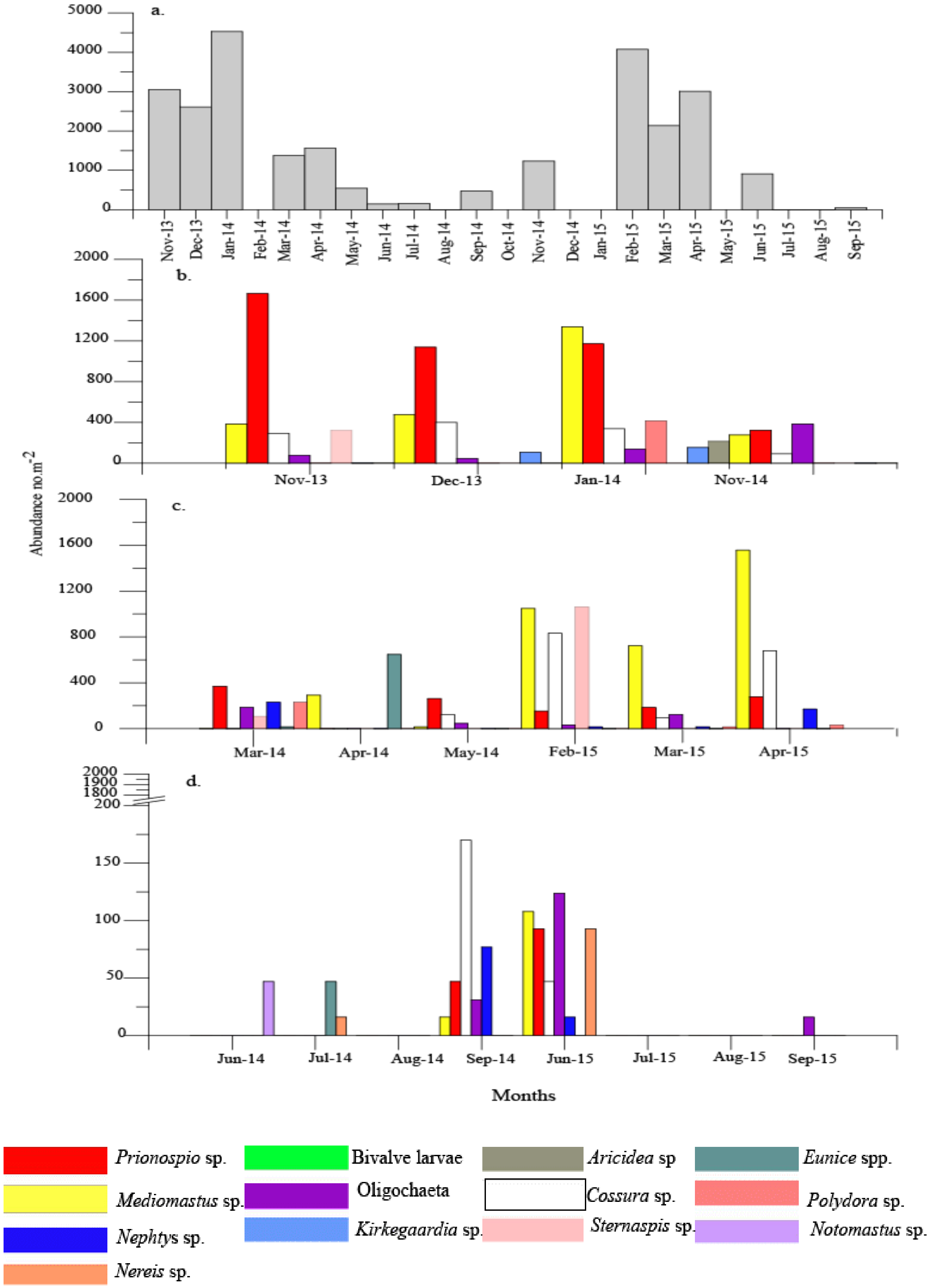


Figure 3.5.6. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Cortalim station.

A constant change in the diversity and abundance of macrobenthos was observed at Cortalim station and their abundance and diversity was comparatively higher than the adjacent stations. A significant monthly variation was observed in the population of macrobenthic taxa Cortalim.The abundance was maximum during January'14 (4534 no.m^{-2}) and the minimum during July '14, and macrobenthos were not reported during August 2014 and 2015 (Figure 3.5.6a). The abundance of macrofauna during the POM months of November, December 2013 and January 2014 was 3056 no.m^{-2}, 2611 no.m^{-2} and 4534 no.m^{-2} respectively.

The total macrobenthos taxa observed during POM, PreM and MON were 40, 40 and 36 respectively at Cortalim. The dominant fauna observed during November 2013 were *Prionospio* sp. 1664 no.m^{-2}, followed by bivalves (1386 no.m^{-2}), , *Mediomastus* sp. (385 no.m^{-2}), *Streblospio* sp. (324 no.m^{-2}) and *Cossura* sp. (293 no.m^{-2}) (Figure 3.5.6a; Table 3.5.2c). In December'13 also *Prionospio* sp. was dominant (1140 no.m^{-2}) followed by *Mediomastus* sp. (478 no.m^{-2}), *Polydora* sp. (416 no.m^{-2}) and *Cossura* sp. (401 no.m^{-2}) (Figure 3.5.6A; Table 3.5.2c). In January '14, the dominant taxa were *Mediomastus* sp., *Prionospio* sp., *Polydora* sp. and *Cossura* sp. (Figure 3.5.6b). Thus a change in the abundance of macrobenthos was observed from November'13 to January'14, and the polychaete *Mediomastus* sp. showed an increase in its abundance (Table 3.5.2c). During PreM months, in March (2014) (Total abundance 1375 no.m^{-2}), spionids were observed during the study and they were *Prionospio* sp. (370 no.m^{-2}), *Polydora* sp. (231 no.m^{-2}) along with *Nephtys* sp. (231 no.m^{-2}) and Oligochaeta (185 no.m^{-2}) (Figure 3.5.6c; Table 3.5.2c). In April and May (2014), the total abundance was 1560 no.m^{-2} and 544 no.m^{-2} (Figure 3.5.6a), and the dominant taxa during this month were *Eunice* sp. (647 no.m^{-2}) followed by *Mediomastus* sp. (293 no.m^{-2}) and in May *Prionospio* sp. (262 no.m^{-2}) was dominant followed by *Cossura* sp. (124 no.m^{-2}) (Figure 3.5.6c; Table 3.5.2c). Constant change in the dominant taxa were reported during the PreM months with April'14 showing sudden increase in *Eunice* spp. and disappearing in the late PreM months. In MON months of June, July and September (2014) the total abundance were greatly reduced compared to POM months the total abundance was 143 no.m^{-2}, 157 no.m^{-2}, 466 no.m^{-2} respectively and during August macrobenthos were absent. The dominant taxa observed during these months were *Notomastus* sp. (47 no.m^{-2}) in June, *Eunice* sp. (47 no.m^{-2}) in July and *Cossura* sp. (170 no.m^{-2}) in September respectively (Figure 3.5.6d; Table 3.5.2c). During POM (November, 2014) month the diversity increased when the freshwater input reduced, and the total abundance was 1236 no.m^{-2} (Table 3.5.2c) during this month. The dominant taxa were Oligochaeta (385 no.m^{-2}), *Prionospio* sp. (324 no.m^{-2}) and *Mediomastus* sp. (278 no.m^{-2}), and both the taxa were sedentary polychaetes (Figure 3.5.6b; Table 3.5.2c). During. PreM months February, March and April (2015), the total abundance was 4075 no.m^{-2}, 2139 no.m^{-2} and 3010 no.m^{-2} respectively and *Sternaspis* sp. 1063 no.m^{-2}, *Mediomastus* sp. 1048 no.m^{-2} and *Cossura* sp. 832 no.m^{-2} were dominant during February 2015, and in March 2015 *Mediomastus* sp. (724 no.m^{-2}), Decapod larvae (216 no.m^{-2}), *Prionospio* sp. (185 no.m^{-2}) and Oligochaeta (124 no.m^{-2}) were dominant. An increase in the abundance of *Mediomastus* sp., (556 no.m^{-2}) was observed during April 2015 which was followed by *Cossura* sp. (678 no.m^{-2}) (Figure 3.5.6c; Table 3.5.2c). In general the abundance of dominant groups decreased during March'15 and further a gradually increase during April'15. The polychaete, *Sternaspis* sp. was reported only during March'14 and February'15, whereas *Nephtys* sp. was abundant during March'14 and April'15 during PreM months. Compared to the previous MON (2014) the abundance during the MON of 2015 was similar except during June 2015. The total abundance was 908 no.m^{-2} during June, 48 no.m^{-2} during September), and macrobenthos were encountered during July and August months. The dominant taxa observed during September 2015 were *Mediomastus* sp. 108 no.m^{-2} and Oligochaeta (124 no.m^{-2}) during June 2015 (Figure 3.5.6d; Table 3.5.2c). Late start of MON, leads to the perseverance of macrobenthic communities, during early monsoon periods leading to higher abundance of macrobenthos

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Table 3.5.2c. Abundance of macrobenthos (no.m^{-2}) observed at Cortalim station during different months. (1)-Nov'13, (2)- Dec'13, (3)-Jan'14, (4)-Mar'14, (5)-Apr'14, (6)-May'14, 7()-Jun'14, (8)-Jul'14, (9)-Aug'14, (10)-Sep'14, (11)-Nov'14, (12)-Feb'15, (13)-Mar'15, (14)-Apr'15, (15)-Jun'15, (16)-Jul'15, (17)-Aug'15 and (18). Sep'15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Mediomastus sp.	385	478	1340		293	16				16	278	1048	724	1556	108				6242
Prionospia sp.	1664	1140	1171	370		262				47	324	154	185	278	93				5688
Cossura sp.	293	401	339			124				170	93	832	93	678	47				3070
Oligochaete	77	47	139	185		47				31	385	31	124		124			16	1206
Sternaspis sp.		16		108								1063							1187
Nephtys sp.	47		262	231						77	16	16	16	170	16				851
Eunice spp.			77	16	647			47											787
Polydora sp.			416	231									16	31	16				710
Ampelisca sp.	108											370							478
Glycera sp.		47	31	47		31						77	154	62	16				465
Decapod larvae												47	201	62	47				357
Nereis sp.		62	16					16					93	47	93				327
Tharyx sp.		16	216										47		47				326
Streblospio sp.	324																		324
Hesione sp.	16				247			16											279
Aricidea sp.			216										16	31	16				279
Family Tanaidacea				108	16		16					77	16		16			16	265
Kirkegaardia spp.		108	154																262
Ampithoe sp.		154									16	47							217

(Table 3.5.2c Contd…).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Anthuridae					154							62							216
Bivalve larvae	31	16								62			16	16	16				157
Gammarus sp.	16											31	93		16				156
Class Ophiuroidea		31										16	47		47				141
Goniada sp.	47			31									62						140
Penaeidae													93		47				140
Ancistrosyllis sp.		31				16						31	16		16				110
Isopoda		16										31	31		31				109
Capitella sp.										31	77								108
Pectinaria sp.		16											16	47	16				95
Cumacea			47									47							94
Naineris sp.					77		16												93
Notomastus sp.					31		47												78
Nemertea			16		16	16						16							64
Isolda sp.								31					16		16				63
Eunice indica					47		16												63
Epidiopatra sp.		16		16								31							63
Onuphinae sp.			47			16													63

(Table 3.5.2c Contd…).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Glycinde sp.						16					31								47
Segocephalus sp.		16						31											47
Harmothoe sp.											16	16							32
Family Capitellidae													16		16				32
Heteromastus sp.													16		16				32
Squilla sp.													16		16				32
Tharyx filibranchia				16				16											32
Scoloplos sp.			31																31
Scolelepis sp.	16													16					32
Megalopa larvae													16		16				32
Order Amphipoda					16					16									32
Pelecypoda							16												16
Melinna sp.	16																		16
Lumbrineris sp.			16																16
Chone sp.										16									16
Maldanella sp.												16							16
Phylo sp.							16												16
Luciferchacei sp.																		16	16
Family Palymridae					16														16
Paraonis sp.	16																		16
Phyllodoce spp.														16					16
Poecilochaetus sp.				16															16
Syllidae												16							16
Syllis sp.							16												16
Total	3056	2611	4534	1375	1560	544	143	157		466	1236	4075	2139	3010	908			48	25862

Seasonal variations in the macrobenthos at Loutolim

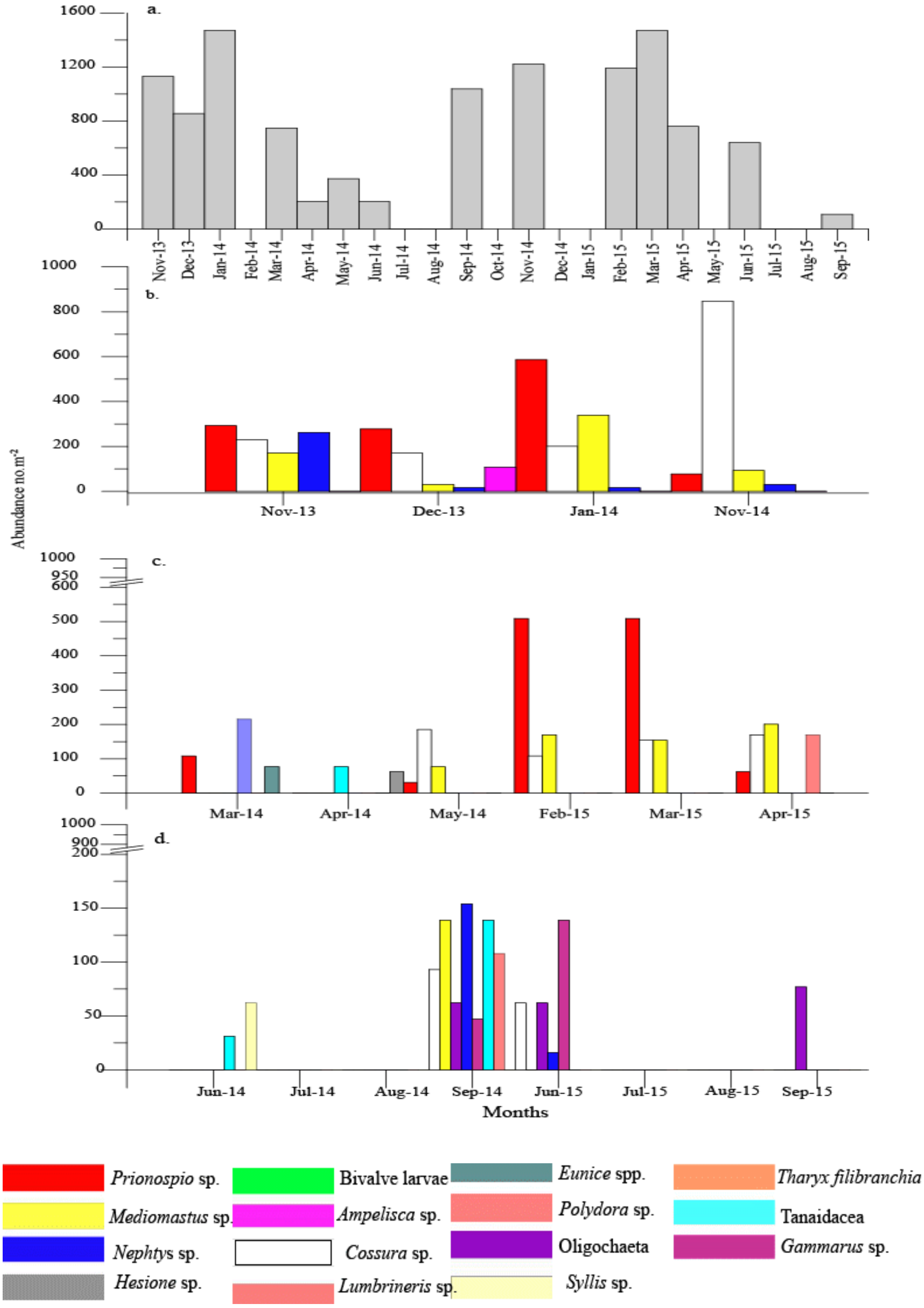

Figure 3.5.7. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Loutolim station.

The station, Loutolim a mid-estuarine station with brackish water salinity during non-monsoon months and low salinity to near fresh water during the monsoon months, and the sediment characteristics were mostly dominated by sand followed by silt. The maximum abundance of macrobenthos was observed during the POM month, January'14 and March'15 and each had total abundance of 1470 no.m^{-2} and the abundance was minimum during July and August of both 2014 and 2015 respectively (Figure3.5.7a). The total macrobenthos taxa observed during POM, PreM and MON were 36, 42 and 35 groups respectively, indicating favourable PreM conditions for the macrobenthos diversity. The total abundance during November, December (2013) and January 2014 were 1130 no.m^{-2}, 854 no.m^{-2} and 1470 no.m^{-2} respectively (Figure 3.5.7; Table 3.5.2d). The abundant macrobenthos were *Prionospio* sp. (293 no.m^{-2}), *Nephtys* sp. (262 no.m^{-2}), *Cossura* sp. (231 no.m^{-2}) in November, and during December the dominant species were *Prionospio* sp. (278 no.m^{-2}), *Cossura* sp. (170 no.m^{-2}) and *Ampelisca* sp. (108 no.m^{-2}). In January 2014, *Prionospio* sp. (586 no.m^{-2}), followed by *Mediomastus* sp. (339 no.m^{-2}) and *Cossur*a sp. (201 no.m^{-2}) were dominant (Figure 3.5.7a; Table 3.5.2d).

The abundance of dominant taxa was higher during November'13 and it decreased during December'13, however, they increased during late POM (January'14) except *Nephtys* sp. (Figure 3.5.7b). Though there is change in abundance of macrobenthos, there was no significant change in the community of the dominant taxa. During, PreM months (March, April and May 2014), the total abundance was 747 no.m^{-2}, 203 no.m^{-2} and 372 no.m^{-2} respectively (Figure 3.5.7c). The polychaete, *Tharyx filibranchia* (216 no.m^{-2}) was dominant followed by *Prionospio* sp. (108 no.m^{-2}) and *Eunice* spp. (77 no.m^{-2}) during March, Tanaidacea (77 no.m^{-2}) and *Hesione* sp. (62 no.m^{-2}) during April and (*Cossura* sp. 185 no.m^{-2}) and *Mediomastus* sp. (77 no.m^{-2}) in May 2014 (Figure 3.5.7c; Table 3.5.2d). A shift in the community of dominant taxa was observed during PreM 2014, as early PreM *Prionospio* sp., *Tharyx filibranchia* and *Eunice* spp. were abundant, while in April only Tanaidacea and *Hesione* sp., were in higher abundance, whereas in May *Cossura* sp. and *Mediomastus* sp. were abundant. The total abundance of macrobenthos was low during MON seasons. It was 203 no.m^{-2} in June, in July and August macrobenthos were not encountered at this station, and in September 2014 the total abundance was 1038 no.m^{-2} (Figure 3.5.7d; Table 3.5.2d). The dominant taxa during June'14 was *Syllis* sp. (62 no.m^{-2}) and during September *Nephtys* sp. (154 no.m^{-2}) followed by *Mediomastus* sp., Tanaidacea 139 no.m^{-2} each and *Lumbrineris* sp. 108 no.m^{-2}. Though macrobenthos were not reported during the mid-monsoon months and the community reappeared in late MON (September month) pointing out towards the restoration of benthic fauna (Figure 3.5.7d). During, November 2014 (POM) the total abundance of macrofauna was 1219 no.m^{-2} and *Cossura* sp. (847 no.m^{-2}) was dominant, followed by *Mediomastus* sp. (93 no.m^{-2}) and *Prionospio* sp. (77 no.m^{-2}) (Figure 3.5.7b; Table 3.5.2d). While compared the November 2013 and 2014, it indicated that the dominant groups almost equally distributed during these months, and *Cossura* sp. dominated with less population expansion of other groups.

During PreM 2015, in the month of Februarythe total abundance was 1191 no.m^{-2}, and the abundance of *Prionospio* sp. was 509 no.m^{-2}, *Mediomastus* sp. was 170 no.m^{-2} and *Cossura* sp. was 108 no.m^{-2} (Figure 3.5.7c). During March (1470 no.m^{-2}) the commonly found taxa were *Prionospio* sp. (509 no.m^{-2}), *Mediomastus* sp. and *Cossura* sp. with an abundance of 154 no.m^{-2} each (Figure 3.5.7c; Table 3.5.2d). During this season, the total abundance was minimum during April 2015 (760 no.m^{-2}). *Mediomastus* sp. (201 no.m^{-2}), *Cossura* sp. and *Polydora* sp. (170 no.m^{-2}) contributed to the total abundance during this month. The abundance of *Prionospio* sp. which was dominant during February and March, its population decreased during April'15, whereas, *Mediomastus* sp. and *Cossura* sp. showed gradual increase in their abundance (Figure 3.5.7c). During 2015 MON, in the month of June the total abundance was 639 no.m^{-2}, and in September it was 108 no.m^{-2}. Macrobenthic organisms were not reported during July and August month. The amphipod, *Gammarus* sp. (139 no.m^{-2}) was dominant during June and in September Oligochaeta (77 no.m^{-2}) was dominant (Table 3.5.2d). Similar pattern was also observed during the MON 2014 (Figure 3.5.7d)

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Table 3.5.2d. Abundance of macrobenthos (no.m^{-2}) observed at Loutolim station during different months. (1)-Nov'13, (2)- Dec'13, (3)-Jan'14, (4)-Mar'14, (5)-Apr'14, (6)-May'14, 7()-Jun'14, (8)-Jul'14, (9)-Aug'14, (10)-Sep'14, (11)-Nov'14, (12)-Feb'15, (13)-Mar'15, (14)-Apr'15, (15)-Jun'15, (16)-Jul'15, (17)-Aug'15 and (18). Sep'15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Prionospia sp.	293	278	586	108		31				31	77	509	509	62	16				2500
Cossura sp.	231	170	201			185				93	847	108	154	170	62				2221
Mediomastus sp.	170	31	339			77				139	93	170	154	201					1374
Oligochaete	16	62	77	16		31				62	108	77	62	47	62			77	697
Nephtys sp.	262	16	16	47						154	31		16	16	16				574
Sternaspis sp.	16	47	16	47								77	47	47	47				344
Gammarus sp.										47			139		139				325
Family Tanaidacea	16				77		31			139									263
Nereis sp.						16				31		16	77		77				217
Tharyx filibranchia				216															216
Goniada sp.				16								31	77	31	31				186
Polydora sp.														170					170
Ancistrosyllis sp.		47	16									31	31		31				156
Order Isopoda	31		47										31		31				140
Family Penaeidae						16						16	77		31				140
Glycera sp.	16	47	77																140
Lumbrineris sp.										108									108
Ampelisca sp.		108																	108
Syllis sp.	16				16		62												94
Pseudopolydora sp.			16							77									93

- (Table 3.5.2d Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Aricidea sp.	47												16		16				79
Tharyx sp.			31									16	16		16				79
Paraonis sp.												62		16					78
Dendroneries sp.										62	16								78
Eunice spp.				77															77
Isolda sp.		16		47															63
Hesione sp.					62														62
Maldane sp.				62															62
Order Cumacea										16			16		16				48
Class Pycnogonida			16										16		16				48
Phylo sp.							47												47
Gastropoda										16								31	47
Syllidae	16											31							47
Phylum Arthropoda				47															47
Class Ophiuroidea													16		16				32
Decapod larvae													16		16				32
Ampithoe sp.		16				16													32
Phyllodoce spp.			16	16															32
Pelecypoda					16		16												32

(Table 3.5.2d Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Pelecypoda					16		16												32
Bivalve larvae			16							16									32
Nemertea					16							16							32
Order Amphipoda										31									31
Kirkegaardia spp.												31							31
Glycinde sp.											31								31
Eunice indica							31												31
Capitella sp.		16																	16
Heteromastus sp.										16									16
Notomastus sp.							16												16
Epidiopatra sp.				16															16
Naineris sp.				16															16
Family Palymridae					16														16
Pilargis sp.											16								16
Segocephalus sp.				16															16
Total	1130	854	1470	747	203	372	203			1038	1219	1191	1470	760	639			108	11404

Seasonal variations in the macrobenthos at Borim

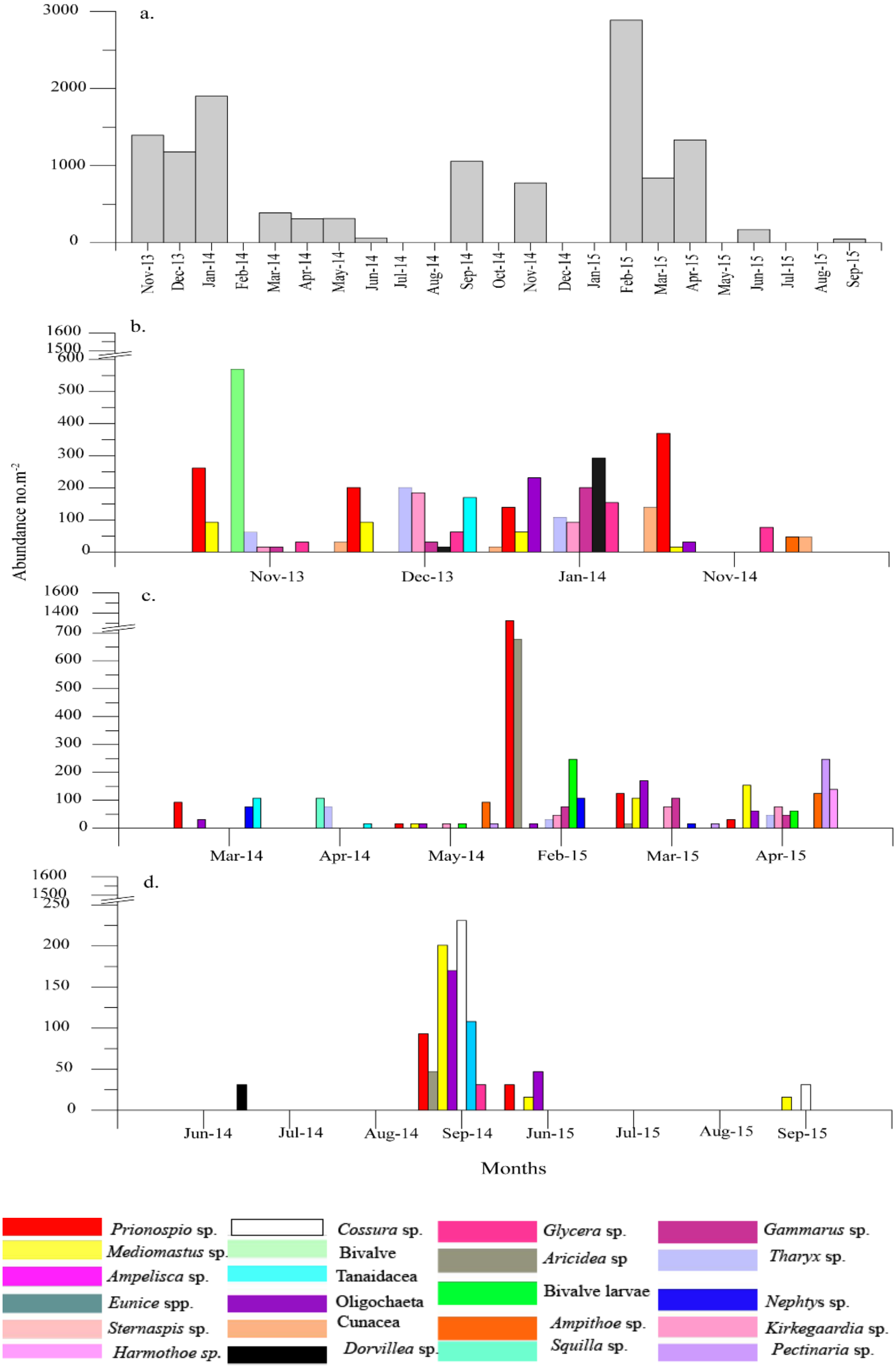

Figure 3.5.8.Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Borim station.

Borim is a mid-estuarine station with brackish water salinity during non-monsoon seasons and low salinity to near fresh water during monsoon season. The benthic sediment is sandy-silt. In the month of February 2015 the abundance was maximum (2888 no.m^{-2}) followed by January'14 (1902 no.m^{-2}). The minimum abundance was reported during the MON months of July'14, August'14, and July'15, August'15, in which no macrobenthos were reported (Figure 3.5.8a). The number of taxa during POM, PreM and MON were 41, 42 and 28 respectively. The total abundance during November, December (2013) and January'14 was 1395 no.m^{-2}, 1178 no.m^{-2} and 1902 no.m^{-2} respectively (Figure 3.5.8; Table 3.5.2e). During November 2013, bivalves (570 no.m^{-2}) were dominant followed by *Prionospio* sp. (262 no.m^{-2}) and *Mediomastus* sp. (93 no.m^{-2}). During December, *Prionospio* sp., *Tharyx* sp. (201 no.m^{-2} each) were in higher abundance followed by *Kirkegaardia* sp. (185 no.m^{-2}) and Tanaidacea (170 no.m^{-2}). Whereas in January'14, *Sternaspis* sp. (293 no.m^{-2}) were dominant followed by Oligochaeta (231 no.m^{-2}), *Gammarus* sp. (154 no.m^{-2}) and *Glycera* sp. (154 no.m^{-2}) (Figure 3.5.8b; Table 3.5.2e) indicating change in the community within different months of the season. During POM season 2013 and 2014, the abundance of *Prionospio* sp. and *Mediomastus* sp. decreased from early to late POM season, whereas *Gammarus* sp. and *Glycera* sp. indicated an increase in their abundance and the other dominant taxa indicated a constant change in their abundance (Figure 3.5.8b).

During PreM months, March, April and May 2014 the total abundance was 388 no.m^{-2}, 312 no.m^{-2} and 316 no.m^{-2} respectively. The dominant taxa were Tanaidacea (108 no.m^{-2}), *Prionospio* sp. (93 no.m^{-2}) and *Nephtys* sp. (77 no.m^{-2}) during March and during April, *Squilla* sp. (108 no.m^{-2}) and *Tharyx* sp. (77 no.m^{-2}) were dominant, however, during May'14, *Ampithoe* sp. (108 no.m^{-2}) was dominant (Figure 3.5.8c; Table 3.5.2e). The abundance of dominant macrobenthos during PreM'14 indicated a significant shift, and Tanaidacea were dominant during March and they decreased during April and absent during May, whereas as both *Squilla* sp., and *Tharyx* sp., were reported only during April. In May'14, *Ampithoe* sp., which was the most abundant macrobenthos and this was absent during other PreM months.

During MON season, the total abundance macrobenthos was 63 no.m^{-2} in June and 1056 no.m^{-2} in September 2014 (Table 3.5.2e). Macrobenthos were not encountered during July and August month at Borim station. During September, *Cossura* sp. (231 no.m^{-2}), *Mediomastus* sp. (201 no.m^{-2}), Oligochaeta (170 no.m^{-2}) and *Paraonis* sp. (108 no.m^{-2}) contributed to the total abundance (Figure 3.5.8d; Table 3.5.2e). A comparison between the November'13 and 2014, the total abundance and diversity reported in November'13 was twice as much as the abundance and diversity reported in November'14.

In 2015, PreM months, the abundance was 2888 no.m^{-2} during February 2015, *Prionospio* sp. (1325 no.m^{-2}), *Aricidea* sp. (678 no.m^{-2}), bivalve larvae (247 no.m^{-2}) and *Nephtys* sp. (108 no.m^{-2}) contributed maximum to the total abundance. The total abundance 841 no.m^{-2} during March 2015, and Oligochaeta (170 no.m^{-2}) followed by *Prionospio* sp. (124 no.m^{-2}) were abundant (Figure 3.5.8c; Table 3.5.2e). In April'15, an increase in the total abundance (1335 no.m^{-2}) was observed when compared to March 2015. *Pectinaria* sp. (247 no.m^{-2}), *Mediomastus* sp. (154 no.m^{-2}) and *Harmothoe* sp. (139 no.m^{-2}) indicated higher abundance during this month. The PreM'15, was highly productive in terms of abundance and dominant taxa when compared to PreM'14. The taxa which were dominant in February'15 (*Prionospio* sp., *Aricidea* sp., Bivalve larvae and *Nephtys* sp.) were either absent or recorded in low abundance during March and April'15. During MON months of 2015, the abundance during June was 174 no.m^{-2}, July and August macrobenthos were not reported and in September the abundance was 47 no.m^{-2} indicating adverse conditions during the peak monsoon months on the benthic macrofauna (Figure 3.5.8d; Table 3.5.2e).

Table 3.5.2e. Abundance of macrobenthos (no.m^{-2}) observed at Borim station during different months. (1)-Nov'13, (2)- Dec'13, (3)-Jan'14, (4)-Mar'14, (5)-Apr'14, (6)-May'14, 7()-Jun'14, (8)-Jul'14, (9)-Aug'14, (10)-Sep'14, (11)-Nov'14, (12)-Feb'15, (13)-Mar'15, (14)-Apr'15, (15)-Jun'15, (16)-Jul'15, (17)-Aug'15 and (18). Sep'15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Prionospio sp.	262	201	139	93		16				93	370	1325	124	31	31				2685
Aricidea sp.			93							47		678	16						834
Mediomastus sp.	93	93	62			16				201	16		108	154	16			16	775
Oligochaete			231	31		16				170	31	16	170	62	47				774
Bivalvia	570													16					586
Tharyx sp.	62	201	108		77							31		47					526
Kirkegaardia spp.	16	185	93			16						47	77	77					511
Gammarus sp.	16	31	201									77	108	47					480
Bivalve larvae	47	47	16			16					16	247		62	16				467
Sternaspis sp.		16	293		16					31		47		31	16				450
Cossura sp.	31	31				16				231		16	16	16				31	388
Glycera sp.	31	62	154								77	31	16						371
Nephtys sp.	16	31		77							47	108	16						295
Family Tanaidacea		170		108	16														294
Ampithoe sp.						93				16	47			124					280
Pectinaria sp.						16							16	247					279
Family Penaeidae	16		154			47					16	16		16					265
Order Cumacea	31	16	139								47			31					264

(Table 3.5.2e Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Goniada sp.		31	77							16		47			16				187
Scolelepis sp.	77		62		47														186
Paraonis sp.						16				108		31		16					171
Harmothoe sp.														139					139
Ampelisca sp.	16		16								31	16	16	31					126
Family Anthuridae		31	16									77							124
Class Ophiuroidea						16							31	77					124
Nereis sp.		16	16										47	16	16				111
Squilla sp.					108														108
Nemertea		16					16			16	31			16					95
Gastropoda	16										16		16		16				64
Pseudopolydora sp.	47										16								63
Syllis sp.						16							16	31					63
Poecilochaetus sp.												62							62
Decapod larvae	16												16	16					48
Eunice spp.				16	16									16					48
Lumbrineris sp.						16				16				16					48
Tharyx filibranchia				47															47

- (Table 3.5.2e Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Glycinde sp.										31	16								47
Amphipoda										16			16						32
Dorvillea sp.							31												31
Isolda sp.			16																16
Chone sp.	16																		16
Capitella sp.	16																		16
Notomastus sp.					16														16
Eunice indica					16														16
Magelona sp.										16									16
Maldane sp.				16															16
Scoloplos sp.												16							16
Phyllodoce spp.										16									16
Ancistrosyllis sp.										16									16
Pilargis sp.							16												16
Megalopa larvae										16									16
Order Isopoda													16						16
Luciferchacei sp.			16																16
Total	1395	1178	1902	388	312	316	63			1056	777	2888	841	1335	174			47	12672

Seasonal variations in the macrobenthos at Shiroda

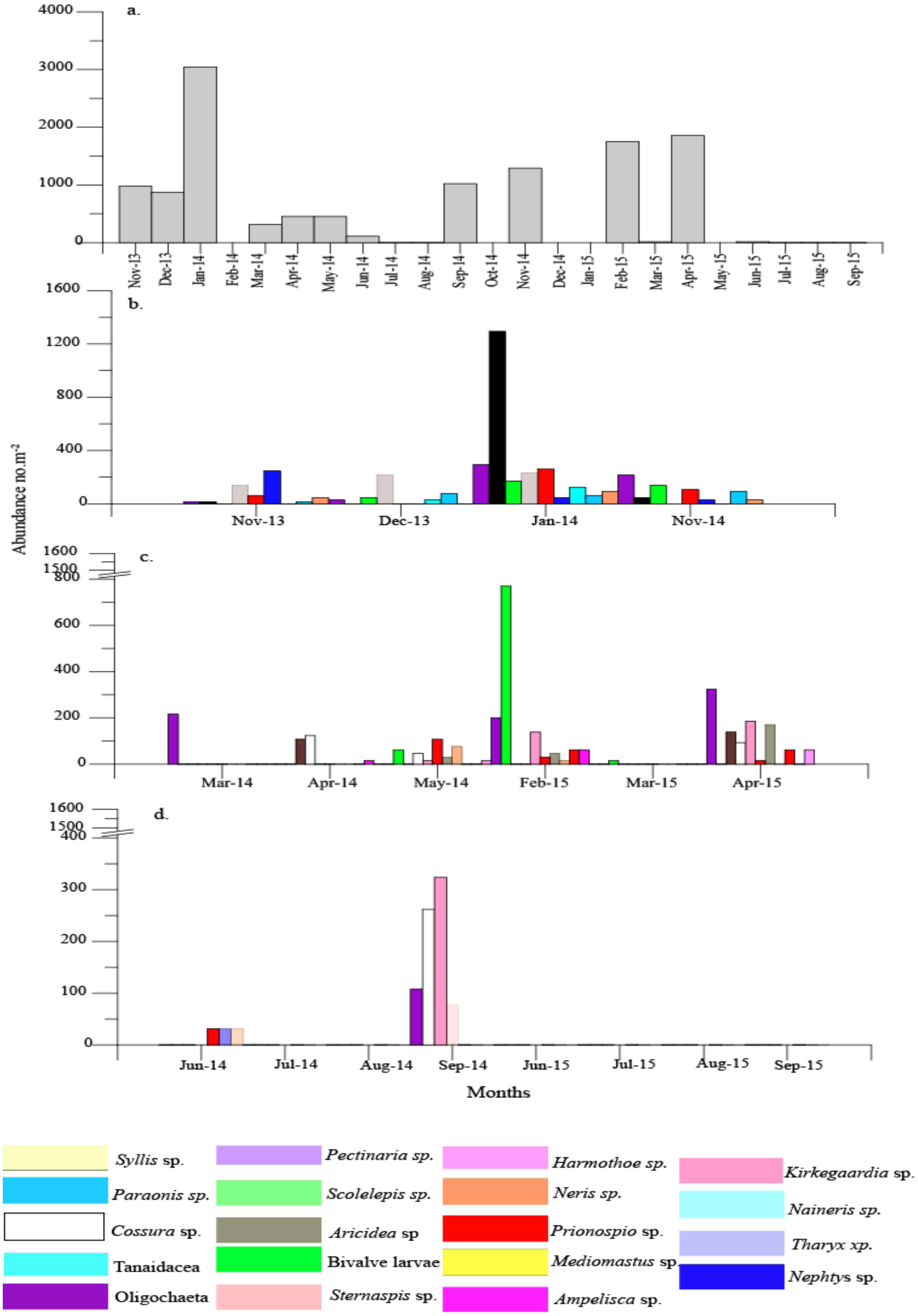

Figure 3.5.9. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Shiroda station.

Shiroda is an upstream station in the Zuari estuary with low salinity during non-monsoon months and fresh water conditions during monsoon season. The macrobenthos observed were mostly brackish water and freshwater tolerant species and there was a constant fluctuation in the occurrence of dominant taxa. The maximum abundance was reported during POM month of January'14 (3044 no.m^{-2}) and the least abundance was during MON months of July'14, August'14, July, August and September'15 and during these months benthic fauna were not reported (Figure 3.5.9a) at this station. The microbenthic taxa reported during POM, PreM and MON months were 48, 34 and 18. The total abundance during November, December (2013) and January 2014 was 980 no.m^{-2}, 874 no.m^{-2} and 3044 no.m^{-2} respectively (Figure 3.5.9a; Table 3.5.2f). The *Nepthys* sp. (247 no.m^{-2}), *Scolelepis* sp. (139 no.m^{-2}), *Prionospio* sp. (62 no.m^{-2}) were abundant during November, while in December *Scolelepis* sp. (216 no.m^{-2}), *Paraonis* sp. (77 no.m^{-2}) and bivalves (47 no.m^{-2}) were abundant (Figure 3.5.9b). In January 2014, the abundant taxa are *Sternaspis* sp. (1294 no.m^{-2}), followed by Oligochaeta (293 no.m^{-2}), *Scolelepis* sp. (231 no.m^{-2}), *Prionospio* sp. (262 no.m^{-2}) and *Scolelepis* sp. (139 no.m^{-2}). In November and December'13 the change in the abundance and community structure was more pronounced than January 2014.

Bivalves, *Prionospio* sp., *Nephtys* sp. and *Nereis* sp. were reported during November'13, and they were absent during December and reported again in January'14. In PreM months (March, April and May 2014), the total abundance was 311 no.m^{-2}, 453 no.m^{-2} and 453 no.m^{-2} respectively (Figure 3.5.9b; Table 3.5.2f). Oligochaeta (216 no.m^{-2}) were abundant during March, *Scolelepis* sp. (108 no.m^{-2}) and *Cossura* sp. (124 no.m^{-2}) during April and *Prionospio* sp. (108 no.m^{-2}), *Ancistrosyllis* sp. (77 no.m^{-2}) and bivalves (62 no.m^{-2}) were abundant in May 2014 (Figure 3.5.9c). PreM'2014 reported less diversity among the dominant groups during PreM, Oligochaeta was only dominant taxa reported during March and they were absent during the other pre-monsoon months. In May'14, even though the abundance was low at this station, it showed increased diversity among the PreM months (Table 3.5.2e). During the MON seasons, the total abundance was 109 no.m^{-2} in June, which is comparatively low than reported during September 2014 (1023 no.m^{-2}) and macrobenthos were not reported during July and August (Figure 3.5.9d; Table 3.5.2f). The dominant taxa during September'14 were *Kirkegaardia* sp. (324 no.m^{-2}), *Cossura* sp. (262 no.m^{-2}), Oligochaeta (108 no.m^{-2}), and *Paraonis* sp. (77 no.m^{-2}). During November 2014 (POM), the total abundance of macrofauna was 1290 no.m^{-2} and the most abundant taxa were Oligochaeta (216 no.m^{-2}), bivalves (139 no.m^{-2}), *Cossura* sp. (124 no.m^{-2}) and *Prionospio* sp. (108 no.m^{-2}) (Figure 3.5.9b; Table 3.5.2f).

Table 3.5.2f. Abundance of macrobenthos (no.m^{-2}) observed at Shiroda station during different months. (1)-Nov'13, (2)- Dec'13, (3)-Jan'14, (4)-Mar'14, (5)-Apr'14, (6)-May'14, 7()-Jun'14, (8)-Jul'14, (9)-Aug'14, (10)-Sep'14, (11)-Nov'14, (12)-Feb'15, (13)-Mar'15, (14)-Apr'15, (15)-Jun'15, (16)-Jul'15, (17)-Aug'15 and (18). Sep'15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Oligochaete	16	31	293	216						108	216	201		324					1405
Sternaspis sp.	16		1294								47								1357
Bivalve larvae		47	170			62				16	139	770	16		16				1236
Scolelepis sp.	139	216	231		108									139					833
Cossura sp.	16	62	62		124	47				262	124			93					790
Kirkegaardia spp.		16				16				324	47	139		185					727
Prionospia sp.	62		262			108				47	108	31		16					634
Mediomastus sp.	77				31					47		16		462					633
Nephtys sp.	247		47		47						31			62					434
Family Tanaidacea		31	124	31	16	16						77		93					388
Aricidea sp.	31	16	62			31				16		47		170					373
Paraonis sp.	16	77	62			16				77	93								341
Order Cumacea	31		31								62	47		47					218
Nereis sp.	47		93							31	31								202
Ancistrosyllis sp.	62					77				16	31	16							202
Magelona sp.	47	31	31								31	31		16					187
Glycera sp.		47	62		31							16							156
Ampelisca sp.	16	16										62		62					156

(Table .5.2f Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Nemertea	31									47	16	31		16					141
Tharyx sp.	16	16					31				47	16							126
Pseudopolydora sp.		31				16					77								124
Pelecypoda	62										16	16							94
Family Anthuridae		16			16							62							94
Gammarus sp.			62									31							93
Cirratulus sp.		16			16	16				16				16					80
Maldanella sp.			47								16			16					79
Harmothoe sp.						16								62					78
Eunice spp.			16								47								63
Dendroneries sp.	16	16	31																63
Naineris sp.				16	16		31												63
Goniada sp.											16	16		16					48
Ampithoe sp.		47																	47
Decapod larvae												47							47
Order Isopoda										16		31							47
Chone sp.											47								47
Lumbrineris sp.														47					47
Family Nereidae		47																	47
Phylo sp.		47																	47
Notomastus sp.							16					16							32
Isolda sp.		16	16																32

- (Table .5.2f Contd…)

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Total**
Micronereis sp.				16	16														32
Megalopa larvae			16								16								32
Poecilochaetus sp.	16					16													32
Syllis sp.							31												31
Gastropoda											16								16
Donax sp.	16																		16
Melinna sp.			16																16
Capitella sp.												16							16
Heteromastus sp.		16																	16
Tharyx filibranchia				16															16
Epidiopatra sp.						16													16
Hesione sp.					16														16
Scoloplos sp.														16					16
Phyllodoce spp.												16							16
Pectinaria sp.											16								16
Order Amphipoda		16																	16
Segocephalus sp.				16															16
Family Penaeidae			16																16
Squilla sp.					16														16
Total	980	874	3044	311	453	453	109			1023	1290	1751	16	1858	16				12178

While, compared the abundance and diversity of macrobenthos during November 2013 and 2014, it indicated that the groups which were dominant during November'13 (*Scolelepis* sp. and *Nephtys* sp.) were low in abundance or absent during November'14, and vice-versa for the year 2013. The total abundance during February'15 was 1751 no.m^{-2}, and the dominant macrobenthos were bivalves (770 no.m^{-2}), Oligochaeta (201 no.m^{-2}) and *Kirkegaardia* spp. (139 no.m^{-2}). During March the abundance was 16 no.m^{-2}, and this was contributed by bivalves. In April, there was an increase in the total abundance along with the diversity and the total abundance was 1858 no.m^{-2} (Table 3.5.2f). The most abundant taxa were *Mediomastus* sp. (462 no.m^{-2}), Oligochaeta (324 no.m^{-2}) and *Kirkegaardia* sp. (185 no.m^{-2}) respectively (Figure 3.5.9c; Table 3.5.2f). During, PreM'15, higher abundance and diversity was observed during early pre-monsoon month and in March the macrobenthos were mostly absent and again reappeared during late PreM month, April'15 (Figure 3.5.9c).

Seasonal variations in the macrobenthos at Kushavati

The maximum abundance of macrobenthos was observed during PreM months of February'15 (2065 no.m^{-2}) and April'14 (1849 no.m^{-2}). The lowest abundance was reported during MON months of August'14, July and August'15 when macrobenthos were not reported (Figure 3.5.10). The number of taxa observed during POM, PreM and MON months were 11, 11 and 5 groups, which is very low compared to other stations. The abundance during POM months of November and December 2013 was 895 no.m^{-2} and 1112 no.m^{-2} respectively and the dominant taxa were bivalves, Oligochaeta and during November and December 2014 only bivalves were reported. In January 2014, the abundance was lower than the previous months with a total abundance of 542 no.m^{-2}, and bivalves (293 no.m^{-2}), Oligochaeta (170 no.m^{-2}) and *Cossura* sp. (47 no.m^{-2}) contributed to the total abundance (Figure 3.5.10b; Table 3.5.2g). Continuous changes in the population of dominant taxa was observed from early to late POM months at this station. *Cossura* was reported only in January'14 during the POM season. During PreM months of 2014 (March, April and May) the total abundance fluctuated but the diversity reported was almost same. The abundance of macrobenthos in March was 988 no.m^{-2}, in April 1849 no.m^{-2} and in May it was 511 no.m^{-2} (Table 3.5.2 or Figure 3.5.10).

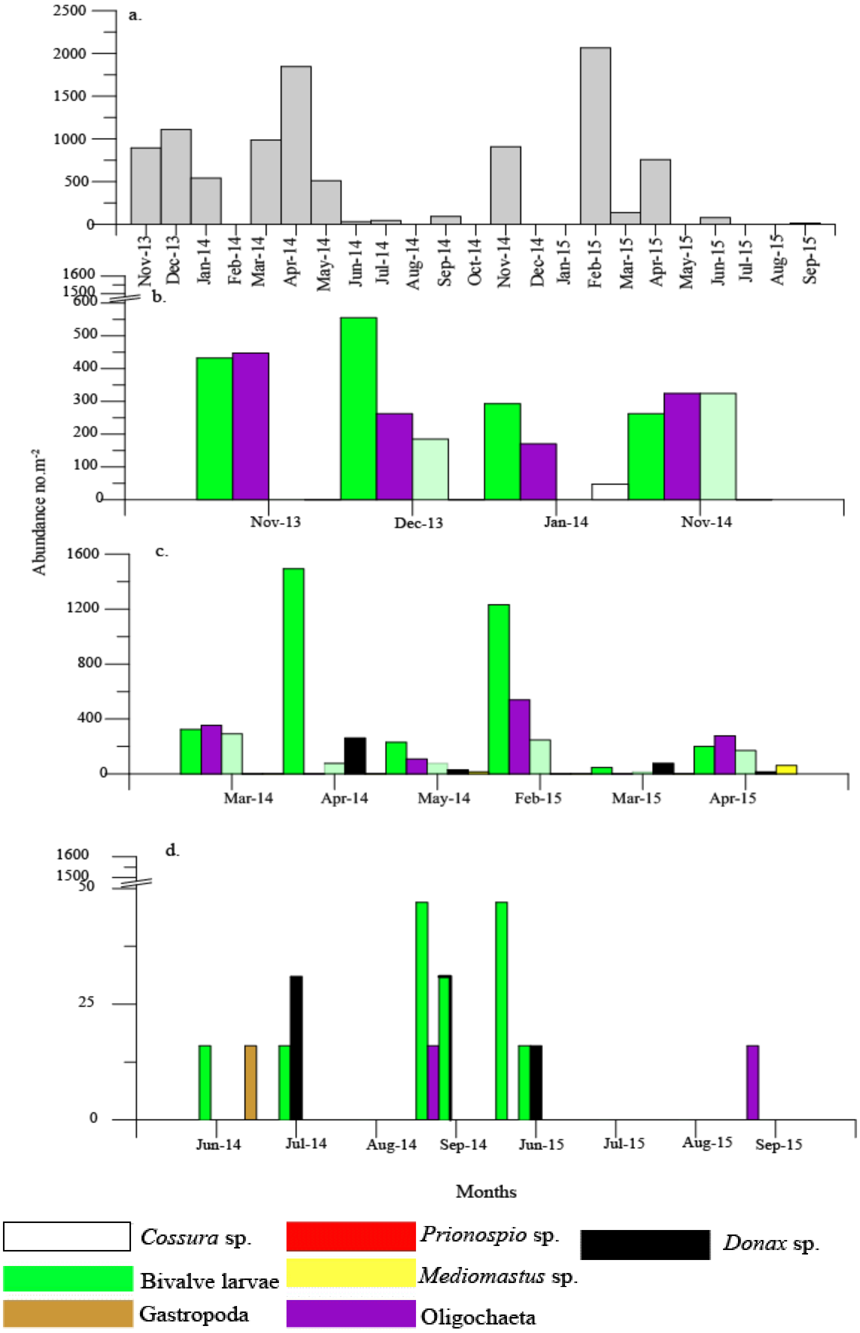

Figure 3.5.10. Variations in (a) Total abundance, and abundance of dominant species during (b) Post monsoon (c) Pre-monsoon and (d) Monsoon month's at Kushavati station.

During these months along with bivalves Oligochaeta were also observed, and macrobenthos such as *Cossura* sp., *Nepthys* sp., Nemertea and *Glycinde* sp., *Aricidea* sp., and *Cirratulus* sp. were also observed, however, their abundance was low (16 no.m^{-2}) (Table 3.5.2g). During MON season the abundance of these organism reduced considerably and the total count was 32 no.m^{-2} in June, 47 no.m^{-2} in July, and 94 no.m^{-2}

during September 2014 and in August macrobenthos were not reported at this station (Figure 3.5.10; Table 3.5.2g). The dominant taxa which were observed during the previous month (May 2014 – PreM) were observed during the MON season, however, their count was low. In November 2014 (POM season), the total abundance was 910 no.m^{-2} respectively (Figure 3.5.10d; Table 3.5.2g). In comparison to November'13 and 2014, apart from bivalve spat, bivalves (adults) were also reported during November'14, but the abundance of bivalve larvae and Oligochaeta were higher during November'13. During PreM (2015), the total abundance in the month of February, March and April was 2065 no.m^{-2}, 140 no.m^{-2}, and 759 no.m^{-2} respectively, and the dominant taxa were Bivalves, Oligochaetes, *Donax* sp. and *Mediomastus* sp. In PreM 2015, in the month of February an increased abundance in the macrobenthos was observed, while in March it was minimum and again increased in April, indicating a strong monthly variation in the macrobenthos abundance at this station. As previously observed (MON 2014) the macrobenthic abundance reduced or nil during MON months of (June, July, August and September) 2015 (Table 3.5.2g).

Monthly variation in the species diversity of macrobenthos at different stations

The species diversity index during different months at all the stations was estimated based on Margalef species richness (d), Shannon-Weiner index (H′) and evenness (J′). The occurrence of maximum number of species during the study varied with the stations. At Dona Paula, the maximum number of taxa were maximum during November 2013 (S=31), at Chicalim - March 2014 (S=23), at Cortalim and Loutolim during March 2015 (S=25 and 18 respectively), Borim - April 2015 (S=24), Shiroda -November 2014 and February 2015 (S=23) and at Kushavati during December 2013 and May-2014 (S=8) (Table 3.5.3). The species richness (d) observed at the various stations during the present study showed that, species richness was high during POM month at Dona Paula and in other stations it was high during PreM months and the lowest species diversity was observed during MON months at all stations. The range of evenness (J′) were 68 (November 2013) to 1. (July 2014) at Dona Paula, .98 (February 2015) to 1. (July 2015) at Chicalim, .97 (November 2013) to 1. (September2015) at Cortalim, .98 (November 2014) to .99 (June 2014) at Luotolim, .97 (September 2015) to 5.6 (April 2015) at Borim, .98 (March 2014)- -to .99 (February 2015) at Shiroda and .95 (November 2015) to 1. (June 2014) at Kushavati station (Table 3.5.3).

Table 3.5.2f. Abundance of macrobenthos (no.m^{-2}) observed at Kushavati station during different months. (1)-Nov’13, (2)- Dec’13, (3)-Jan’14, (4)-Mar’14, (5)-Apr’14, (6)-May’14, 7()-Jun’14, (8)-Jul’14, (9)-Aug’14, (10)-Sep’14, (11)-Nov’14, (12)-Feb’15, (13)-Mar’15, (14)-Apr’15, (15)-Jun’15, (16)-Jul’15, (17)-Aug’15 and (18). Sep’15).

Fauna/Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Nematoda	16																		16
Gastropoda		16					16												32
Bivalvia		185		293	77	77	16	16		31	324	247	16	170	16				1468
Donax sp.		31			262	31		31					77	16	16				464
Bivalve larvae	432	555	293	324	1494	231				47	262	1232	47	201	47				5165
Nemertea		16										31							47
Mediomastus sp.						16								62					78
Tharyx sp.		16																	16
Kirkegaardia spp.														16					16
Cirratulus sp.						16													16
Cossura sp.			47	16															63
Glycinde sp.						16													16
Nephtys sp.		31	16									16							63
Aricidea sp.						16													16
Prionospia sp.			16																16
Scolelepis sp.					16									16					32
Oligochaete	447	262	170	355		108				16	324	539		278				16	2515
Total	895	1112	542	988	1849	511	32	47		94	910	2065	140	759	79			16	10039

Monthly variation in the abundance of macrobenthic organisms was analysed using Bray Curtis similarity index. At Dona Paula, the months were divided into three groups, however, most of the months did not clustered to form groups. The group I (March and May 2015), represented an average similarity of 51.3%. The commonly reported macrobenthos during these months were bivalve spats, *Magelona* sp., *Sternaspis* sp., *Chone* sp, *Nephtys* sp., *Ancistrosyllis* sp. and *Prionospio* sp. which contributed to the macrobenthic diversity (Figure 3.5.11a). Group II comprised of November and December 2013, January and March 2014 and February 2015 months and these were mostly the POM and early PreM months. This group had an average similarity of 48.9%. The macrobenthos taxa that contributed to the total abundance were *Prionospio* sp., *Mediomastus* sp., *Ampelisca* sp., bivalve spats, *Nephtys* sp., Tanaidacea, *Magelona* sp., *Pseudopolydora* sp., Cumacea, Anthuridae and *Gammarus* sp. (Figure 3.5.11a). The months April, August and September 2015 were clustered as group III, and the average similarity was 29.4% and macrobenthos responsible for such a grouping were *Prionospio* sp., *Cossura* sp., *Nephtys* sp., and *Aricidea* sp. which were the dominant taxa during these months at Dona Paula (Figure 3.5.11a). Most of the months (April, May, June, July, August, September and November 2014) and June 2015 did not join to form cluster (Figure 3.5.11a). At Chicalim station the cluster analyses indicated four groups. In group I, (November and December 2013) the similarity was 43.49% and the macrobenthic taxa contributing to their similarity were bivalve spat, *Prionopio* sp., *Glycera* sp., and Gastropoda (Figure 3.5.11b. In group II similarity was 59.3%, and the organisms contributing to the abundance were *Prionsopio* sp., *Cossura* sp., and *Mediomastus* sp. The Group III comprised of May 2014 and March, April and June 2015 and the average similarity was 43.4%. The macrobenthos contributing to this similarity were bivalve spats, *Prionsopio* sp., *Glycera* sp., and Gastropoda (Figure 3.5.11b). In group IV, February and September 2015 were clustered together with a similarity of 36.9%, and in these months *Mediomastus* sp., *Prionospio* sp., and *Cossura* sp. (Figure 3.5.11b) were dominant taxa. Several months (April, June, July, August, September and November 2014 and June and August 2015) did not form any cluster indicating difference in the community structure of macrobenthos at this station during the above months. At Cortalim station, cluster analyses indicated three groups of different months and the macrobenthos taxa reported at these stations indicated 50% resemblance. Group I had similarity of 59.2% (January 2014 and June 2015 months), with contribution from *Mediomastus* sp., *Cossura* sp., *Prionsopio* sp., and *Nephtys* sp. (Figure 3.5.11c). The months (December'2013, February'15, March'15 and June '15) were clustered together to form group II, and the similarity was 37.6%. The macrobenthos contributed to such a similarity were *Mediomastus* sp., *Prionsopio* sp., *Cossura* sp., and Oligochaete (Figure3.5.11c). In group III the months May, September and November 2014) clustered with an average similarity of 37.69% and the major taxa reported during these months were *Prionospio* sp., *Cossura* sp. and Oligochaeta respectively (Figure 3.5.11c). The non-grouped months at Cortalim station were April, June, July, and August 2014 and June, August and September) 2015 respectively indicating most of these months represent the monsoon season (Figure 3.5.11c) which had low abundance and diversity in general. At Loutolim station the similarity among the macrobenthos taxa was grouped into two groups, group I (May and November 2014) had a similarity of 40.7% contributed by *Cossura* sp., and *Mediomastus* sp.(Figure 3.5.11d). Whereas, Group II (November and December 2013, January 2014, February, March, April and June 2015) clustered with mostly the POM and PreM months with an average similarity 48.9%. The macrobenthos *Prionospio* sp., *Cossura* sp. and *Mediomastus* sp. which contributed about 70% to the total abundance were responsible for this cluster (Figure 3.5.11d). The months that were not clustered were March, April, June, July, August and September 2014 and June, August and September 2015 (Figure 3.5.11d), which are mainly the PreM and MON months.

Depending upon the similarity, the months were clustered into three groups at Borim station. Group I (May 2014 and April 2015) with PreM months had an average similarity of 34.5% (Figure 3.5.11e). The organisms contributing to this group were *Ampithoe* sp., bivlave larvae, *Mediomastus* sp., *Kirkegaardia* sp., *Cossura* sp., *Lumbrineris* sp., *Paaronis* sp., *Pectinaria* sp., *Prionospio* sp., *Syllis* sp., Oligochaeta and Penaeidae respectively (Figure 3.5.11e). In Group II, the months December 2013, January 2014 and February 2015 clustered together with an average similarity of 29.7% and the contributing macrobenthos were *Prionospio* sp., *Kirkegaardia* sp., *Tharyx* sp., *Glycera* sp., *Gammarus* sp., and *Goniada* sp. representing taxa from different groups (Figure 3.5.11e).

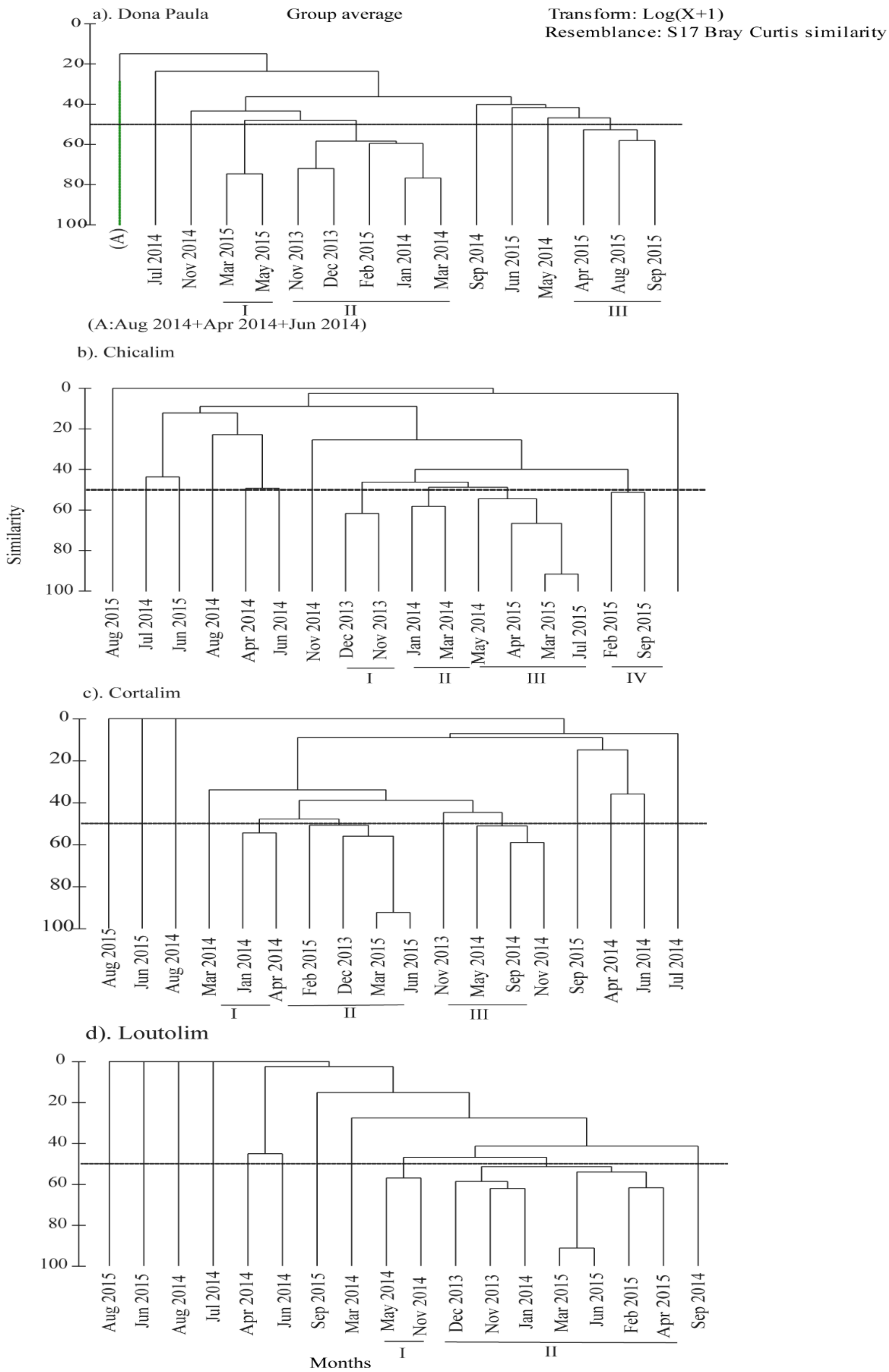

Figure 3.5.11: Dendrogram representing the similarity in the abundance of macrobenthos among different stations during different months.

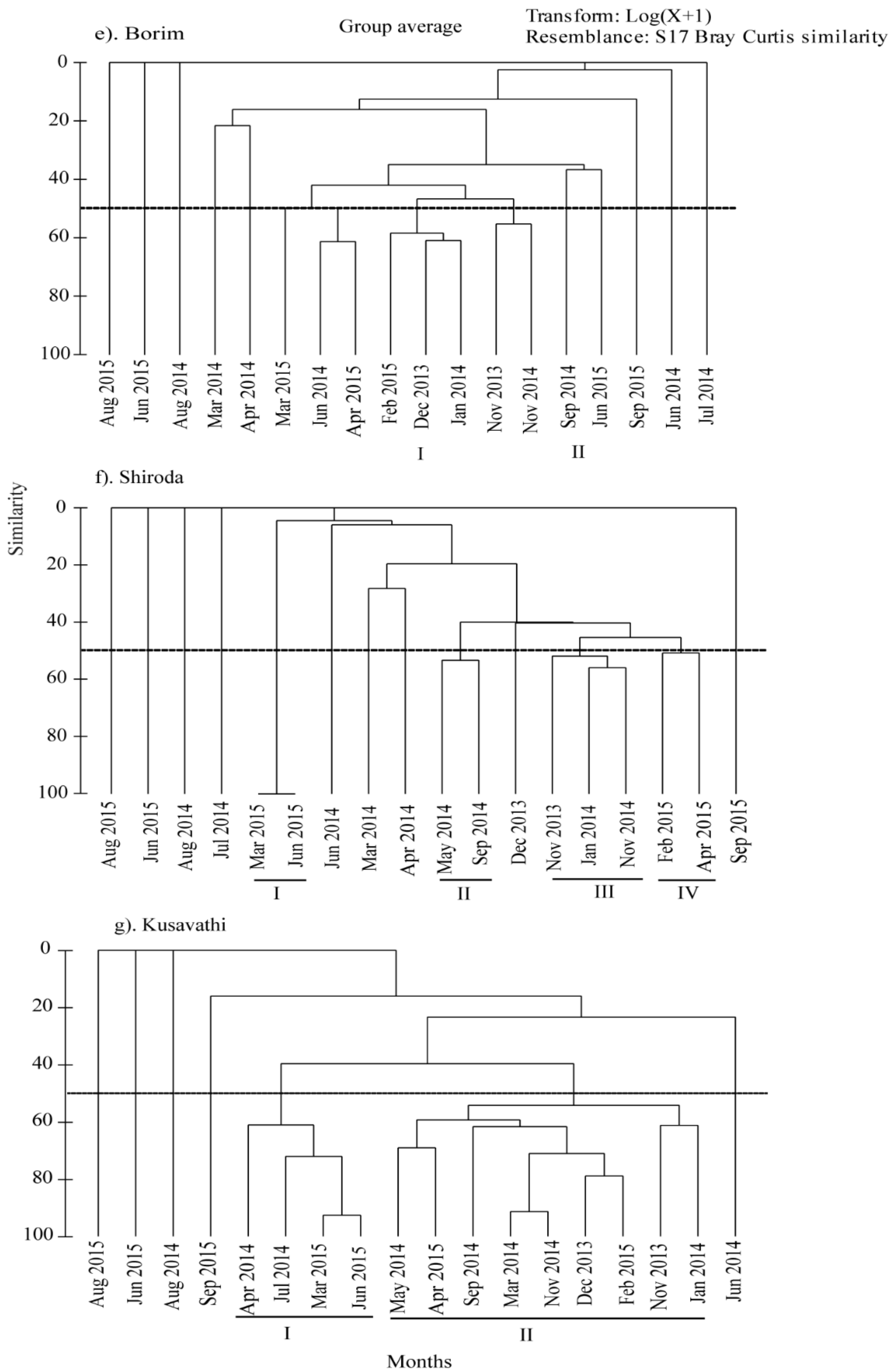

Figure 3.5.11 (Continued): Dendrogram representing similarity in the abundance of macrobenthos among different stations during different months.

Table 3.5.3. Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou's evenness (J′), Shannon index (H), of macrobenthic organisms during different seasons at Zuari estuary.

Stations	Dona Paula					Chicalim					Cortalim					Loutolim				
Months	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)
Nov-13	31	6064	3.444	0.6892	2.367	20	39	5.186	0.9911	2.969	14	59	3.185	0.9795	2.585	12	46	2.87	0.9816	2.439
Dec-13	29	4512	3.328	0.7519	2.532	17	36	4.449	0.9911	2.808	17	68	3.797	0.9819	2.782	12	46	2.873	0.9889	2.457
Jan-14	27	3571	3.178	0.7849	2.587	22	47	5.463	0.9911	3.063	17	80	3.652	0.985	2.791	14	53	3.268	0.9823	2.592
Mar-14	25	2938	3.005	0.7272	2.341	23	47	5.709	0.9933	3.114	12	50	2.811	0.9847	2.447	14	51	3.305	0.991	2.615
Apr-14	13	1778	1.604	0.7463	1.914	13	27	3.647	0.9927	2.546	11	46	2.616	0.9807	2.352	6	20	1.674	0.989	1.772
May-14	17	1549	2.178	0.7183	2.035	10	20	3.025	0.9914	2.283	9	32	2.31	0.9843	2.163	7	25	1.864	0.9863	1.919
Jun-14	10	343	1.542	0.9459	2.178	10	18	3.134	0.9971	2.296	7	21	1.975	0.9965	1.939	6	21	1.652	0.9944	1.782
July-14	4	64	0.7213	1	1.386	1	3		****	0	6	19	1.689	0.9956	1.784	0	0	****	****	0
Aug-14	8	204	1.316	0.9598	1.996	4	7	1.576	0.9983	1.384	0	0	****	****	0	0	0	****	****	0
Sep-14	6	233	0.9173	0.9057	1.623	1	2		****	0	9	33	2.289	0.9906	2.177	16	62	3.629	0.9925	2.752
Nov-14	25	3585	2.932	0.725	2.334	12	25	3.423	0.9949	2.472	9	38	2.196	0.9804	2.154	8	33	2.003	0.9806	2.039
Feb-15	19	1520	2.457	0.7619	2.243	10	23	2.878	0.9826	2.263	22	90	4.662	0.9842	3.042	14	54	3.257	0.9885	2.609
March-15	9	683	1.226	0.7984	1.754	18	38	4.687	0.9901	2.862	25	95	5.276	0.9882	3.181	18	69	4.013	0.9886	2.857
Apr-15	12	1114	1.568	0.7562	1.879	14	31	3.794	0.9882	2.608	13	56	2.98	0.981	2.516	9	37	2.222	0.9887	2.172
Jun-15	8	236	1.281	0.9167	1.906	18	32	4.919	0.997	2.882	24	81	5.233	0.9934	3.157	17	58	3.941	0.9938	2.816
Jul-15	13	315	2.086	0.924	2.37	3	5	1.27	1	1.099	0	0	****	****	0	0	0	****	****	0
Aug-15	8	204	1.316	0.9598	1.996	0	0	****	****	0	0	0	****	****	0	0	0	****	****	0
Sept-15	13	1238	1.685	0.7811	2.003	12	26	3.37	0.9934	2.468	3	8	0.9346	1	1.099	2	8	0.4861	0.9906	0.6866

Table 3.5.3: - (Contd…). Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou’s evenness (J′), Shannon index (H), of macrobenthic organisms during different seasons at Zuari estuary.

Sations	Borim					Shiroda					Kusavathi					
Months	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	S	N	d	J'	H'(loge)	1-Lambda'
Nov-13	19	48	4.647	0.9866	2.905	20	71	4.459	0.9922	2.972	3	15	0.7384	0.9528	1.047	0.6807
Dec-13	16	43	3.984	0.9898	2.744	22	75	4.857	0.9942	3.073	8	33	2.01	0.9755	2.029	0.8891
Jan-14	19	56	4.477	0.9897	2.914	22	91	4.651	0.989	3.057	5	20	1.327	0.9744	1.568	0.8239
Mar-14	7	18	2.065	0.9915	1.929	6	20	1.664	0.9809	1.758	4	20	0.9985	0.9738	1.35	0.7722
Apr-14	8	19	2.386	0.9905	2.06	12	40	2.979	0.9914	2.463	4	20	1	0.9605	1.332	0.7612
May-14	13	28	3.612	0.9959	2.554	13	43	3.187	0.9924	2.546	8	29	2.073	0.9838	2.046	0.8969
Jun-14	3	6	1.081	0.9971	1.095	4	13	1.162	0.9974	1.383	2	6	0.5765	1	0.6931	0.6071
July-14	0	0	****	****	0	0	0	****	****	0	2	6	0.5434	0.9927	0.6881	0.5884
Aug-14	0	0	****	****	0	0	0	****	****	0	0	0	****	****	0	****
Sep-14	17	43	4.256	0.9878	2.799	13	50	3.073	0.9872	2.532	3	10	0.8623	0.9927	1.091	0.7335
Nov-14	14	34	3.678	0.9894	2.611	23	86	4.94	0.9934	3.115	3	17	0.7039	0.9999	1.098	0.7079
Feb-15	18	52	4.303	0.979	2.83	23	84	4.965	0.9902	3.105	5	25	1.239	0.9656	1.554	0.811
March-15	18	43	4.511	0.9909	2.864	1	3		****	0	3	11	0.8321	0.9861	1.083	0.722
Apr-15	24	61	5.599	0.9925	3.154	19	76	4.152	0.9881	2.909	7	29	1.787	0.9785	1.904	0.8759
Jun-15	8	17	2.472	0.9975	2.074	1	3		****	0	3	10	0.8868	0.9896	1.087	0.7359
Jul-15	0	0	****	****	0	0	0	****	****	0	0	0	****	****	0	****
Aug-15	0	0	****	****	0	0	0	****	****	0	0	0	****	****	0	****
Sep-15	2	4	0.6792	0.9951	0.6897	0	0	****	****	0	1	3		****	0	0

Group III (November 2013 and 2014) with an average similarity of 40.1% was represented by *Prionospio* sp., along with *Glycera* sp. and Cumacea (Figure 3.5.11e). The most of the non-grouped months (March, April, June, July, August and September 2014 and March, June, July, August and September 2015) represented by MON and PreM (Figure 3.5.11e). At station Shiroda, the similarity among the months was represented by four groups. Group I (March and June 2015), group II (May and September 2014) and group IV (February and April 2015) had the similarity of 100%, 25.7% and 36.1% respectively and in particular months clustered to form group IV indicated 100% contribution from bivalve spat (Figure 3.5.11f). The group III had an average similarity of 29.8% contributed by *Prionospio* sp., Oligochaeta, *Scolelepis* sp., *Nephtys* sp., *Nereis* sp. and bivalve spat (Figure 3.5.11f). Several months (December 2013, March, April, June and August 2014 and June, August and September 2015) depending upon the occurrence of macrobenthos did not clustered into groups. The Kushavati station which has fresh water input all-round the year has two groups with most of the months having similar taxa. In group I (April and July 2014, March and June 2015) the average similarity was 33.4% and the taxa contributed to the abundance were bivalvia, gastropoda and *Donax* sp., respectively belonging to mollusca (Figure 3.5.11g). In group II (November and December) 2013, (January, March, May, September and November) 2014, and (February and April) 2015), most of the months belonging to non-monsoon season with an average similarity of 52.% and the organisms contributed were *Donax* sp., *Syllis* sp. and gastropoda (Figure 3.5.11g). The non-grouped stations observed at Kushavati stations (June and August 2014 and June, September and August 2015) belonged to monsoon season (Figure 3.5.11g). The correspondence values of the Shannon–Weiner index (H′) of each station were at an average of 2. at Dona Paula, Chicalim and Cortalim, 1.7 at Loutolim, 1.8 at Borim, 1.6 at Shiroda and 1. at Kushavati (Table 3.5.2).

Influence of environmental variables on the macrobenthic communities at Zuari estuary

Canonical Correspondence Analysis (Figure 3.5.12) of the study indicated sediment characteristics and the salinity are the important factors which influenced the community structure of macrobenthos at different stations during different months. Length of gradient value >2 was observed for all the stations, and thus CCA plots were used for the analysis. The correlation percentage between macrobenthos abundance and the environmental variables was high for all the stations (Dona Paula - 94%, Chicalim - 99%, Cortalim - 95%, Loutolim - 94%, Borim - 99%, Shiroda - 99% and Kushavati - 98%) (Figure 3.5.12).

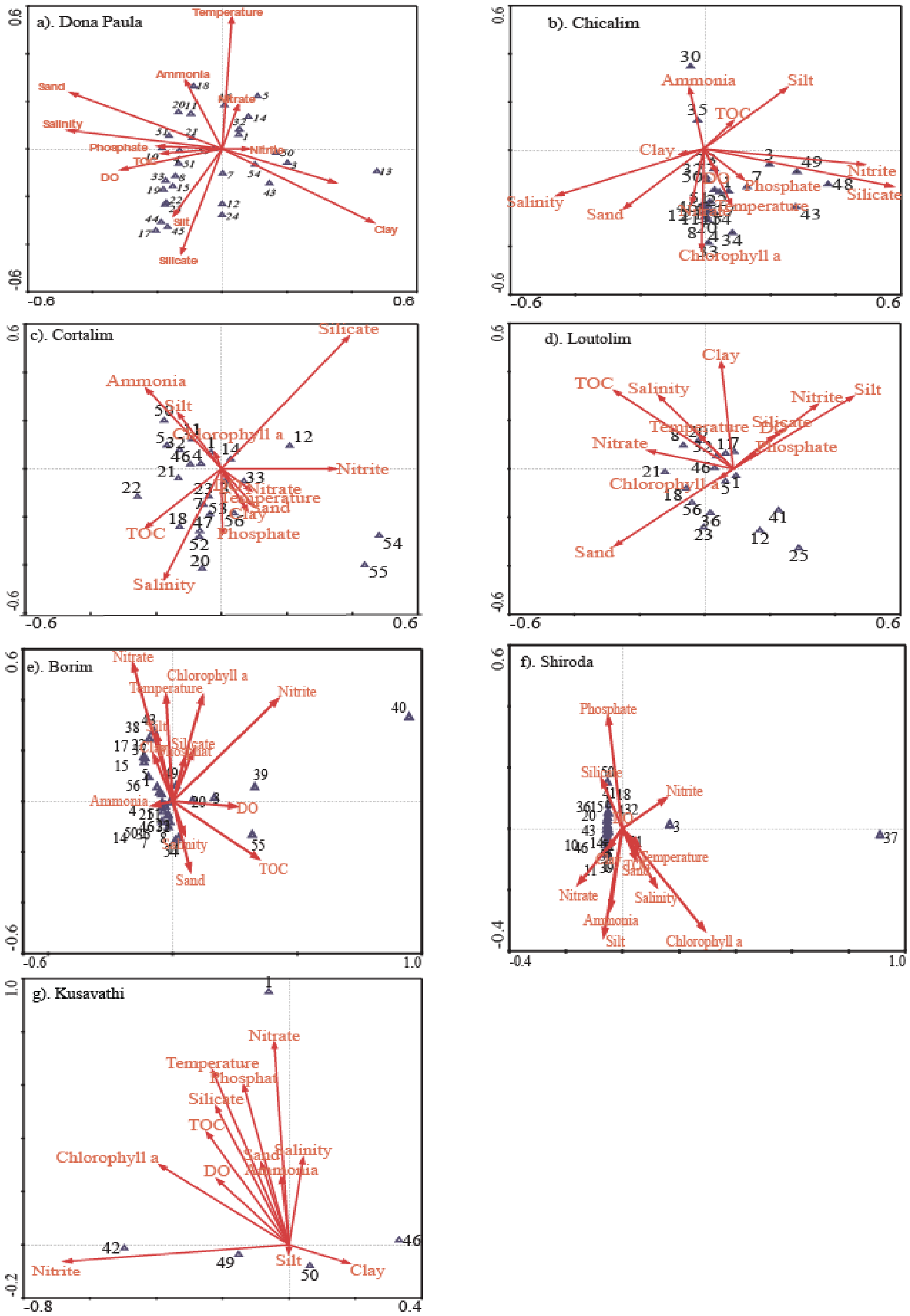

Figure 3.5.12:- Canonical correspondence analysis to illustarate the correlation between the environmental parameters and macrobenthos diversity at different stations. (1. *Mediomastus* sp., 2. *Notomastus* sp., 3. *Tharyx* sp., 4. *Kirkegaardia* sp., 5. *Cossura* sp., 6. *Eunice* sp., 7. *Glycera* sp., 8. *Goniada* sp., 9. *Hesione* sp., 10. *Magelona* sp., 11. *Nephtys* sp., 12. *Dendronereis* sp., 13. *Naineris* sp., 14. *Aricidea* sp., 15. *Paraonis* sp.,

16. *Phyllodoce* sp., 17. *Pectinaria* sp., 18. *Ancistrosyllis* sp., 19. *Poecilochaetus* sp., 20. *Sternaspis* sp., 21. *Ampelisca* sp., 22. *Ampithoe* sp., 23. *Gammarus* sp., 24. *Stegocephalus* sp., 25. *Lumbrineris* sp., 26. *Tharyx* filibranchia, 27. Isolda sp., 28. Capitella sp., 29. Eunice indica, 30. *Glycinde* sp., 32. *Prionospio* sp., 33. *Polydora* sp., 34. *Streblospio* sp., 35. *Lucifer* sp., 36. *Nereis* sp., 37. *Syllis* sp., 38. *Harmothoe* sp., 39. *Scolelepis* sp., 40. *Squilla* sp., 41. *Pseudopolydora* sp., 42. *Donax* sp., 43. Nemertea, 44. Hydrozoa, 45. Anthozoa, 46. Oligochaeta, 47. Ophiuroidea, 48. Gastropoda, 49. Bivalvia, 50. Bivalve larvae, 51. Cumacea, 52. Isopoda, 53. Decapoda larvae, 54. Anthuridae, 55. Tanaidacea and 56. Penaeidae.

The canonical correspondence analysis for Dona Paula station indicated that *Mediomastus* sp., *Aricidea* sp., *Cossura* sp. and *Prionospio* sp. are the most abundant organisms and their abundance was influenced by nutrients except silicate and temperature and indicated that these organisms can survive low concentration of DO and lower percentage of silt (Figure 3.5.12a). The macrobenthic organisms such Cumacea, *Ampithoe* sp., *Gammarus* sp., Tanaidacea, *Goniada* sp., *Poecilochaetus* sp., *Sternaspis* sp., *Nephtys* sp., *Magelona* sp., *Ancistrosyllis* sp. and *Pectinaria* sp. were positively influenced by sandy-silt sediment with low percentage of clay, high salinity and low chlorophyll *a*. The macrobenthos *Glycera* sp., Anthuridae, *Dendronereis* sp. *Stegocephalus* sp. and Nemertea were more inclined towards silty sediment and low organic carbon (Figure 3.5.12a). At Chicalim station, *Cossura* sp., *Dendronereis* sp., *Nepthys* sp., *Polydora* sp., *Aricidea* sp., *Paraonis* sp., *Kirkegaardia* sp., *Streblospio* sp., *Isolda* sp., *Ampithoe* sp., *Ampelisca* sp. which are mostly free moving organisms and require higher percentage of sand and high salinity for their survival and are less influenced by silt and organic carbon (Figure 3.5.12b). *Lucifer* sp., *Gammarus* sp., *Prionsopio* sp. and the Bivalve spat at this station were influenced by salinity, sandy sediment, higher concentration of ammonia, and mid to low concentrations of DO, Chlorophyll *a* and organic carbon (Figure 3.5.12b). *Mediomastus* sp., *Kirkegaardia* sp., *Cossura* sp., *Nephtys* sp., *Prionospio* sp., Oligochaeta and Bivalve spat were dominant and their abundance was influenced by silty sediment with high chlorophyll *a* and low to medium salinity and organic carbon. These are mostly sedentary except *Nephtys* sp. (Figure 3.5.12c). High salinity with organic carbon in sandy sediments and medium to low DO, Nitrate and Phosphate influenced *Glycera* sp., *Ancistrosyllis* sp., *Gammarus* sp., Ophiuroidea, *Sternaspis* sp. and Decapod larvae (Figure 3.5.12c).

At Loutolim, the higher abundance of *Goniada* sp., *Nephtys* sp., *Sternaspis* sp. and *Prionospio* sp. was influenced by salinity, organic carbon and nitrate with medium to low sand and chlorophyll *a* (Figure 3.5.12d). Whereas motile species such as *Cossura* sp., *Ancistrosyllis* sp., *Ampelisca* sp., *Nereis* sp. and Penaeidae thrive well in sandy sediment with high chlorophyll *a*, moderate organic carbon, brackish water conditions with medium salinity and low silt. The polychaetes, *Mediomastus* sp., *Cossura* sp., *Paraonis* sp., *Pectinaria* sp., *Syllis* sp., *Harmothoe* sp. and Gastropoda were dominant at Borim and they could thrive well in low percentage of sand and high silty sediment with low organic carbon, salinity and DO (Figure 3.5.12e). *Tharyx* sp., *Sternaspis* sp. and *Scolelepis* sp. were influenced by sandy-silt sediment, high DO, moderate salinity and their abundance reduced or they were absent during the monsoon months (Figure 3.5.12e). Shiroda is located at the up-stream region and the salinity is considerably low during the monsoon months. The amphipod, *Ampelisca* sp. was abundant and influenced by sandy sediment with high organic carbon content and positively influenced by salinity and temperature (Figure 3.5.12f), whereas, *Aricidea* sp., *Nephtys* sp., Oligochaeta and *Magelona* sp. were positively influenced by the silty sediment with low to medium sand, organic carbon and salinity. Kushavati, the fresh water dominant station except during PreM and the dominant macrobenthos were mollusks such as *Donax* sp., Bivalvia and Bivalve spat which were supported by higher DO, organic carbon, sand along with high concentration of chlorophyll *a* for their higher abundance. *Mediomastus* sp. is found near the banks of the estuary during non-monsoon months, is observed at this station is an indicator species found to live in diverse environments (Figure 3.5.12g).

3.5.3. Discussion

The study on the ecology of macrobenthos is associated with understanding the relationship between the environmental parameters and the organisms inhabiting the benthic region (Aller et al, 2001). The present study was carried out in the Zuari estuary by carrying out sampling at regular interval (monthly) over a period of 18 months indicated spatio-temporal variation in the macrobenthic organisms and such a variation was correlated with the changes in the physio-chemical, hydrobiological and most importantly the sediment characteristics which also varied with space and time. As a typical tropical monsoon influenced estuary, Zuari estuary is influenced by spatial and temporal variation in the salinity along with temporal variation in the monsoon patterns indicating inter-annual variation. Environmental factors such as salinity, temperature, food availability, recruitment of new population (Butman, 1987) and hydrographic conditions regulates the macrobenthic community structure (Heip et al, 1992; Henning and KrÖncke, 2005;Gaonkar et al, 2013). The salinity at most of the stations during the study was almost similar during non-monsoon seasons, however, during monsoon the salinity dropped to near fresh water conditions at most of the stations (Shetye et al, 2007), which showed a definite pattern from the estuarine head to the mouth of the estuary. The fresh water influx in the estuary is estimated at >10,000 ML day^{-1} during the monsoon and during non-monsoon due to less changes in the salinity along the estuary indicate well mixed conditions at most of the stations (Shetye, 1995). Zuari estuary is influenced by the mixed tides with semi-diurnal influence and the range is about 2.3m to 1.5m during spring and neap tides (Manoj and Unnikrishnan, 2009). Salinity has been considered as one of the limiting factor for the survival of marine organism (Gibson, 1982; Jayaraj et al, 2007), and the variation in salinity due to dilution and evaporation determines the macrobenthic faunal distribution in an environment (Ananthan et al, 2005). In the present study salinity indicated a clear difference between stations towards the seaward side which is mixoeuhaline, in the midstream it was polyhaline and towards the estuarine head oligohaline conditions (Chertoprud et al, 2013). Zuari River has a catchment area of about 973 km^2 and receives 491×10^6 m^3 of run-off annually (Qasim and Sengupta 1981; Shetye et al. 2007). The salinity was generally high during POM and PreM (summer months) and low during MON (monsoon months) due to the fresh water runoffs which drains in the estuary (Vijayalakshmi et al; 1993), as observed in the present study. Hydrography of the Zuari estuary reflects typical tropical conditions in which there is a steady increase in temperature during post- and pre-monsoon seasons, whereas during monsoon months the temperature decreases and such a pattern in temperature was observed during the study. Similar observations were also observed in the Cochin estuary (Ansari, 1982; Nandan and Azis, 1996; Hossain et al, 2009; Noyel et al, 2020) located along the southeast coast of India. The dissolved oxygen has been considered as an important parameter influencing the macrobenthic community, and its deficiency in the water column along with increased nutrients due to anthropogenic activity result in eutrophication leading to hypoxic and anoxic conditions (Diaz and Rosenberg, 1995, Cloern, 2001). Dissolved oxygen showed difference in concentration in the near bottom water during monsoon months (1.36 $mg.m^{-3}$) and gradual increase was observed during non-monsoon months (1.95 $mg.m^{-3}$), and the reduction in the DO in the estuarine region during the south west monsoon has been related to the coastal upwelling (Shenoy and Patil, 2003) and such phenomenon lead to the increase in the primal productivity (Madhupratap et al. 1996; Shenoy and Patil, 2003). Lower concentration of DO may be attributed to the changes in temperature and salinity, which in turn affects the oxygen dissolution (Vijayakumar et al; 2000). The decrease in the near bottom water DO may be related to higher organic carbon owing to higher productivity in the surface water and following their sinking along with the fresh water runoff carrying organic carbon load during monsoon which result in higher oxygen consumption (Singhbal, 1985). Nutrients in the water column play a major role in the productivity of an ecosystem. An increase in the bottom water nutrients during monsoon season was observed, and may be attributed to the riverine runoff during this season, a unique feature of tropical estuary affected by monsoons (Qasim, 1982). The chlorophyll a content in the near bottom water indicated seasonal variation, and it was higher during Pre-monsoon season compared to POM and MON months and the concentration nutrients in the near bottom water were also high during PreM indicating a correlation between the nutrient concentration and chlorophyll *a*. Lower concentration in the near bottom water chlorophyll *a* during the monsoon months, may be due to the influence of strong tidal movement, washout of sediment organic matter and sediment-water interference leading to disruption in the algal distribution (Jenness and Duineveld, 1985). Suspended particulate matter which indicated a seasonal variation and chlorophyll *a* concentration in the water column determines the macrobenthic abundance especially the deposit and suspension feeders, this may indicate increase in primary productivity (Carvalho et al, 2011). The abundance of deposit feeders in particular is positively corresponds to the organic matter as this provides higher amount of food for these organisms (Pranovi et al, 2008), in-turn affect the community structure of benthic organisms.

Sediment characteristics play an important role in determining the macrobenthic communities' survival and diversity (Sanders, 1958; Ingole, 1998; Jayaraj et al, 2008). Thus the present study also showed that influence of riverine runoff in estuaries lead to the intermixing of different sediment texture such as the sand, silt and clay in varying percentage along the salinity gradient of the estuary. Similar distribution in the sediment texture was observed by Nair and Ramachandran (2002) at Beypore estuary, along the south west coast of India. Various sediment properties such as sediment water content, permeability, sediment resuspension, penetrability in the sediments, mixture of organic matter and low sulphides are the determining factor for the distribution, abundance and community structure of macrobenthic fauna (Sarkar et al., 2005; Kumar and Khan, 2013). The present study showed spatial and temporal variations in the sediment texture and physio-chemical characteristics owing to the influence of south-west monsoon (June –

September) which also lead to significant changes in the macrobenthic diversity and abundance. Earlier studies also reported similar observations in tropical conditions influenced by monsoon (Balachandran, 2010; Sivadas et al, 2011; Desai et al., 2020). In the benthic environment, sediment grain size and organic matter influences the distribution of rare elements and anthropogenic pollutants (total nitrogen and total phosphorus) (Rodríguez-Barroso et al., 2010). In Zuari estuary, the percentage of sand was maximum at the stations, Dona Paula (estuary mouth) and Kushavathi (estuary head), but it is observed that the grain size is finer (125µm to 2mm - fine and coarse sand) at Dona Paula station and compared to Kushavathi, where the grain size of sand is larger and coarse (2mm to 16 mm - gravel), and this will have an influence on the community structure of macrobenthos. At Kushawati, the macrobenthos were dominated by the organism belonging to molluscs which is not the case at Dona Paula. Previous studies have indicated sediment texture as the determining factor for macrobenthic organism's survival and proliferation since they provide both food and shelter to these organisms (Sanders 1958; Gray, 1981; Ingole et al. 1998). In the estuarine sediments, organic matter input is mostly due to the runoff carrying terrestrial material, primary productivity, sediment texture and removal rate of organic to inorganic matter (Nair and Ramachandran, 2002; Desai et al., 2020). As reported by Manoj and Unnikrishnan, (2009), in Zuari estuary the tidal currents are stronger and the longitudinal and cross-shore flow at the Zuari mouth is homogenous during PreM and POM months but during MON months the tidal magnitude and its ebb flow was high due to the freshwater discharge (Sundar et al, 2015). Organic carbon distribution is related to the sediment grain size and the sediments with higher surface area are in fine sediment and possess higher organic carbon (Valdés et al., 2005; Rodríguez-Barroso et al., 2010; Paneer Selvam et al., 2012), and in the present study the benthic sediment is dominated by sandy-silt, silty-sand and sand (Figure 3.3.2) indicating the presence of coarse sand with uneven surface and this maybe the reason for low organic carbon content (<3). Previous studies showed that the organic matter enrichment in the sediment may lead to hypoxic conditions, depleting macrofauna and this lead to the invasion of opportunistic organisms (Pearson and Rosenberg, 1978; Ansari et al, 1986). In the present study owing to the low organic matter in the sediment which was observed at most of the stations, in turn showed higher macrobenthic diversity during PreM and POM months. As described by Pearson and Rosenberg, (1975), increased organic carbon in sediments leads to faunal depletion.

Spatio-temporal variation in the macrobenthic community

Macrobenthic organisms comprised of Annelida as the dominant Phyla, followed by Arthropoda, Mollusca, Nemertea and Cnidaria. Among the Annelida, polychaetes were the most dominant and this was observed in the most of the studies carried out along the coastal environments and estuaries (Damodaran, 1973; Parulekar et al, 1976; Ansari, 1976; Harkantara and Parulekar, 1994; Jayaraj et al, 2007; Joydas and Damodaran, 2009; Musale and Desai, 2011; Noyel and Desai, 2020; Noyel et al. 2020). Variations in the macrobenthic organisms was observed with the stations during the study, and they were dominating towards the estuarine mouth stations (Dona Paula, Chicalim and Cortalim) represented by marine organisms and mid-stream stations (Salinity tolerant macrofauna), and at the upstream stations the macrobenthos community was dominated by fresh water oligochaetes and bivalves. Monthly observations showed that maximum abundance and diversity of macrobenthos during POM followed by PreM and MON. As described by Kumar (2001), along the west coast of India, the macrobenthic diversity is high during POM months, and this may be due to the seasonal variability and recruitment of larvae and juveniles during this season leading to their higher abundance (Sivadas et al, 2010). During MON the abundance was minimum and this may be attributed to the changes in salinity due to high amount of freshwater runoff in the estuary which might directly influence the macrobenthic population and such observations were also reported earlier (Parulekar et al, 1980; Harkantara and Rodrigues, 2003; Currie and Small, 2006). Heavy rains during the monsoon seasons cause decline in macrobenthic fauna due to mortality of benthic organism or their migration (Alongi, 1990). In the Zuari estuary the macrobenthic population was substantially low (11,361 no.m^{-2}) during MON, compared to PreM (53,215 no.m^{-2}) and it was maximum during POM season (58,780 no.m^{-2}). The reduction in the macrobenthic abundance was recovered substantially during POM seasons, and this may be due to the stabilised conditions in the estuary during POM months (Parulekar et al, 1980; Harkantara and Rodrigues, 2003). This increase in macrobenthic population during POM season may also be due to the decreased salinity during MON which leads to the release of gonads (Kinne, 1970) due to the extreme condition in MON season, and the larvae may adapt to cyst formation or postponement of settlement (Richer and Sarnthein, 1977; Kinne 1977; Osman, 1977) and settle and recruit during favourable POM months leading to an increase in macrobenthic abundance. The upstream region of the Zuari estuary is comparatively shallow (Dona

Paula -16m, Chikalim- 5m, Cortalim- 9.6m, Luotolim- 10.5m, Borim- 12.9, Shiroda-9.1 and Kusavati-6m) and this will have implication to the benthic biodiversity. Higher inflow of fresh water during the MON season might wash away the upper few centimetres of the benthic habitat thereby either completely eliminating the benthic organisms or alter the community structure and their abundance. The decrease in the benthic population may also be due to the increase in the organic carbon, which in turn causes the depletion of oxygen leading to population depletion (Jorgensen 1977; Jorgensen and Revsbech 1986; Snelgrove and Butman 1994; Hyland et al. 2005). The organic carbon was <3% during this study throughout the estuary along with high DO indicating a healthy benthic habitat for the growth and survival of benthic population. The decrease in the macrobenthic abundance observed during the monsoon months (July, August and September) at the seaward stations (Dona Paula, Chicalim and Cortalim) (Table 3.5.2 a, b and c), may be attributed to the sediment characteristics and salinity. In PreM and POM months there is increase in the abundance of macrobenthos with maximum abundance and diversity at Dona Paula station. Significant variation was observed in the diversity and abundance at mid-stream stations (Luotolim, Borim and Shiroda) where the salinity ranged between 15-25 and the sediment was mostly dominated by sand which might have influenced such a variation. The CCA plots indicated that most of the organisms towards the estuarine mouth are positively influenced by salinity, DO, organic carbon, sand and silt, whereas towards the upstream stations near bottom water nutrients, chlorophyll *a* and sediment characteristics influenced the macrobenthic organisms (Figure 3.5.12). At the upstream station (Kushavati) salinity was .5-1., and the dominant macrobenthos were fresh water bivalves and oligochaetes. This study corresponds with the previous studies on the west coast of India indicating higher abundance of macrobenthic organisms with correspondence to the optimal salinity except in Kushavati, which is mostly fresh water (Neyman, 1969; Harkantra et al., 1980; Parulekar et al., 1982; Jayaraj et al., 2007). With reference to the dominant taxa observed among the stations, the macrobenthic fauna in Zuari estuary are mostly surface deposit feeders, sub-surface deposit feeders, with sand and silt being dominant the succession of the deposit feeders were stable, even though community shifts were observed among the dominant taxa it was entirely among the same feeding habits, only at Kushavati it was dominated by suspension feeders due to the sand size and low silt content. This similarity can be observed Nasci, (1988) on the Calcasieu estuary (Lousiana), where the estuarine deposit feeders and suspension feeders occupy

90% of the entire estuary macrobenthic community. In Zuari estuary, the dominant taxa was entirely occupied by the deposit feeders and towards the estuarine mouth (Dona Paula) and Upstream (Kushavati) due to the influence of sand. The suspension feeders such as Bivalve spat, *Ampelisca* sp. and Tanaidacea were more dominant at Dona Paula and in Kushavati suspension feeders such as Bivalves, *Donax* sp were more abundant. The *Prionospio* sp. was the most abundant organism at most of the stations in the Zuari estuary, and this can be attributed to the dominance of sandy-silt texture of the sediment, as these organisms are deposit feeders, and are also considered as opportunistic organisms tolerant to pollution (Kingston, 1995). These taxa were observed in higher abundance at the stations towards the estuarine mouth, except during MON months and towards the upstream their abundance was lower or they were absent throughout the year, indicating that salinity as a limiting factor (Figure 3.5.1 and Table 3.5.2). The *Mediomastus* sp. was the second most dominant organism found in Zuari estuary during the study, and these are the sub-surface deposit feeders (Jumars et al, 2015), which require medium organic carbon and high DO levels (Pearson & Rosenberg, 1978). The presence of *Mediomastus* sp. also indicate that the benthic environment is well ventilated and has normal oxygen circulation within the sediments (Long et al, 2007). *Mediomastus* sp. is the most dominant organism observed at Cortalim station, and since they are deposit feeders higher percentage of silt at this station compared to other stations may have led to their high abundance. It can be noted that the water column depth is comparatively shallow at most of the stations and due to the semidiurnal tides the transport of water from the Arabian sea in to the estuary and vice-versa is continuous during the day and this might support in oxygenation of benthic habitat. The polychaete, *Cossura* sp., a good indicator organism and also known as an opportunistic species (Sivadas, 2010), and these are deposit feeders (Musale et al, 2015). In this study, *Cossura* sp., was observed as the dominant taxa in Cortalim, Chikalim and Luotolim stations where the sediment texture is well balanced with sand and silt, compared to Dona Paula where sand is dominant. Such sediment characteristics may have increased the survival rate of this taxa by providing food and shelter leading them to dominate towards the stations at estuarine mouth. The upstream stations doesn't have such high abundance of *Cossura* sp. even with silt concentration due to the influence of low salinity. This species along with *Tharyx* sp. are capable of feeding on organic matter, both fresh and decayed available in the sediments (Long et al, 2007). In the present study *Tharyx* sp. was found at all the stations, however, their abundance reduced towards the upstream stations, and this species is also considered as an opportunistic species. All the above mentioned dominant taxa were observed to be dominant towards the estuarine mouth and their abundance is greatly reduced or absent at the upstream or during the MON months throughout the estuary. Marine bivalves in higher abundance towards the seawards side (higher salinity) and their abundance reduced when the salinity decreased (Pillay and Perissinotto, 2008) to mesohaline conditions, however, their abundance increased towards the upstream stations (lower salinity -1), indicating their preference to low salinity conditions. The bivalves, which are observed at the mouth of the estuary are those which could tolerate wide variations in the salinity, whereas those reported in the upstream stations are fresh water tolerant bivalves. The sediment characteristics and organic carbon also differed from the estuarine mouth towards the upstream. The estuarine mouth is dominated by fine sand and at the upstream stations the sand was coarse with comparatively high organic carbon than at the mouth (Figure 3.5.2). Macrobenthic bivalve population found near the estuarine mouth disappeared during the monsoon months owing to lowering of the salinity. The presence of bivalve lead to the increase in the biomass and abundance in soft sediments (silty sediment) (Giles et al, 2006; Norkko and Shumway, 2011), and these organisms also provide suitable space for other subsurface organisms such as amphipods and also help in the recruitment of other benthic fauna (Mills, 1967; Dauvin and Bellan-Santini 1990). The concentration of bottom water chlorophyll *a* is found to be moderate to low during POM months towards the upstream where the abundance of bivalves was higher, and this may be due to the constant feeding of bivalves as they are filter feeders and source their food from the water column (Barnard, 1970), whereas the depositing feeding bivalves consume the dead phytoplankton and microphytoplankton deposited in the sediments (Desai et al, 2020). Crustaceans were the second most dominant group in the Zuari estuary, and this may be due to the less polluted condition along with silty sediments (Musale et al, 2015). The amphipod, *Ampelisca* sp. was the most common and dominant macrobenthos reported during this study, and they are both suspension and deposit feeders with an opportunistic behaviour (Santos and Pires-Vanin, 2004; Paganelli et al. 2012). Study suggests that the presence of sandy sediments with silt, which are stable in shallow waters is an ideal environment for the survival of polychaetes, Amphipods and Bivalves, however, the influence of environmental parameters which are mainly related to the tropical monsoon condition alters the entire estuarine ecosystem and this led to the shifts in the community of macrobenthos in this estuary.

Chapter 4

Ecology and biology of the selected macrobenthic organisms

4.1 Introduction

Biodiversity is the full range of variety and variability within and among the living organisms and the ecological complexities in which they occur, and encompasses ecosystem or community, species and genetic diversity. The benthic organisms which usually constitute the biomass of marine sediment are the species rich group of invertebrates those are large enough to be retained on a 300µm sieve, but too small to be identified using underwater photographs (Snelgrove, 1998). These macrofaunal taxa usually include annelids, arthropods, molluscs, and many other phyla. Macrofauna in marine sediments also play important roles in ecosystem processes such as the nutrient cycling, pollutant metabolism and dispersion, burial and secondary production. They also act as food for many of the benthic dwelling higher invertebrates and fishes. Thus, evaluating and understanding biodiversity of microbenthic organisms in marine sediments is both important and challenging**.**

The intimate relationship with the sediment substrata, physical and chemical attributes influences the macrobenthos living in a specific environment (Sanders, 1968). Due to this benthic macrobenthos are often used as ecological indicators to understand the impacts of pollutants, alterations in water quality and disturbances in the sediment (Thrush, 1994; Knox, 2000). Thus, the ecology of these organisms, which are mostly sedentary in nature is regulated by the changes that occur in the habitat characteristics, more precisely the benthic sediment and also in the pelagic environment. This indicates that the environmental parameters such as the salinity, temperature, dissolved oxygen, the availability of food, etc. play an important role in determining the habitat characteristics of the macrobenthic organisms (Sanvicente-An˜orve et al., 1996; Rees et al., 1999; Ellingsen, 2002; Anbuchezhian et al, 2009). Salinity has been considered as one of the limiting factor for the survival of marine organisms (Gibson, 1982; Jayaraj et al, 2007), and the variation in salinity due to dilution and evaporation determines the macrobenthic faunal distribution in an environment (Ananthan et al, 2005), especially in an estuarine environment (Noyel et al, 2020). From the perspective of tropical monsoon influenced environments such as the estuaries and the ports in this study indicated a wide variation in the salinity between the monsoon and non-monsoon season, and this has resulted in the seasonal variation in the occurrence of macrobenthic organisms. The observations carried out in the Zuari estuary indicated a clear difference in the salinity between stations towards the seaward side which is mixoeuhaline, in mid-estuarine region which is polyhaline and towards the estuarine head it was oligohaline The change in the salinity of the water in an estuarine environment is mainly due to the salt water intrusion by tidal activity and dilution by freshwater runoff. Estuaries influenced by monsoon have an additional factor of influencing the salinity and these frequent changes in salinity have a considerable effect on the organisms inhabiting these areas thus affecting the species diversity and trophodynamics (Short and Neckles, 1999; Li et al., 2010).

Study of ecology and biology of the macrobenthic fauna is crucial since they play a major role in the marine benthic community through their involvement in mineralization, sediment mixing, oxygen flux in the sediment, nutrient cycling and recovery of organic matter (Snelgrove, 1998). Among the macrobenthic community, polychaetes are the dominant fauna which are abundant, significantly diverse, and have ecologically important functions in due to their high stability and ability to adapt to different environment (Simboura, 2000). Because of their short life cycles and limited mobility, benthic organisms are often used as bio-indicators in monitoring studies, tertiary level feeders in food web and also as food for several economically important fishes (Gray and Elliot 2009). Macrobenthic polychaete is the dominant group among the organisms present in Cochin port, Visakhapatnam port, Paradip ports and along the south west coast of India (Joydas and Damodaran, 2009; Musale and Desai 2011, Noyel and Desai, 2020; Noyel et al 2020). Spionids were the most dominant among the polychaetes as observed in the estuaries along the West coast of India (Joydas and Damadoran, 2009; Noyel et al, 2020). The changes in the abundance and diversity of benthic organisms in different regions or ecosystems has been attributed to the influence of discharge of different origin, such as the municipal and industrial origin, the amount of organic matter as higher amount organic matter leads to eutrophication in the estuary (Devi and Venugopal, 1989; Devi et al 1991; Geetha et al, 2010). Such changes will impact the survival and growth of the microbenthic organisms inhabiting the estuarine and coastal habitats there by altering their biodiversity and population dynamics. The experiments were carried out with dominant macrobenthic polychaetes in order to evaluate the impact of salinity stress which is generally experienced by the organisms inhabiting the tropical monsoon influenced estuarine region on their survival and growth along with changes in the biochemical composition.

4.2 Materials and methods

Field observations carried out in the Zuari estuary indicated that the salinity was the major factor influencing the diversity and distribution of the polychaetes in this estuary. The polychaetes were the most abundant organisms, among these sedentary polychaetes followed by errantiate were dominant. Thus, a sedentary polychaete, *Prionospio* sp. and an errantiate polychaete, *Dendronereis* sp. isolated from the Zuari estuary during Pre-monsoon and monsoon seasons were selected to carryout different experiments. These polychaetes were cultured in the laboratory to study their survival, growth and bio-chemical composition. The cultures were maintained at room temperature (31±2°C), and at optimum dissolved oxygen concentration (4.8±0.2 mg. l^{-1}). The salinity was altered during the experiment. The initial salinity was 14(±1.8) during PreM at the time of collection of specimens and it was increased to 35 while carrying out the experiment in the laboratory, and during MON the salinity was 0.33(±0.23) at the time of collection, and it was increased to 20 during the treatment in the laboratory. The sediment samples used for culture of the organisms were collected from the same site where the macrobenthos were collected and is was not treated. The organisms were cultured without food as *Prionospio* sp. is a deposit feeder which can survive on organic matter from the sediment. The *Dendronereis* sp. were fed with matured or collapsed mixed phytoplankton culture as a source of food.

4.2.1 Collection of *Prionospio* sp. and *Dendronereis* sp.

Sediment samples were collected from the Zuari estuary (Loutolim station) using a Van Veen grab and samples were brought to the laboratory, sieved and sorted for the organisms. Sedentary polychaete, *Prionospio* sp. and the errantiate polychaete, *Dendronereis* sp. were isolated from these samples and used to carry out the experiments.

4.2.2 Sediment texture and organic carbon analysis

Total carbon (TC) and inorganic carbon (IC), were analysed by expressing the sediment dry weight was determined by CHNS analyser ((Vario MICRO Select, Germany) (TOC = TC-IC) (Kristensen and Andersen, 1987; Byers et al, 1978). The percentage of sediment texture composition was analysed by pipette analysis (Buchanan, 1984).

4.2.3 Water parameters analysis

The surface and near-bottom water samples were collected using a Niskin water sampler for the analysis of chlorophyll *a*, salinity and dissolved oxygen (DO) following the methods described by Parsons et al. (1984), and temperature using standard protocols.

4.2.4 Analysis of biochemical composition

The extraction of protein from the specimens followed the procedure of Danovaro et al, (1993), by adding 0.5 M NaOH for 4hr and their content was determined by Hartree, (1972) method. Carbohydrates (CHO) estimation was carried out using phenol and sulphuric acid following the method described by Dubois et al. (1956). Extraction of lipids was done by the ultra-sonication with chloroform: methanol (2:1 *v*/v) (Bligh and Dyer, 1959) for 20 min, and estimated following the method of Barnes and Blackstock (1973). Bovine serum albumin, glucose, and cholesterol were used as calibration standards for PRT, CHO, and LPD respectively. All these analyses were carried out in triplicate, and concentration is expressed as mg. g^{-1} WW (specimen wet weight). The blanks for each of the analysis were prepared by pre-combusting sediment samples at 450–500 °C for 4 hr in the muffle furnace. The concentrations of PRT, CHO, and LPD were then converted to carbon equivalents using the conversion factor 0.49, 0.40, and 0.75, respectively (Fabiano and Danovaro, 1994; Danovaro et al., 1999).

4.3 Results

4.3.1 Variation in the biochemical parameters in the organisms collected during Pre-monsoon season

The near bottom water parameters during the period of sample collection were - temperature 30.1(±0.02) °C, salinity 14(±1.8), pH 7.94 and dissolved oxygen 4.05(±0.6) mg l^{-1} during the PreM season. The percentage of sand, silt and clay was 67.56%, 2.32% and 30.12% respectively, and the organic carbon was 2.01%. The concentrations of carbohydrate, protein and lipids in *Prionospio* sp. collected from the field (control specimen) were 23.12(±0.02) mg.g^{-1} WW, 70.16(±0.38) mg.g^{-1} WW, and 11.51(±0.29) mg.g^{-1} WW respectively of the organism collected during this season (Figure 4.3.1a).

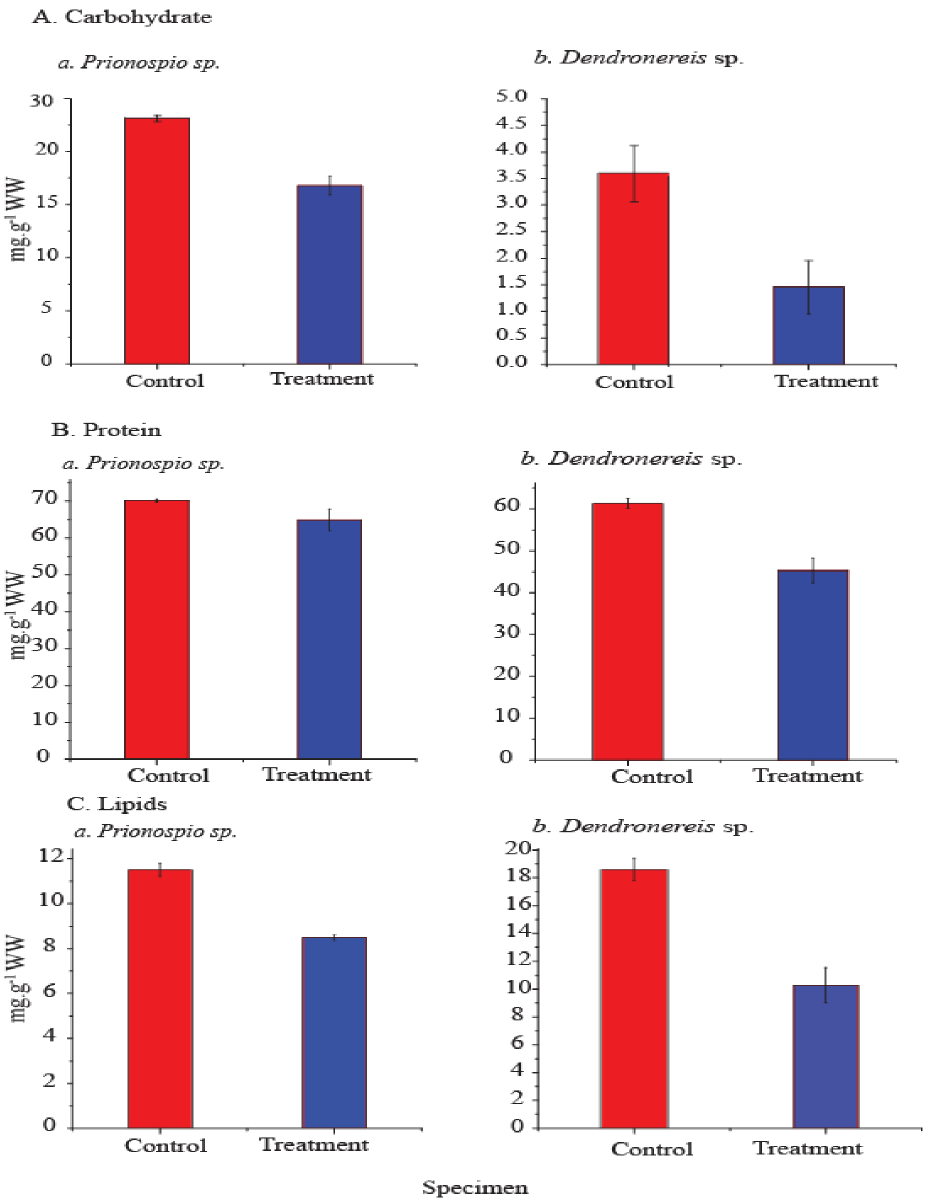

Figure 4.3.1. Bar-diagram depicting the A. Carbohydrate, B. Protein and C. Lipid concentrations of a) *Prionospio* sp. and b) *Dendronereis* sp. during the PreM season showing the control period and after the treatment.

The organisms were reared for 15 days at 31(±1.8) °C temperature, 35 (±1.0) salinity and 4.81(±0.1) mg l^{-1} DO. The concentration of different biochemical components after a period of 15 days was 16.8(±0.89) mg. g^{-1} WW of carbohydrate, 64.92(±2.9) mg. g^{-1} WW of protein and 8.5(±0.12) mg. g^{-1} WW of lipids in *Prionospio* sp. (Figure 4.3.1a; Table 4.3.2), indicating a reduction in all three parameters after an exposure of 15 days at higher salinity.

The biochemical composition of the *Dendronereis* sp., collected from the field was 3.59(±0.52) mg. g^{-1} WW of carbohydrate, 61.36(±1.17) mg. g^{-1} WW of protein and

18.6(±0.8) mg. g^{-1} WW of lipids (Figure 4.3.1b). After a period of 15 days at 35 salinity the concentrations were 1.46(±0.5) mg.g^{-1} WW of carbohydrate, 45.33(±2.9) mg.g^{-1} WW of protein and 10.29(±1.25) mg.g^{-1} WW of lipids (Figure 4.3.1b; Table 4.3.2), indicating a decrease in their concentration. The mortality rate in *Dendronereis* sp. was high and the growth was stunted after exposing to increased salinity for a period of 15 days. The reduction in the biochemical components in *Prionospio* sp. was lower compared to *Dendronereis* sp.

4.3.2 Variation in the biochemical parameters in the organisms collected during the monsoon season

During monsoon season, the bottom water temperature was 28.16(±0.17) °C, salinity - 0.33(±0.23), pH - 7.09 and DO - 4.94(±0.45) mg l^{-1}. The composition of sand, clay and silt was 25.7%, 0.89% and 73.41% indicating higher percentage of silt in the sediment during the monsoon season and the percentage of total organic carbon was low (1.61%) (Table 4.3.1). During MON season, the dominant polychaete, *Prionospio* sp. specimens were collected for carrying out the experiment in the laboratory.

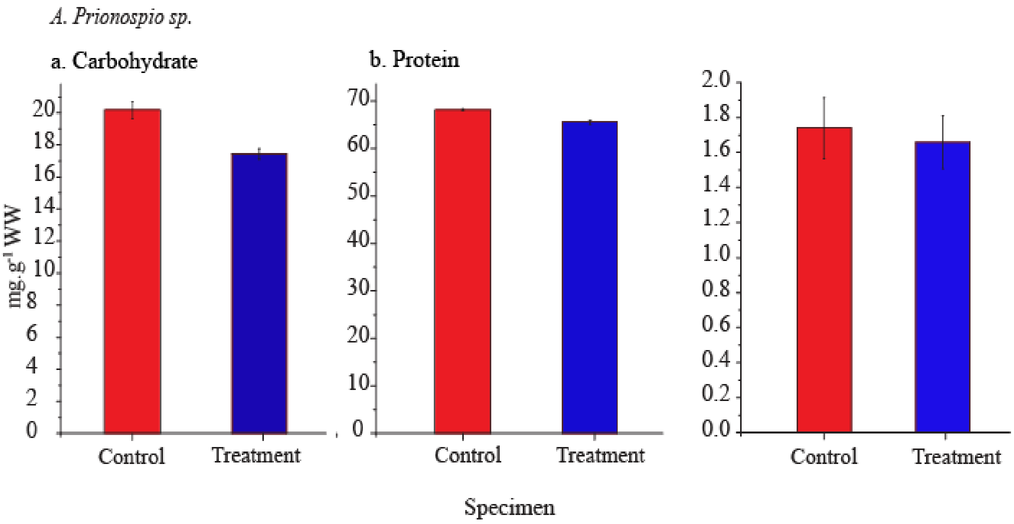

Figure 4.3.2. Bar-diagram depicting the a. Carbohydrate, b. Protein and c. Lipid concentrations of A). *Prionospio* sp. during the MON season showing the control period and after the treatment.

The biochemical composition of the freshly collected organisms from the field was 20.18(±0.52) mg. g^{-1} WW, 68.13(±0.22) mg. g^{-1} WW and 1.74(±0.17) mg. g^{-1}WW of carbohydrate, protein and lipids respectively. After the treatment at increased salinity of 20 (±1.7) for a period of 15 days at 28.3(±0.1)°C temperature the concentration of carbohydrate was 14.26(±0.33) mg. g^{-1}WW, protein was 65.54(±0.42) mg. g^{-1}WW and lipids was 1.66(±0.09) mg. g^{-1}WW (Figure 4.3.2; Table 4.3.2). The results indicated comparatively lower variation in the biochemical composition indicating their higher tolerance to changing environment than *Dendronereis* sp.

4.4 Discussion

Benthic communities play a major role both ecologically and economically along with their morphological diversity and ability to adapt to various changes in the habitat conditions which makes them important in an environment (McIntyre 1977; Gerlach 1978). In the estuaries, the macrobenthic diversity varies spatially and temporally (Rainer, 1981), and polychaetes are one of the most abundant and diverse macrobenthic taxa in a benthic ecosystem ranging from intertidal zone to the deep sea. The polychaetes, *Prionospio* sp. and *Dendronereis* sp. were chosen to carry out the experiments. It has been reported that these two polychaetes are stress tolerant organisms (Sivadas et al, 2009), and are small and short lived (Khan and Murugesan, 2004). The Zuari, a tropical estuary influenced spatially and temporally with wide variation in salinity during the monsoon season. Panikkar, (1969) reported that the macrobenthic community in Zuari estuary undergoes partial or complete destruction during the summer monsoon periods, and re-emerge after the withdrawal of monsoon along with the increase in the salinity. Chlorophyll *a* concentration in the water column determines the macrobenthic abundance especially the deposit and suspension feeders, and this also indicates increase or decrease in primary productivity (Carvalho et al, 2011). The present study showed that the sudden changes in salinity lead to the decrease in the abundance of macrobenthos along the estuary and this is also highlighted in the organisms cultured under the laboratory conditions and also in their bio-chemical composition as it decreased after a prolonged treatment at altered salinity.

Survival and diversity of macrobenthic organisms depend on the sediment characteristics (Sanders, 1958; Jayaraj, 2008). In the laboratory the sediment characteristics and organic carbon maintained was almost similar to those observed in the natural environment to culture the polychaetes in the laboratory. Spatial and temporal variation in the sediment texture and organic carbon was observed in the study area in the natural conditions during different seasons. The significant change was observed during the summer monsoon (South-west monsoon months), which lead to a significant change in the macrobenthos community structure. In the estuarine sediments, organic matter input is mostly due to the runoff carrying terrestrial material, primary productivity, sediment texture and removal rate of organic to inorganic matter (Nair and Ramachandran, 2002; Desai et al., 2020). Organic carbon distribution is related to the sediment grain size and the sediments with higher surface area are in fine sediment and possess higher organic carbon (Rodríguez-Barroso et al., 2010; Paneer Selvam et al., 2012), and in the present study the sediment was sandy-silt which is advantageous for deposit feeders.

Biochemical studies related to annelid worms are scarce and the available information is mainly limited to a few species, mostly from temperate regions or from the polar environments (Pocock et al. 1971; Luis and Passos 1995; Parrish et al. 1996; García-Alonso et al. 2008). In the present study the dominant sedentary polychaete, *Prionospio* sp. and a motile polychaete, *Dendronereis* sp. are inhabitants of a region which experience wide variation in the salinity. The sediment at the sampling sites was sandy-silt, and the organism *Prionospio* sp. is a deposit feeder which prefers the sandy-silt sediments (Kingston, 1995). The *Dendronereis* sp. are inhabitants of the silty sediment with low organic matter (Jayachandran et al, 2019). Comparing the biochemical composition of these two organisms indicated that, *Prionospio* sp., which is among the most dominant taxa in the Zuari estuary has higher tolerance limit to the changing salinity than compared to the *Dendronereis* sp., as the *Dendronereis* sp. showed higher mortality compared to *Prionospio* sp. during the experiment.

The earlier studies on the biochemical composition of on macrobenthic organism indicated carbohydrate levels in *Laeonereis ankyloseta* (9.4%; Balasubramanian et al. 2012), *Perinereis anomala* (6.5 – 18.7%: Dorgham et al. 2014), *Nereis virens* (13.0 - 17.0 mg. g^{-1}: Brown et al. 2011) and *Perinereis helleri* (6.0 -8.0 mg.g^{-1}). The present study showed higher CHO levels during PreM for *Prionospio* sp. and it was lower during MON seasons when compared to the previous studies, whereas, *Dendronereis* sp., showed low carbohydrate content. The experimental results also indicated lower carbohydrate content in *Dendronereis* sp. compared to *Prionospio* sp.

The lower level of lipids in *Prionospio* sp. during monsoon may be attributed to the decrease in salinity during monsoon which triggers the gonadal release in macrobenthic fauna (Kinne 1977). Studies on temperate bivalves' indicated that lipids and glycogen were stored during the growing season to use these reserves during reproduction, leading to the decrease in the lipids content (Gonzalez et al. 2001; Orban et al. 2002; Fuentes et al. 2009). The previous studies on macrobenthic fauna showed lipid levels of 13.4% in *Perinereis nuntia* (Limesuwatthanathamrong et al. 2012), *Perinereis helleri* (9.1-13%: Palmer et al. 2014), *Diopatra neapolitana* (10.0%: Luis & Passos 1995), *Nereis virens* (2.4 $mg.g^{-1}$: Brown et al. 2011). Compared to the previous studies, except *Nereis virens,* all the other organisms showed almost similar lipid content during PreM season, but during MON *Prionospio* sp. indicated low concentration of lipids in the present study.

The protein levels in *Perinereis cultrifera* (55.1-59.9% of DW: Dorgham et al, 2015), *Nereis virens* (3.6-3.9%: Lemieux et al. 1997), *Perinereis anomala* (56.2-66.5%: Dorgham et al. 2014), *Marphysa* sp. (51.0 $mg.g^{-1}$: Meunpol et al. 2005) and in (75.0 $mg.g^{-1}$ and 69.0 $mg.g^{-1}$: Marsden et al. 1992) respectively. A similar study conducted by Carregosa et al. (2014) that subjected clam species of the genus Venerupis to a range of salinity treatments (0–42 g/L), showed high tolerant to salinity whereas, study conducted by Goncalves et al, (2017), on bivalves *Cerastoderma edule* and *Scrobicularia plana* showed comparatively less tolerance, and they suggested that this may be due to the enzyme activities in the organisms leading to the low tolerant levels towards the stress. Compared to the earlier reports, the *Prionospio* sp. had higher protein content. The reduction in the biochemical components may be attributed to the stress due to the fluctuating salinity and this in turn will impact their survival and growth resulting in lowered abundance and diversity of macrobenthos during the monsoon season, when compared to other non-monsoon season as observed in this study.

Chapter 5. Summary

The study was carried out at four major ports of India and Zuari estuary. Among these, Cochin port is situated in the Cochin backwaters along the west coast of India, which is a natural and highly dynamic complex ecosystem influenced by the tropical monsoon and the semi-diurnal tides as the natural stressors and it was also influenced by the anthropogenic activities such as disposal of untreated waste water of domestic and industrial origin. The other three ports are situated along the north-east coast of India. The Paradip port is located in the state of Odisha, which is a coastal port which is also termed as lagoon port and is directly connected to the Bay of Bengal. This port is influenced by both south-west monsoon and north-east monsoon receiving approximately 70% and 30% of rain respectively during these monsoons and is a deep-water artificial port. The Haldia and Kolkata port are located along the Hooghly river in the state of West Bengal. The distance from the estuarine mouth and the type of port makes these two ports as different ecosystems from the perspectives of flushing of port water with the estuarine water. Haldia port is a major brackish water port located at the mouth of the Hooghly river, one of the tributaries of river Ganges and is an enclosed dock affected by the semi-diurnal tides. Whereas, the Kolkata port which is also located along the Hooghly river delta is a major fresh water port with no salt water intrusion unlike other ports, leading to the dominance of fresh water. The Zuari estuary, a typical tropical monsoon influenced estuarine environment along the south west coast of India, which drains into the Arabian sea. The salinity along this estuary during the study was almost similar during non-monsoon seasons, however, during monsoon the salinity dropped to near fresh water conditions at most of the stations depicting a definite pattern from the head to the mouth of the estuary. The fresh water influx in this estuary is estimated at >10,000 ML day^{-1} during the peak monsoon period and during non-monsoon due to less changes in the salinity along the estuary indicate well mixed conditions. Zuari estuary is influenced by the mixed tides with semi-diurnal influence. The salinity in Zuari estuary indicated a clear difference between stations towards the seaward side which is mixoeuhaline, in the mid-estuarine region it was polyhaline and towards the estuarine head oligohaline conditions.

As these study sites are located in different geographical regions with different environmental settings, seasonal variations in the environmental parameters, sediment characteristics along with the changes in the diversity and abundance of macrobenthos was expected. At Cochin port, salinity and temperature along with sediment characteristics varied seasonally and spatially within the port region. The organic carbon ranged between 1.28 to 3.65% and the sediment is mostly dominated by sandy-silt and silty-sand. In the bottom waters, salinity and temperature showed considerable variations from non-monsoon to monsoon seasons (Table 5.1). Whereas in Paradip port sediment texture indicated less changes in the sediment characteristics with the seasons, and it was dominated by silty-clay and silty-sand, however the variations in the organic carbon content in the sediment was considerable with seasons (Table 5.1). The bottom water salinity showed variations with seasons, however, it was lower compared to the other ports. The temperature ranged from 25°C to 30.4°C, up by nearly 5°C from winter months (POM) to summer months (MON) (Table 5.1). The ports along the Hooghly river, Haldia and Kolkata showed considerable change in the near bottom water temperature when compared to the other study areas (Table 5.1) with a difference of ~11°C observed between monsoon and non-monsoon seasons at Haldia port and ~13 °C at Kolkata port (Table 5.1). The salinity at Haldia port was mostly brackish water ranging from 0.6 to 8.4, whereas Kolkata port was entirely freshwater. The sediment characteristics and organic carbon also varied at Haldia port and it had the highest organic carbon content at the station S08 (61.2%) during monsoon seasons and at S04 (32.8% and 42.1%) during non-monsoon seasons, however the overall range at other stations was not so high (0.2% to 23.9%). The sediment was dominated by sand and silty-sand sediments (Table 5.1). The sediment at Kolkata port also had high organic carbon content which is ranged between 0.88 to 36.94%), and since it was an enclosed port the changes in the sediment texture was meagre, and the sediment was dominated by sand, silty-sand and sandy-silt (Table 5.1). In the Zuari estuary, observations were carried out along the salinity gradient from the mouth till the head of the estuary. Zuari estuary showed variations in the salinity from the head to the mouth of the estuary ranging from 0.14 to 33.3 indicating near fresh water during monsoon seasons, and the temperature ranged between 26.2°C to 33.3°C, (Table 5.1). The sediment texture varied spatially, with sand being dominant at both estuarine head and mouth stations, however, considerable difference was observed in the size of the sand (Dona Paula – fine sand; Kushavati – pebbles). In general the sediment in Zuari estuary is dominated by sand and silt. The organic carbon content was low compared to the other study areas ranging from 0.14 to 2.19% (Table 5.1).

Table 5.1: - Comparative account of environmental parameters, organic carbon, diversity index, seasonal abundance of macrobenthos, feeding behaviour, sediment texture and occurrence of opportunistic species at different study sites. (SDF- Surface deposit Feeders, SuDF- Sun-surface deposit Feeders, SF- suspension feeders, OC- organic carbon and T- Temperature).

Port	**OC (%)**	**T (ºC)**	**Salinity**	**Diversity index**	**Abundance (no. m^{-2})**				**Feeding Behaviour**	**Sediment texture**	**Opportunistic species**
					I	**II**	**III**	**IV**			
Cochin (backwaters)	1.28 - 3.65	24.1-30.6	4.5-35.0	0.54-1.92	6222 (POM I)	2171 (PreM)	416 (MON)	9487 (POMII)	SDF SuDF	Sandy-silt silty-clay	*Prionospio* sp., Oligochaete, *Nephtys* sp.
Paradip (Open ocean)	0.03-31.62	25.0-30.4	25.9-33.9	0.56-1.73	2059 (MON I)	998 (POM)	875 (PreM)	1581 (MONII)	SDF SuDF	Silty-clay Silty-sand	*Tharyx* sp., *Mediomastus* sp., *Cossura* sp.
Haldia (Brackish)	0.02-61.2	20.8-31.1	0.6-8.4	0.3-0.44	488 (MON I)	2268 (POM)	949 (MONII)	532 (PreM)	SDF Carnivorous	Sand Silty-sand	Oligochaete, *Nephtys* sp.
Kolkata (Freshwaters)	0.88-36.94	18.6-31.5	0.2-0.4	0.44-2.29	14930 (MON)	4676 (PreMI)	4010 (PreMII)	4382 (POM)	SDF SF	Sand Silty-sand,	*Helodrilus* sp., *Aelosoma* sp., *Branchiura* sp.
Zuari (Estuarine)	0.14-2.99	26.2-33.3	0.04-34.8	0.68-3.18	54870 (POM)	53310 (PreM)	11392 (MON)		SDF, SuDF, SF	Sandy-silt silty-sand sand	

Owing to these variations in the environmental parameters and sediment characteristics, the macrobenthic community showed significant changes in their abundance and community structure. At Cochin port, seasonal variations in the total abundance of macrobenthos was observed in which it was minimum during MON<PreM<POM I<POM II (Table 5.1). The diversity was maximum during POM seasons (Table 5.1). The macrobenthic fauna was dominated by opportunistic species and this can be attributed to the natural and anthropogenic stress at this port. Among the macrobenthic fauna, Annelids were the dominant organisms, and in annelids polychaetes dominated the macrobenthic community and this was also true for most of the study sites. Other dominant macrobenthos reported at this port were Oligochaetes, Arthropods and Amphipods. Sediment enrichment indicated by high organic carbon in the sediment in a eutrophicated port like Cochin and the significant seasonal changes in the sediment characteristics led to the dominance of opportunistic species such as *Prionospio* sp., *Nephtys* sp. and Oligochaeta during different seasons. Polychaete species such as *Prionospio* sp. (an indicator of oxygen depletion) and *Cossura coasta* (an indicator of sediment instability) were observed in higher abundance during the study. At Paradip port, organic carbon in the sediment played an important role in determining the community structure. The abundance at this port was low compared to Cochin port. The seasonal variation in the abundance indicated maximum abundance during MON I followed by MON I, POM and PreM (Table 5.1). At Paradip port MON seasons were highly productive and the diversity index ranged between 0.56 – 1.73. Polychaetes were the most abundant taxa, followed by Pantopoda and Crustaceans. The silty-sand sediment which is rich in organic material led to the dominance of pollution indicator organisms such as *Tharyx* sp., *Prionospio* sp., *Cossura* sp., *Magelona* sp. and *Mediomastus* sp. at this port. The environment is influenced by seasonal variation mostly brought in by the monsoons and the anthropogenic activities; however, healthy bottom-water quality and high amount of organic carbon accumulated in the sediments lead to the survival and proliferation of indicator macrobenthos species, albeit their lower count.

The abundance and diversity was minimum at Haldia port (Table 5.1). With the dominance of silty-sand sediment, Annelids were the dominant phyla, followed by Arthropoda, Mollusca and Echinodermata. Polychaeta were the most diverse and abundant taxa constituting 70% of the total abundance. *Nephtys* sp. and *Cossura* sp. were observed during all the seasons. Among them Oligochaeta, *Nephtys* sp. and *Cossura* sp. are the indicator organisms of the sediment instability and anthropogenic impacts. During

MON season, the concentration of organic carbon at station S08 was 62.2%, which is the maximum percentage of organic carbon observed during the study, and at this station low abundance of *Nephtys* sp., Alpheidae (snapping shrimp) and Actinaria was observed and at S04 which also indicated high percentage of organic carbon during non-monsoon seasons, *Nephtys* sp. and *Nototropus* sp. observed in higher abundance. At Kolkata port, the abundance of macrobenthos was maximum during monsoon compared to other seasons, however the diversity was restricted to a single phyla of Annelids. Even though the diversity index was high within this phyla ranging 0.44 to 2.29, the abundance varied seasonally (Table 5.1). During MON season, the commonly observed organisms were *Drawida* sp., *Helodrilus* sp., *Branchiura* sp. *Branchiodrilus* sp., and *Aelosoma* sp. Oligochaeta reported at this port were mostly stress tolerant and pollution indicator species. The diversity and abundance was lower during POM and PreM when compared to MON season, and the difference or rather decrease in the temperature of ~ 13°C during POM and PreM when compared to monsoon lead to such a seasonal variation in the abundance of macrobenthos. Occurrence of macrobenthos belonging to Annelida, indicates the survival of only opportunistic species, even though the abundance of macrobenthos was higher compared to other ports, however, the species diversity was low at this port.

The anthropogenic stress compared to other study sites was less at Zuari estuary, except seasonal variations in the environmental parameters and sediment characteristics the diversity and abundance of macrobenthos was maximum at this estuary. The diversity index ranged from 0.68 to 3.18, with seasonally and spatially varying macrobenthic community was observed (Table 5.1). The impact of lowering of salinity during the monsoon and increase in salinity during the non-monsoon season resulted in the community shift of the dominant macrobenthos. The experiments carried out with the sedentary polychaete, *Prionospio* sp. and the errantiate polychaete, *Dendronereis* sp. to evaluate the salinity stress indicated that changes in the salinity led to the change in biochemical (carbohydrates, proteins and lipids) composition, and also morphological changes such as reduction in the biomass of these organisms. The diversity of macrobenthos considerably varied among the stations, and at Dona Paula the diversity was maximum whereas at Kushavati, which is a fresh water dominant station indicated the minimum diversity. Eight major groups of macrobenthos were observed during the study in Zuari estuary such as Polychaeta, Oligochaeta, Gastropoda, Plecycopoda, Malacostraca, Nemertea, Echinodermata, Cnidaria and Nematoda. Healthy environment with low organic carbon showed higher abundance and diversity. Bivalves were observed at Dona Paula which is located at the estuarine mouth and Kushavati located at estuarine head. However, bivalves observed at Dona Paula were mostly brackish or saline water tolerant, whereas, the bivalves observed at Kushavati were mostly fresh water tolerant and this attributed to the changes in the size of the sand particles, which is higher at Kushavati compared to Dona Paula. The seasonal changes were observed in the abundance at this station, and the diversity was low compared to other stations. The macrobenthic organisms observed in this study were mostly deposit feeders (Surface deposit feeders and Sub-surface deposit feeders) and suspension feeders. Among the dominant taxa reported during the study, most of the organisms were surface deposit feeders or suspension feeding macrobenthos those live on the sediment surface. Due to tidal influx and flushing of the entire estuary by fresh water during monsoon result in dislodgment of macrobenthic organisms living at the sediment surfaces or few centimetres within the sediment may wash out, and recruitment of new macro fauna during non-monsoon season may lead to community shift among the dominant macrobenthos as observed in this study.

The study carried out at the ports and the estuary will help in understanding the various interactions between the environmental parameters, sediment characteristics, and the macrobenthic communities along with their ecology. This will also help in understanding the seasonal and spatial changes in the benthic communities leading to the succession of the opportunistic organisms and also to indirectly assess the anthropogenic activities occurring in these heavily industrialized ports and how they affect the macrobenthic communities leading to the changes in the food web dynamics. Understanding the occurrence of opportunistic organisms is useful in studying bioaccumulation, bio-invasion and the depletion of native species in the port and the estuarine environments. Data collected on benthic biodiversity at the major ports of India can be a baseline data for future studies which is scarce otherwise, and such information on the biodiversity of macrobenthos will help in developing ballast water management plan for ports of India and in decision support system.

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Table 3.1.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Cochin port during different seasons (POM I - Monsoon I, PreM – Pre-monsoon, MON – monsoon, POM II – Post Monsoon II.

	Nitrate (µM)				Nitrite (µM)				Phosphate (µM)				Silicate (µM)				Ammonia (µM)			
Station	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II	POM I	PreM	MON	POM II
1	1.9	5.9	5.1	2.5	0.0	1.1	0.5	0.6	1.2	6.7	4.4	3.1	17.5	52.3	47.2	29.2	21.7	33.3	28.0	24.8
2	1.0	3.2	6.9	2.5	0.9	1.1	0.7	0.6	2.2	2.4	4.5	3.1	18.1	27.4	40.8	34.9	21.0	31.6	29.5	19.5
3	2.5	4.1	8.5	3.2	0.8	1.2	0.5	0.6	4.3	4.3	3.5	2.5	35.8	37.0	29.2	34.0	33.0	48.4	20.7	16.8
4	4.3	5.4	4.2	1.7	0.0	1.4	0.8	0.9	4.8	5.0	6.6	3.6	37.5	42.3	39.0	25.0	31.7	54.7	21.5	16.9
5	2.9	6.4	3.3	2.0	0.5	1.3	0.6	0.4	5.1	4.3	5.0	4.0	38.6	46.9	29.8	14.7	28.7	47.4	25.4	11.1
6	4.1	5.0	3.7	1.9	0.3	1.2	1.0	0.6	4.9	4.6	3.6	2.5	21.2	36.0	28.5	15.4	24.6	65.5	25.0	17.2
7	5.5	4.1	3.3	1.2	0.4	1.5	1.6	0.5	2.3	3.8	5.3	1.8	17.2	24.6	32.9	18.9	24.0	46.6	22.0	19.7
8	3.9	6.2	3.4	1.6	0.8	1.5	1.8	0.6	1.4	4.9	4.0	2.5	39.8	44.7	39.6	13.1	21.8	53.4	22.4	18.3
9	3.8	3.5	1.7	1.7	0.8	1.0	2.3	1.1	3.1	3.2	4.9	2.3	29.4	34.9	39.5	11.9	30.1	54.0	30.7	15.0
10	4.8	6.4	2.1	1.8	0.0	1.0	2.6	0.5	2.2	2.9	4.2	2.9	22.6	34.3	38.5	12.6	22.6	43.6	24.4	14.2
11	4.9	6.8	0.6	3.1	0.3	1.2	2.0	0.4	2.9	4.6	3.3	1.9	10.8	50.4	34.6	18.7	28.8	46.8	16.0	11.4
12	3.9	6.2	0.6	2.1	0.0	0.8	2.1	0.6	4.0	4.4	3.4	1.2	23.5	44.9	35.6	11.0	30.0	47.9	15.7	14.9
13	4.5	5.8	8.1	2.4	0.0	1.0	2.2	0.5	4.6	4.7	3.1	2.0	15.6	55.6	36.3	20.6	31.9	42.8	17.1	13.1
14	3.9	5.0	3.0	2.3	0.0	1.0	2.5	0.9	2.8	4.4	3.6	1.2	40.6	41.7	41.2	13.4	26.9	37.2	19.2	19.8
15	5.3	4.3	1.8	1.8	0.0	1.4	2.6	0.3	5.0	3.4	3.3	1.3	64.8	28.3	36.2	14.4	32.3	43.6	22.6	14.0
16	3.6	6.5	4.6	1.5	0.0	0.8	2.6	0.3	2.8	4.6	3.9	2.6	24.7	52.2	47.8	19.4	23.9	49.7	23.4	18.9
17	4.1	3.5	1.9	1.4	0.5	0.8	1.9	0.3	4.0	4.6	3.1	1.1	16.1	25.2	30.9	12.9	22.4	36.5	13.6	9.3
18	3.0	2.9	2.3	1.6	0.8	1.0	1.6	0.5	2.8	3.0	3.1	1.5	19.6	20.1	32.2	13.0	27.6	52.0	17.9	14.7
19	4.9	5.0	8.0		0.8	0.9	0.9		4.0	4.8	3.8		38.6	46.5	41.9		27.8	44.8	36.0	
20		4.8	2.7	1.6		0.3	0.8	0.4		4.3	4.1	1.6		43.7	30.8	12.5		47.9	15.8	16.0
21		5.2	10.5	2.8		0.6	1.8	0.3		3.5	3.3	2.8		54.3	44.6	57.0		33.5	27.5	16.1

Table 3.4.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Paradip port during different seasons (MON I - Monsoon I, PreM – Pre-monsoon, POM – post monsoon, MON II – Monsoon II.

	Nitrate [µm]				Nitrite [µm]				Phosphate [µm]				Silicate [µm]				Ammonia [µm]			
Stations	MONI	POM	PreM	MON II	MONI	POM	PreM	MON II	MONI	POM	PreM	MON II	MONI	POM	PreM	MON II	MONI	POM	PreM	MON II
1	5.3	2.9	14.7	4.2	1.0	1.3	1.5	1.0	2.6	1.9	3.0	NIL	26.4	38.9	67.7	15.3	64.1	2.7	2.8	2.7
2	5.4	2.6	17.6	6.8	0.9	1.3	1.4	2.0	2.3	1.9	2.7	0.1	29.5	38.4	69.5	24.9	18.8	3.0	3.1	2.7
3	5.6	2.9	13.1	5.2	1.2	1.3	1.5	3.1	2.2	1.9	2.8	0.1	21.1	38.5	70.6	133.2	18.5	1.4	3.0	3.8
4	4.8	5.4	13.0	3.6	1.2	1.5	1.3	1.2	2.0	2.1	2.5	0.1	18.0	34.6	72.4	28.0	46.2	4.0	5.2	3.8
5	5.1	7.5	5.7	4.8	1.1	1.6	1.2	1.1	2.0	2.4	1.9	0.1	17.5	45.1	66.8	27.9	23.8	2.4	2.1	3.2
6	5.1	3.4	8.3	5.3	0.8	1.2	1.9	1.8	1.6	2.0	2.4	0.1	17.1	40.7	88.4	11.3	24.1	11.9	1.4	2.9
7	3.4	3.5	12.0	4.2	0.9	1.1	1.9	1.2	1.5	1.9	3.5	0.2	13.8	41.7	89.1	129.9	7.7	10.4	2.3	2.9
8	3.9	5.6	4.8	3.2	1.0	1.1	1.9	1.0	1.6	2.1	2.5	0.1	16.4	41.9	84.7	134.9	6.4	8.6	3.3	3.9
9	5.1	7.5	6.4	4.5	1.2	1.1	1.8	0.7	1.8	2.0	2.4	0.2	16.2	42.7	78.4	128.3	17.9	12.3	1.4	5.6
10	3.3	10.8	2.4	3.4	0.9	1.1	1.7	0.7	1.4	2.2	1.9	0.2	13.9	48.1	64.0	89.2	16.1	9.1	3.6	4.8
11	4.6	7.4	2.7	4.8	1.3	1.2	1.7	1.3	2.2	2.2	1.9	0.2	17.2	46.1	65.4	34.7	5.4	15.8	3.9	2.1
12	2.0	6.3	1.6	1.5	0.5	0.7	1.3	0.5	1.3	1.0	1.6	0.0	15.4	85.1	52.3	98.6	8.2	15.4	3.8	3.1
13	4.8	6.0	5.2	4.0	0.7	1.2	1.4	0.8	1.8	1.9	2.3	0.2	16.0	42.4	74.1	96.3	18.4	16.8	6.1	3.0
14	4.9	6.3	18.9	4.1	0.3	1.6	1.8	0.7	1.6	2.0	1.4	0.2	16.1	41.7	46.0	102.8	17.1	6.1	5.2	3.6
15	6.2	5.8	2.2	3.6	0.7	1.3	1.8	1.6	1.9	2.0	2.6	0.1	16.8	36.6	91.0	90.7	45.1	7.7	6.8	4.1
16	4.5	4.0	7.4	4.5	0.9	1.4	1.9	1.0	1.7	1.9	2.7	0.2	17.0	37.4	91.0	94.5	52.9	10.3	10.0	4.2
17	5.0	4.5	1.1	3.8	0.8	1.2	1.9	0.9	1.7	1.6	2.8	0.1	16.9	37.0	100.0	16.3	14.1	8.5	7.2	3.8
18	4.9	3.7	1.2	5.0	0.9	1.2	1.9	1.1	1.7	1.9	2.5	0.1	16.8	36.7	86.7	89.9	24.0	13.6	10.4	3.2
19	4.4	3.8	5.5	4.8	0.9	0.9	1.8	0.9	1.9	2.0	2.7	0.2	16.2	37.5	94.9	71.4	8.4	10.9	1.2	3.8
20	4.0	4.7	4.5	3.8	0.9	1.3	2.0	1.3	1.7	1.9	2.6	0.2	15.8	41.1	96.9	67.2	13.1	12.4	3.4	4.8
21	4.6	2.2	1.8	4.9	1.1	1.4	1.9	1.4	1.7	1.8	2.2	0.2	15.4	32.5	75.2	72.4	22.0	16.4	5.1	5.8
22	5.6	4.3	1.9	3.9	1.2	1.0	1.8	1.6	1.9	1.9	2.0	0.2	17.1	40.9	64.7	65.5	24.7	9.8	5.3	3.8

Table 3.5.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Zuari estuary at different stations.

Ammonia

Months	DP	CH	CR	LU	BR	SR	KV
November-13	15.43	11.42	13.95	12.84	10.56	4.61	4.75
December-13	11.48	19.13	18.19	12.68	15.82	93.1	90.42
January-14	11.9	12.59	12.24	11.17	6.9	9.84	5.79
March-14	27.2	32.5	29.2	41.5	29.2	30.1	35.41
April-14	21.04	10.79	11.05	26.01	25.46	21.45	8.58
May-14	8.83	1.14	8.27	7.14	5.95	4.08	4.17
June-14		15	15.8	12.47	10.59	10.01	10.33
July-14		13.18	10.57	8.63	8.91	8.3	8.38
August-14		10.59	10.33	8.63	8.3	16.16	9.29
September-14		115.42	91.75	17.44	2.32	14.38	13.7
November-14	20.6	8.46	11.78	22.1	23.86	4.28	2.2
February-15	1.79	1.62	0.82	1.65	0.56	6.88	1.99
March-15	2.47	1.33	28.35	1.54	138.34	0.2	2.19
April-15	114.825	23.24	23.905	30.435	24.17	43.65	58.135
June-15	10.34	6.165	12.855	7.53	11.015	6.075	13.495
July-15	21.945	33.31	32.25	10.88	11.025	12.1	13.32
August-15	15.52	29.915	13.735	31.44	9.22	4.78	4.51
September-15	14.325	13.795	16.34	11.96	5.035	5.24	7.07
Min	1.79	1.14	0.82	1.54	0.56	0.2	1.99
Max	114.825	115.42	91.75	41.5	138.34	93.1	90.42
Std.deviation	27.86621	25.81212	19.59086	10.85134	30.82971	21.9192	23.08248

Table 3.5.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Zuari estuary at different stations.

Phosphate

Months	DP	CH	CR	LU	BR	SR	KV
November-13	1.04	0.48	1.08	1.65	1.65	0.77	0.68
December-13	1.41	2.36	1.85	2.69	1.75	1.4	0.66
January-14	2.66	3.46	3.6	4.02	3.78	4.5	0.21
March-14	2.54	1.98	2.65	2.1	2.47	1.54	1.41
April-14	1.93	2.73	1.24	1.87	2.68	1.45	2.14
May-14	2.14	22.97	3.96	5.32	2.54	22.59	22.43
June-14		6.14	5.6	5.17	2.94	2.41	1.63
July-14		2.69	3.03	2.1	1.68	2.07	1.92
August-14		8.49	5.02	7.21	2.885	3.505	6.785
September-14		0.91	1.64	1.37	2.87	0.32	0.27
November-14	2.29	1.05	2.67	1.35	2.95	1.83	0.2
February-15	2.9	2.86	4.26	3.63	1.87	4.45	1.68
March-15	1.28	1.28	0.76	1.53	1.68	0.63	1.59
April-15	0.95	0.93	1.56	1.23	2.67	2.1	3.33
June-15	0.51	1.01	1.16	2.11	1.63	2.92	2.02
July-15	2.25	3.12	1.84	3.83	4.3	4.54	3.62
August-15	1.25	1.31	2.91	1.68	3.02	3.6	1.78
September-15	2.33	2.72	3.29	3.73		3.64	2.58
Min	0.51	0.48	0.76	1.23	1.63	0.32	0.2
Max	2.9	22.97	5.6	7.21	4.3	22.59	22.43
Std.deviation	0.735726	5.205526	1.411962	1.687101	0.775943	4.934438	5.081093

Table 3.5.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Zuari estuary at different stations.

Silicate

Months	DP	CH	CR	LU	BR	SR	KV
November-13	10.53	7.46	21.57	44.85	67.61	49.12	46.48
December-13	12.69	25.82	22.21	51.94	44.86	56.31	48.51
January-14	11.95	23.73	24.48	51.71	28.67	68.94	6.24
March-14	10.44	18.7	15.4	22.01	17.5	15	25.4
April-14	13.84	21.63	16.88	17.01	35.9	14.88	46.82
May-14	7.84	18.09	24.7	40.66	59.8	50.44	45.46
June-14		29.71	29.93	43.66	49.78	23.4	13.26
July-14		45.44	67.19	21.77	45.55	36.54	24.43
August-14		76.065	90.78	80.205	4.445	50.985	58.31
September-14		7.51	17.28	19.4	25.87	8.94	7.75
November-14	6.44	2.63	19.26	16.99	58.71	51.6	3.81
February-15	7.45	6.33	7.8	9.07	11.61	19	20.06
March-15	4.87	5.47	4.86	9.92	13.9	9.21	22.01
April-15	3.95	3.43	5.93	8.53	21.06	23.2	50.04
June-15	0.56	5.53	6.02	16.52	13.63	35.24	27.35
July-15	14.74	44.04	30.54	98.66	107.34	107.89	87.11
August-15	9.66	11.13	17.9	18.01	44.21	65.18	29.79
September-15	8.03	8.63	23.94	42.69		70.31	43.15
Min	0.56	2.63	4.86	8.53	4.445	8.94	3.81
Max	14.74	76.065	90.78	98.66	107.34	107.89	87.11
Std.deviation	3.99933	19.133	21.56909	25.1792	25.99525	26.39315	21.39193

Table 3.5.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Zuari estuary at different stations.

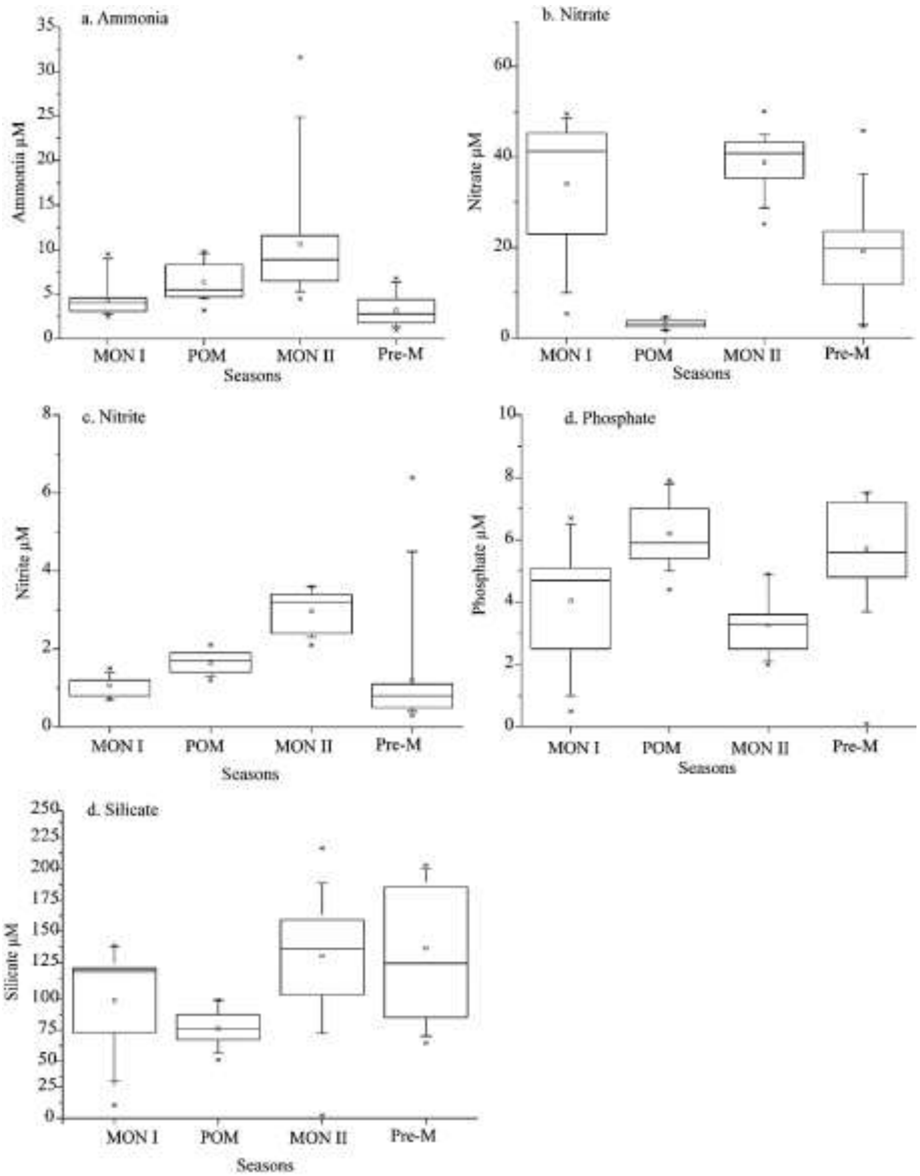
Nitrite

Months	DP	CH	CR	LU	BR	SR	KV
November-13	0.64	0.19	0.22	0.11	0.17	-	0.01
December-13	0.42	0.65	0.6	0.55	0.43	1.01	1.11
January-14	1.64	1.74	2.12	2.41	0.88	1.64	0.42
March-14	1.41	1.52	2.65	2.41	1.4	1.62	1.65
April-14	2.52	4.39	2.35	3.81	5.33	1.87	0.92
May-14	1.07	4.31	4.26	5.4	4.03	4.73	1.03
June-14		2.75	3.39	4.54	1.65	3.42	1.98
July-14		2.12	2.42	2.31	2.33	2.27	2.46
August-14		0.915	0.75	0.72	0.685	0.65	0.645
September-14		0.82	0.38	0.24	0.07	0.1	0.07
November-14	1.62	1.37	1.69	0.85	0.32	0.27	0.12
February-15	0.84	0.76	0.56	0.76	1.39	2.16	0.9
March-15	0.67	0.94	0.73	1	2.05	1.32	1.53
April-15	1.02	1.07	1.33	1.2	1.495	2.215	0.725
June-15	1.305	1.27	1.775	1.12	0.955	2.5	1.33
July-15	5.56	2.97	1.88	0.38	0.435	0.305	0.4
August-15	1.03	1.125	0.98	0.6	0.06	0.02	0.045
September-15	0.545	0.645	0.85	0.37	0.02	0.015	0.1
Min	0.42	0.19	0.22	0.11	0.02	0.015	0.01
Max	5.56	4.39	4.26	5.4	5.33	4.73	2.46
Std.deviation	1.305222	1.219501	1.110835	1.567133	1.426551	1.301423	0.719906

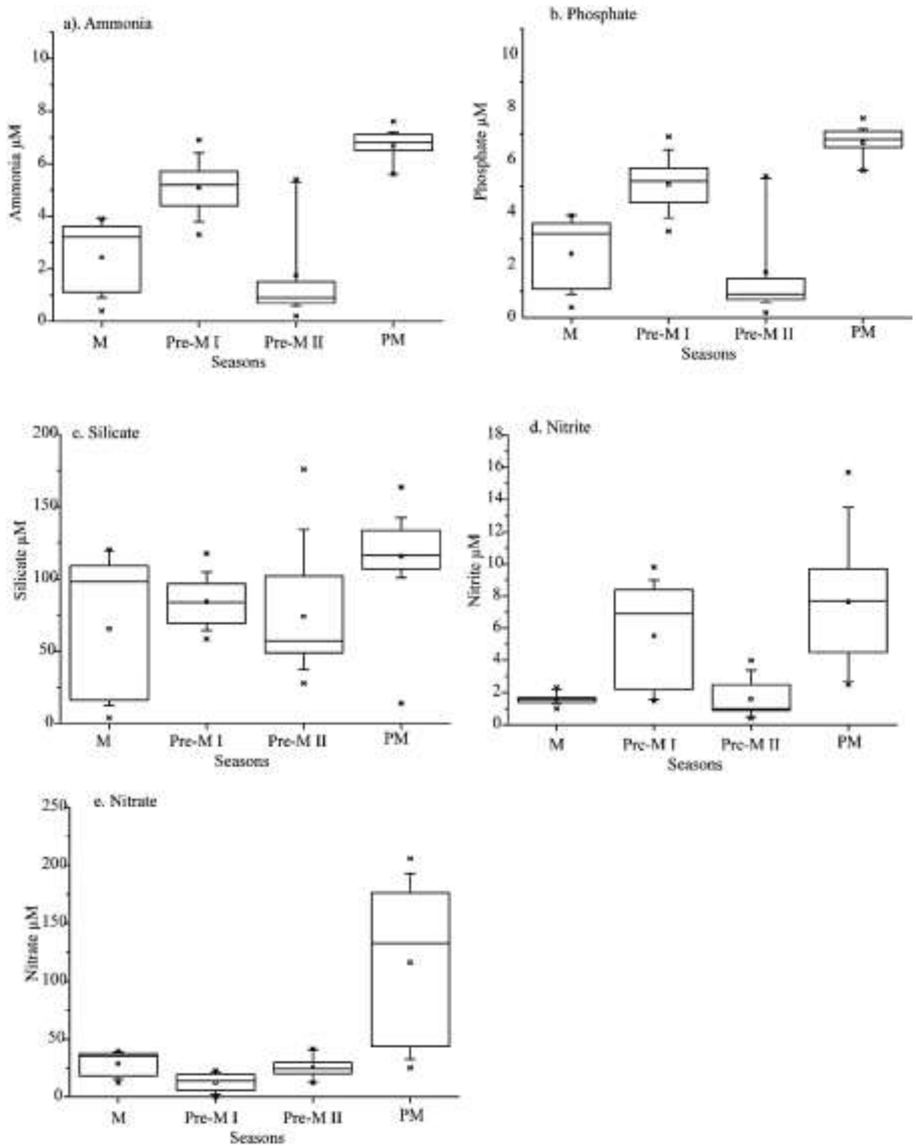
Table 3.5.1: - Near bottom water nutrients (Nitrate, Nitrite, Phosphate, Silicate and Ammonia) of Zuari estuary at different stations.

Nitrate

Months	DP	CH	CR	LU	BR	SR	KV
November-13	2.02	0.97	1.94	1.85	1.62	1.95	4.28
December-13	7.59	10.34	7.82	13.17	7.57	7.73	5.06
January-14	7.45	7.79	7	7.78	5.59	5.06	5.32
March-14	5.74	6.25	5.87	5.3	5.25	4.2	3.5
April-14	6.38	7.32	8.75	5.34	8.22	4.48	5.75
May-14	5.21	6.76	7.57	7.13	10.3	6.86	4.84
June-14		1.57	1.85	0.83	1.31	0.23	0.17
July-14		10.79	6.36	5.32	5.21	5.3	4.92
August-14		7.065	7.92	7.105	1.465	6.785	8.3
September-14		8.17	8.87	2.53	7.81	7.46	4.85
November-14	2.49	1.27	5.2	0.29	5.93	0.78	3.98
February-15	2.65	0.48	2.58	1.48	0.88	6.73	6.01
March-15	0.08	0.59	0.82	0.32	1.3	0.35	3.71
April-15	8.47	7.84	8.86	14.69	44.93	25.9	17.59
June-15	2.87	11.1	18.38	13.6	7.86	41.87	6.02
July-15	147.05	75.43	28.47	19.29	23.82	20.26	9.61
August-15	7.26	5.19	25.65	8.7	6.97	10.39	8.19
September-15	32.46	38.76	34.32	15.23		2.53	4.48
Min	0.08	0.48	0.82	0.29	0.88	0.23	0.17
Max	147.05	75.43	34.32	19.29	44.93	41.87	17.59
Std.deviation	38.23487	18.07172	9.689811	5.817603	10.79353	10.56185	3.576146



Appendix figure 3.2.1. Figure showing the near bottom water nutrients at Haldia port.



Appendix figure 3.3.1. Figure showing the near bottom water nutrients at Kolkata port.

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Macrobenthic diversity and community structure at Cochin Port, an estuarine habitat along the southwest coast of India

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Biomass

ABSTRACT

Estuarine habitats are highly dynamic owing to tidal and seasonal changes in physical and chemical properties, which, in turn, have a profound influence on the diversity and community structure of its living components. At the same time, estuaries have served as centres of maritime trade. Therefore, benthic organisms inhabiting the estuarine environment can act as bio-indicators of natural and anthropogenic changes, but our current knowledge of these components is still poor in the tropics. A study of the macrobenthos (principally comprising polychaetes), along with associated environmental variables was therefore assessed during October 2011 to November 2012 in and around Cochin port, a tropical estuarine habitat influenced by the monsoon and port-related activities. Our results showed that the diversity, abundance and community structure of the macrobenthos varied with season. Maximum diversity and abundance occurred following the southwest monsoon (post-monsoon II; November 2012), while both variables were at their minimum during the monsoon. The abundance of macrobenthos was lower in clayey-silt compared to sandy sediment. Polychaetes were the dominant organisms, followed by oligochaetes and amphipods. Sediment enrichment and seasonal changes in the sediment characteristics led to the dominance of opportunistic species such as *Prionospio* sp., *Paraprionospio* sp., *Nephtys* sp. and Oligochaeta observed during different seasons. Polychaete species such as *Prionospio* sp. (an indicator of oxygen depletion) and *Cossura coasta* (an indicator of sediment instability) were observed during the study. The multivariate index of trophic state (TRIX) indicated highly eutrophic waters and would be the main cause for the seasonal changes in the macrobenthos diversity. This study will serve as a baseline for future studies on the diversity of macrobenthos and benthic ecology of monsoon-influenced coastal habitats especially in a busy port subjected to severe physical and anthropogenic stress.

1. Introduction

Estuaries are among the most productive natural ecosystems and perform crucial ecological functions, which include ecosystem services such as nutrient cycling, organic matter decomposition, food for resident and migratory fauna, shoreline protection, and fisheries resources. At the same time, estuaries often serve as commercial harbours (Kennish, 2002; Dolbeth et al., 2003; Paerl, 2006; Dolbeth et al., 2007). Since estuaries are a connecting point of freshwater, sea, and land, they are supplied with large amounts of nutrients and pollutants derived from agricultural, industrial and urban effluents (Lillebø et al., 2005; Paerl, 2006; Dolbeth et al., 2007). As reported by Ramaraju et al. (1979), typically the estuary is highly stratified with respect to salinity during the monsoon season and during the post and pre-monsoon, they are partially mixed owing to a balance between river flows and tidal influence. Cochin Port is one such environment located along the Cochin backwaters of Kerala. The Cochin backwaters are among the largest and most complicated ecosystems in India, which is influenced by the southwest and the northeast monsoons. Heavy rainfall results in stratification, with freshwater at the surface and denser seawater at the bottom. In pre and post-monsoon periods, there is sedimentation due to tidal influence, which brings more silt and clay to the estuarine mouth (Menon et al., 2000).

Ports are considered as the lifeline of a country's economic development. However, maritime trade and transport activities also cause substantial damage to natural habitats owing to their interactions with the port environment, whether accidental (e.g., oil and chemical spills) or intentional (e.g., dredging, reclamation) (Button, 1999; Talley, 2003, Ng and Song, 2010). Port waters are often characterized by low dissolved oxygen and the presence of pollutants in the sediment and water (Danulat et al., 2002; Rivero et al., 2005; Ingole et al., 2009; Musale et al., 2015). Cochin, a natural estuarine port, has been expanded over the years, dredged, and developed with deeper channels for modern cargo handling.

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The development has led to adverse consequences for the environment, air, water, and sediments (Gupta et al., 2005; Cooper, 2003; Ray, 2008; Grifoll et al., 2011; Dinwoodie et al., 2012; Puig et al., 2014). Ports are also prone to bio-invasion through ballast water due to their empty niches (Rilov and Crooks, 2009).

Understanding the ecology of macrobenthic fauna in the Cochin port is crucial, because they play a significant role in the marine community through their involvement in mineralization, sediment mixing, oxygen flux in the sediment, nutrient cycling and recovery of organic matter (Snelgrove, 1998). Polychaetes are significantly diverse, abundant and have ecologically important functions in coastal waters. They also provide sediment stability and adapt to different environments (Simboura et al., 2000). Their short life cycles and limited mobility have led to them being used as bio-indicators in monitoring studies (Gray and Elliott, 2009). Yet, even though ports are important both ecologically and economically, few studies have been carried out to determine macrobenthic diversity in the ports of India (Anil et al., 2002). The Cochin port is a tropical habitat influenced by the southwest and the northeast monsoons, and the objective of this study is to describe the spatio-temporal variation in the diversity and abundance of macrobenthos and to examine the impact of sediment characteristics and environmental variables on benthic diversity in a dynamic port environment.

2. Materials and methods

2.1. Study area

Sampling was carried out in and around Cochin port (9° 34′ 48″ N, 76° 08′ 24″E) located in the state of Kerala along the west coast of India (Fig. 1). The port is at the entrance of Cochin backwaters, which is a shallow brackish water system within a tropical estuary (Qasim and Reddy, 1967). It is a complex microtidal estuary receiving 2×10^{10} m^3 $year^{-1}$ of freshwater through six rivers (Srinivas et al., 2003). The annual rainfall of the region is around 320 cm, of which more than 60% is accounted for during the southwest monsoon (June–September). During premonsoon (February–May), increased tidal activity modifies the flushing characteristics of the estuary considerably (Balachandar et al., 2016). Cochin port is located in the northern part of the Cochin backwaters and is one of the two permanent openings, the other one being at Azhikode, that flush the river water into the Arabian Sea (Fig. 1). The estuarine mouth connected to the sea is a ∼450 m wide channel through which the water is flushed out during the ebb tide, and the seawater enters the port during the flood tide. The depth of the estuary varies considerably and the major portion of the estuary has a depth range of 2–7 m. A total of 21 sampling (port) stations (see Fig. 1) were located along the two channels (Mattancherry channel and Ernakulam channel) in the port area where samples were collected: S01 — custom bay, S02 — fishery harbour, S03 — dry dock, S04 — south coal berth, S05 — quay 1, S06 — quay 2, S07 — north coal berth, S08 — boat train pier, S09 — container terminal, S10 — DC jetty, S11 — quay-10, S12 — Ro-Ro jetty, S13 — naval jetty, S14 — Cochin shipyard, S15 — bunker oil jetty, S16 — integrated fisheries project jetty, S17 — south tanker berth, S18 — north tanker berth, S19 — Ernakulam ferry jetty, S20 — Cochin oil terminal, and S21 — Ernakulam creek mouth. The tides at the port stations are mixed semidiurnal with a range of about 1 m (Qasim and Gopinathan, 1969). Cochin port has three dredged channels where the stations are located with one being the Approach Channel and two inner channels (Fig. 1). The Approach Channel is around 10 km in length and ∼450 m wide where five stations were located (S1, S9–10, and S19–21). The other two inner channels sampled were the Ernakulam Channel (eight stations: S11–S18) which is ∼5 km long and 250–500 m wide and the Mattancherry Channel (seven stations: S2–S8), which is about 3 km long with a width of around 170–250 m. The Ernakulam channel and the Mattancherry channel are located on the either side of the Willingdon Island (Menon et al., 2000). Water depth at the port stations varied between 8–10 m.

2.2. Sampling and analysis

Sampling was carried out during October 2011 (Post Monsoon I — PM I), May 2012 (pre-monsoon), August 2012 (monsoon) and November 2012 (Post Monsoon II — PM II) representing different seasons. The surface and near-bottom water samples were collected using a Niskin water sampler for the analysis of Chlorophyll *a*, salinity, dissolved oxygen (DO), temperature, and suspended particulate matter following the methods described by Parsons et al. (1984). Nutrients such as nitrate (NO_3), phosphate (PO_4), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_4) were analysed by SKALAR SAN ^{plus} analyser. The seawater samples for analysis were collected in triplicate. Sediment samples were collected from an average depth of 8–10 m using a Van Veen grab (0.04 m^2). At each station, sediment samples were collected in triplicate and washed separately through a 500 µm nylon mesh at sea and then transferred to polythene bags and preserved in 10% formaldehyde in seawater containing Rose Bengal stain. In the laboratory, the sediment samples were sieved through a 500 µm metal sieve, and all macrobenthic fauna were sorted and preserved in plastic vials containing 10% formaldehyde solution for further microscopic analysis. Polychaetes were identified to the highest taxonomic level (genus or species) possible with the help of available identification keys (Fauvel, 1953; Day, 1967; Fauchald and Jumars, 1979; Theodore and William, 1979). The macrobenthos other than polychaetes were identified to family or genus level. The numerical abundance of each species was recorded and expressed as the number of individuals per square metre (indiv m^{-2}).

Biomass was determined by wet weight method and expressed as milligramme per metre square (mg m^{-2}) (Mason et al., 1985). Organic carbon (OC) and percentage composition of sediment (sand, silt and clay) were determined by standard titration method and pipette analysis, respectively (Wakeel and Riley, 1957; Buchanan, 1984). Organic carbon was expressed as the percentage of sediment dry weight.

Macrobenthic fauna, especially polychaetes, reflect the ecological and environmental status of the seabed and this was assessed in terms of the number of individuals or specimens (N), number of taxa (S), total abundance (A), Margalef species richness (d), Pielou's evenness (J′) and Shannon index (H′) using log2 scale at each station (Clarke and Gorley, 2006) (Table 1). Bray–Curtis similarity for species diversity of macrobenthic polychaetes was determined using PRIMER-v5 (Clarke and Gorley, 2006). Seasonal variation in the total macrobenthic community, polychaetes and other invertebrate taxa were performed using SURFER-6 (developed by Golden Software Inc., USA). Canonical correspondence analysis (CCA) was performed to evaluate the relationship between environmental variables and macrobenthic polychaetes as well as other taxonomic groups. The multivariate index of trophic state (TRIX) method was used to evaluate the trophic status of Cochin port (Vollenweider et al., 1998; Malhadas et al., 2014), which was later used to assess the relationship between sediment and trophic status of water. TRIX was calculated where chlorophyll *a* is in mg m^{-3}, a%O_2 is the absolute value of the percentage using the equation TRIX = (log10 (Chl $a \times a\%O_2 \times$ DIN $\times$ DIP) + k)/m, of DO saturation (abs $|100 - \%O_2| = \%O_2$) [DIN = dissolved inorganic nitrogen including NO_3, NO_2, NH_4 in mg m^{-3}, DIP = dissolved inorganic PO_4 in mg m^{-3}]. The constants, k- 3.5 and m- 0.8 are scale values obtained from Vollenweider et al.

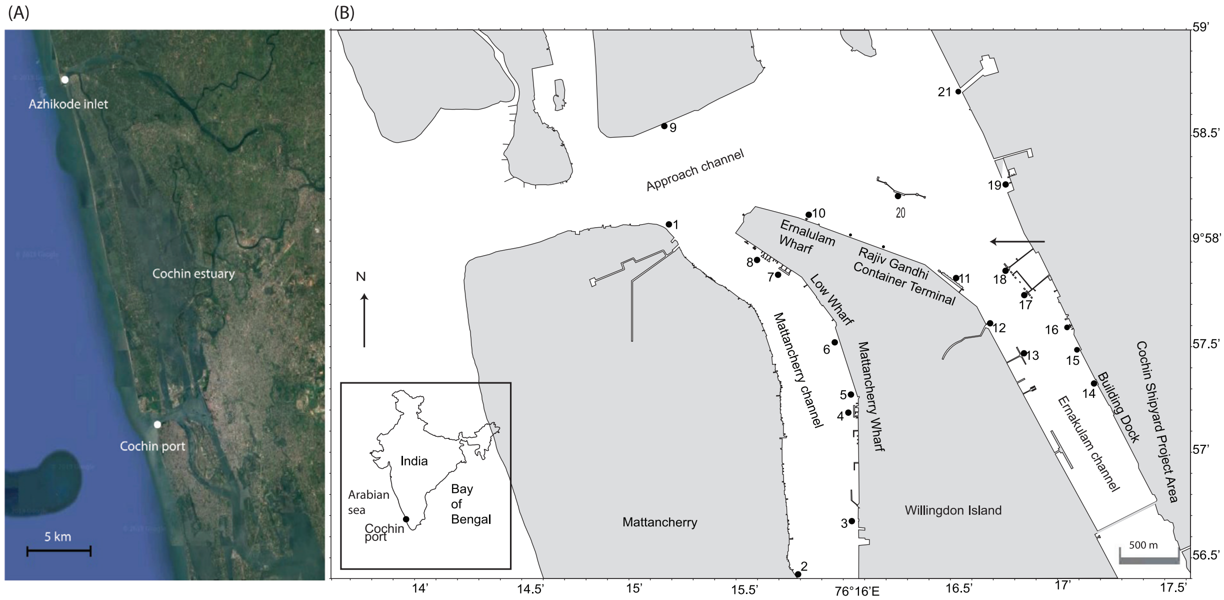

Fig. 1. Map showing (A). Cochin estuary and (B). Study areas along the three channels and sampling stations in and around Cochin port. (1) Custom buoy, (2) Fishery harbour, (3) Dry dock, (4) South coal berth, (5) Quay-1, (6) Quay-2, (7) North coal berth, (8) Boat train pier, (9) Container terminal, (10) DC jetty, (11) Quay-10, (12) Ro-Ro jetty, (13) Naval jetty, (14) Cochin shipyard, (15) Bunker oil jetty, (16) Integrated fisheries project jetty, (17) South tanker berth, (18) north tanker berth, (19) Ernakulam ferry jetty, (20) Cochin oil terminal, (21) Ernakulam creek mouth.

(1998) to adjust TRIX scale values (reads from 0 to 10) with a level of eutrophication in the Cochin Port. According to this method, TRIX scores less than 4 indicate high state of water quality with low eutrophication; scores between 4 and 5 indicate good state of water quality with medium eutrophication; scores between 5 and 6 indicate bad state of water quality with high eutrophication and scores greater than 6 indicate poor state of water quality with elevated levels of eutrophication.

3. Results

3.1. Environmental parameters

Seasonal variation in temperature, salinity and dissolved oxygen across all 21 stations in Cochin port are shown in Table 2. The average values of these parameters were given along with the standard deviation at each station. The average seawater temperature during monsoon season was 25.3 ± 0.4 °C and it ranged from 29.0 ± 0.7 °C to 31. ± 0.2 °C during pre-monsoon and post-monsoon respectively. The mean surface water temperatures during PM I and PM II, pre-monsoon and monsoon were 29. ± 0.8 °C, 30.1 ± 0.4 °C, 30.1 ± 0.4 °C and 27.5 ± 0.4 °C respectively (Table 2). The near-bottom water temperature, in general, was 1±0.8 °C lower than the surface water temperature. During PM I and PM II, the difference in the tidal amplitude was 0.50–0.91 (±0.10) m. The tidal amplitude during pre-monsoon and monsoon season was 0.4–0.6 (±0.1) m and 0.6–0.7 (±0.5) m respectively. The salinity of surface and near-bottom water during post-monsoon was 24.7 ± 6.5 PSU and 31.2 ± 5.5 PSU, during pre-monsoon 18.9 ± 4.7 PSU and 24.3 ± 5.5 PSU and during monsoon 5.3 ± 1.3 PSU and 20.5 ± 10.8 PSU respectively indicating a wide seasonal variation in the salinity and depth stratification (Table 2). The mean DO of near-bottom water during PMI and PMII was 4.2 ± 1.4 mg l^{-1} and 2.6 ± 1.1 mg l^{-1} respectively and during pre-monsoon season, the mean DO was 3.5 ± 0.8 mg l^{-1}. During monsoon season, DO was lower compared to other seasons and it was 1.9 ± 1.1 mg l^{-1} (Table 2). The concentration of nutrients varied across seasons and stations during the study (Supplementary Figure 9). The average value of TRIX was 5.15 during the study, indicating poor water quality which was highly eutrophic. The TRIX scores ranged from 1.64 to 7.37 during the course of this study (October 2011 to November 2012). Pre-monsoon and monsoon seasons showed a rise in eutrophication, and it was moderate during the post-monsoon seasons (PM I and PM II).

Sediment composition varied spatio-temporally within the port (Fig. 2). In general, silt was the most dominant component – 49.5 ± 22.5% followed by clay – 32.2 ± 25.4% and sand – 18.3 ± 15.6% during all the seasons in most of the stations. The percentage of silt in the sediment ranged between 10% at S-20 to 91% at S-06 (Fig. 2). The percentage of sand was comparatively lower ranging from 0.3% to 62% and dominated during PM I (Fig. 2A), and was merely present during PM II (Fig. 2D). Sand showed significant variation during the pre and post-monsoon seasons (pre-monsoon 18.98 ± 14.2%, monsoon 10.7 ± 12.6% PM I and PM II 29.8 ± 11.3% and 10.7 ± 12.6% respectively) (Fig. 2). Clay is the second most dominant component of the sediment and ranged between 0.2% at S-08 to 85% at S05. The total organic carbon of the sediment ranged from 1.4% to 3.6% during all the seasons. During PM I and II (Fig. 2A, D), higher organic carbon content was observed in the sediment 2.7 ± 0.40% and 2.6 ± 0.30% respectively. However, during monsoon and pre-monsoon, the organic carbon content was lower, 1.9 ± 0.8% and 1.7 ± 0.6% respectively (Fig. 2C, D).

The chlorophyll *a* content was higher in near-bottom water during monsoon at S-19 (82.9 mg m^{-3}), and lower at S-09 during PM I (0.5 mg m^{-3}) (Fig. 3A). The average chlorophyll *a* content during PM I was 2.2 ± 1.8 mg m^{-3}, pre-monsoon: 21.6 ± 21.4 mg m^{-3}, monsoon: 13.6 ± 7.1 mg m^{-3} and during PM II, it was 14.6 ± 0.4 mg m^{-3} (Fig. 3A). Sediment chlorophyll *a* content during PM I, pre-monsoon, monsoon and PM II was 0.77 ± 0.1 mg m^{-2}, 0.74 ± 0.3 mg m^{-2}, 0.60 ± 0.4 mg m^{-2} and 0.56 ± 0.2 mg m^{-2} respectively (Fig. 3B). The maximum sediment chlorophyll *a* content was observed during pre-monsoon at S-14, and minimum during monsoon at S-21 (Fig. 3B).

3.2. Seasonal variation in macrobenthos

The macrobenthos reported during this study comprised of Annelida (Polychaeta and Oligochaeta), Arthropoda (amphipods,

Table 1
Number of species (S), Number of specimens (N), Margalef species richness (d), Pielou's evenness (J′), Shannon index (H), of macrobenthic polychaetes during different seasons in Cochin port. (Note: Stations in which organisms were not present are not included in the table during different seasons.).

Post monsoon I						Pre-monsoon						Monsoon						Post-monsoon II					
Stations	S	N	d	J′	H′ (loge)	Stations	S	N	d	J′	H′ (loge)	Stations	S	N	d	J′	H′ (loge)	Stations	S	N	d	J′	H′ (loge)
1	3	17	0.6993	0.9099	0.9996	1	5	16	1.452	0.9941	1.6	2	1	3	0	****	0	1	4	16	1.092	0.9929	1.376
5	3	36	0.5565	0.6828	0.7502	6	4	14	1.123	0.9909	1.374	4	1	4	0	****	0	2	5	19	1.368	0.9929	1.598
6	1	4	0	****	0	8	4	17	1.066	0.9855	1.366	5	4	12	1.213	0.9967	1.382	4	3	9	0.9078	0.9952	1.093
7	2	24	0.3148	0.7809	0.5413	10	2	7	0.5277	0.9817	0.6805	10	1	4	0	****	0	5	4	20	1.006	0.995	1.379
8	3	31	0.5798	0.7874	0.865	12	3	12	0.7939	0.9917	1.09	16	2	7	0.5026	0.9979	0.6917	6	4	17	1.053	0.9816	1.361
9	1	10	0	****	0	13	1	6	0	****	0	17	1	3	0	****	0	8	5	26	1.222	0.9944	1.6
10	4	66	0.7163	0.7135	0.9892	14	3	8	0.9402	1	1.099	19	2	6	0.5454	0.9919	0.6875	9	3	13	0.7917	0.9659	1.061
11	3	23	0.6374	0.7987	0.8774	15	4	13	1.163	0.99	1.372							10	4	19	1.017	0.9923	1.376
12	2	8	0.4854	1	0.6931	17	6	21	1.652	0.9892	1.772							11	4	14	1.129	0.9926	1.376
13	2	8	0.4854	1	0.6931	20	1	3	0	****	0							12	3	14	0.7657	0.9825	1.079
14	1	4	0	****	0	21	2	9	0.4629	0.9985	0.6921							13	1	5	0	****	0
15	2	19	0.3423	0.9476	0.6568													14	5	22	1.303	0.9932	1.598
16	1	6	0	****	0													15	5	24	1.265	0.997	1.605
18	1	25	0	****	0													16	0	0	****	****	0
20	2	19	0.3423	0.9476	0.6568													17	7	35	1.689	0.988	1.923
21	0	0	****	****	0													18	5	21	1.318	0.9868	1.588
																		20	2	7	0.5277	0.9817	0.6805
																		21	3	13	0.7715	0.9987	1.097

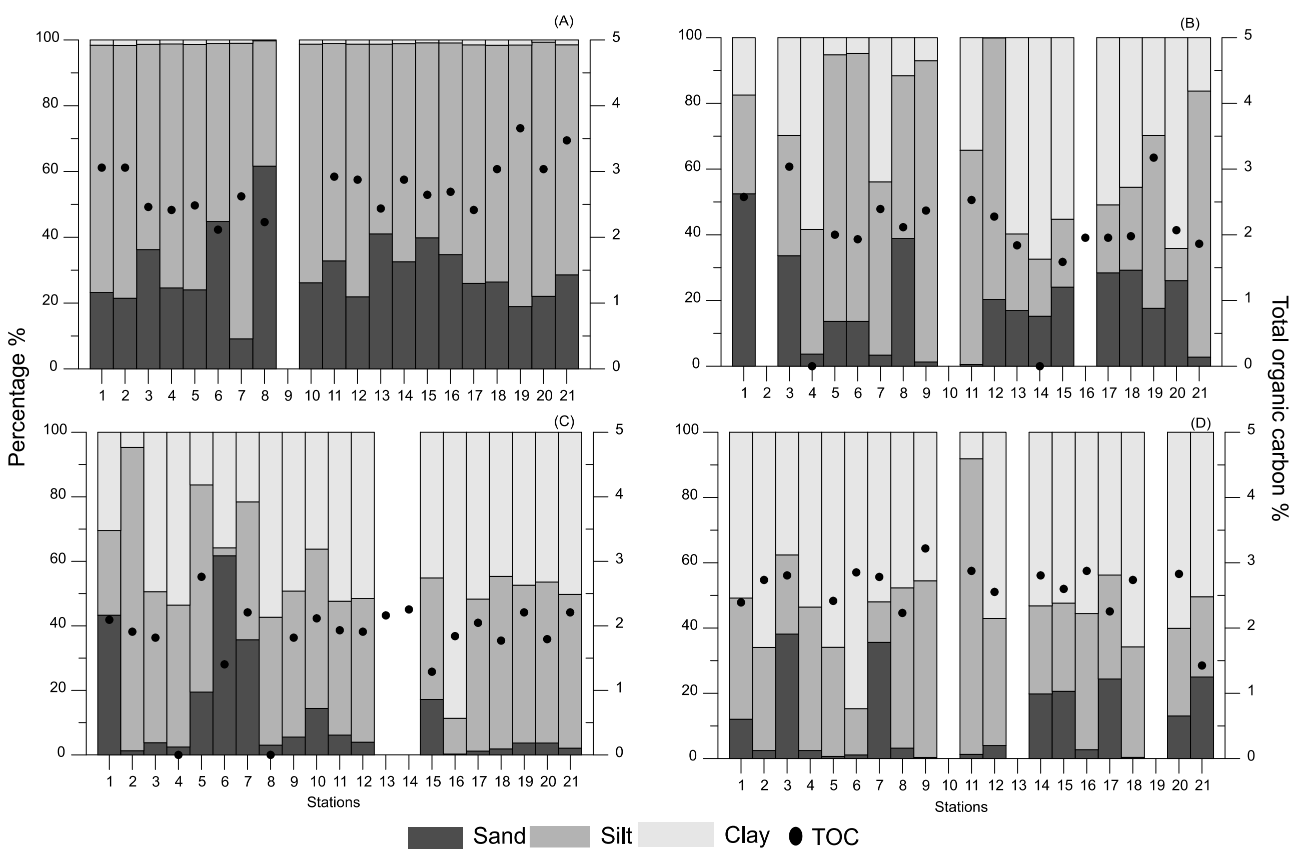

Fig. 2. Seasonal variation in the sediment texture and organic carbon in Cochin port during (A) Post monsoon I (B) Pre-monsoon (C) Monsoon (D) Post monsoon II.

and isopods and tanaids), Mollusca (bivalves) and Gobiidae (mud skippers). Among these groups, polychaetes were the most common and abundant organisms during all the seasons. Among the 36 macrobenthic taxa, 21 were polychaetes contributing more than 50% to the total macrobenthic abundance. Spionid and nephtyid polychaetes were observed during all the seasons. The maximum abundance of macrobenthos was during PM II (9487 indiv m^{-2}), followed by PM I (6222 indiv m^{-2}), pre-monsoon (2171 indiv m^{-2}) and monsoon season (416 indiv m^{-2}) (Fig. 5B). The stations with maximum abundance during PM I, pre-monsoon, monsoon and PM II are S17 — South tanker berth (2494 indiv m^{-2}), S10-DC jetty (2279 indiv m^{-2}), S08-boat

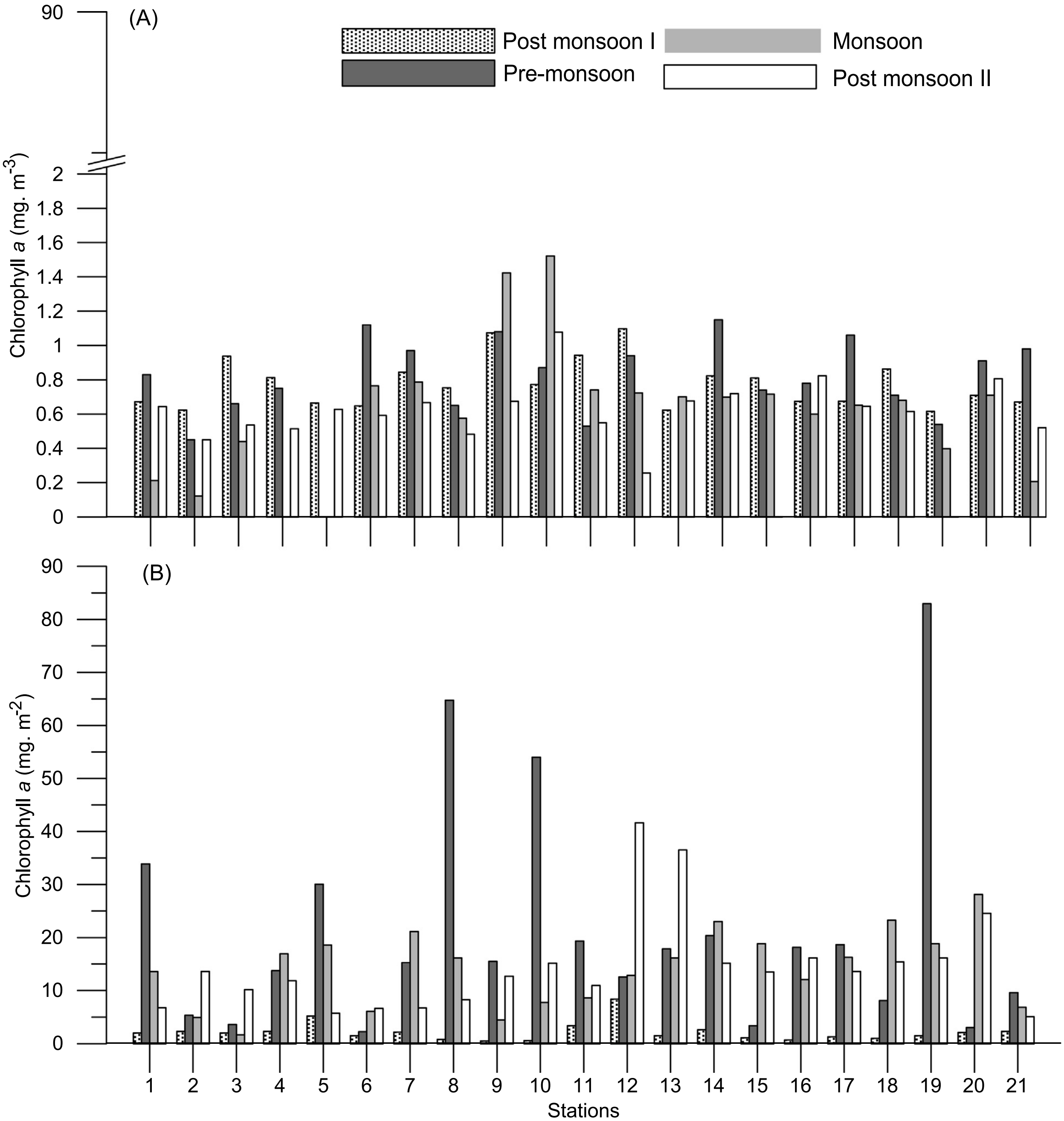

Fig. 3. Seasonal variation in (A) bottom water Chlorophyll *a* (B) sediment Chlorophyll *a* at different stations in Cochin port.

train pier, S13-Naval jetty (323 indiv m^{-2}) and S19-Ernakulam ferry jetty (92 indiv m^{-2}) respectively (Fig. 5B). The maximum biomass of macrobenthos was reported during PM II — 59797 mg m^{-2} (Fig. 5A), followed by pre-monsoon 14287 mg m^{-2} (Fig. 4C), PM I -13466 mg m^{-2} (Fig. 4A), and it was minimum during monsoon season 6375 mg m^{-2} (Fig. 4E). Abundance and biomass were directly related to each other during all the seasons except pre-monsoon, where the corresponding biomass was higher even though the abundance was lower (Fig. 4C–D). The maximum biomass observed during post-monsoon II season was 4249 mg m^{-2} in S08 and the minimum was 24 mg m^{-2} in S14 (Fig. 4G). During pre-monsoon and monsoon seasons, the biomass was higher at S15 (3030 mg m^{-2}) and S19 (2422 mg m^{-2}), and lower at S14 (108 mg m^{-2}) and S17 (121 mg m^{-2}) respectively (Fig. 4C–E). Both abundance and biomass of macrobenthos were higher during PM II. The stations S-08 had the maximum (15084 mg m^{-2}) biomass and S-11 had minimum (251 mg m^{-2}) biomass of macrobenthos during PM II (Fig. 4G). During pre-monsoon season few stations showed the lower abundance of macrobenthos, whereas the biomass was higher (e.g., S08 and S13 had the abundance of 323 indiv m^{-2}; however the biomass differed between these two stations, S08–3001 mg m^{-2} and S13–1313 mg m^{-2} respectively) (Fig. 4C–D).

During PM I, the maximum abundance of macrobenthic organisms at S10 was contributed by the spionid, *Prionospio* sp. (1910 indiv m^{-2}) which was the dominant taxon (Fig. 6; Table 3). The number of *Prionospio* sp. was high during PM I season contributing about 77% to the total abundance, followed by Oligochaeta (8%) and *Ancistrosyllis* sp. (3%) (Table 3). Other polychaetes observed during this season were *Capitella capitata* at S08, *Mediomastus* sp.at S07, S10, S12, and *Cossura coasta* at S10 and S20 stations (Table 3). The Errantiate polychaetes found during this season were *Nephtys* sp. at S05, S08 and S11 and *Dendronereis* sp. at S01, S05 and S10. The most abundant errantiate polychaete was *Ancistrosyllis* sp. with a total abundance of 246 indiv m^{-2} (Fig. 6) at S08, S10, S11 and S20 (Table 3).

During the pre-monsoon season, the higher abundance of the macrobenthic organisms was observed at S08 and S13 (Fig. 5D). The most abundant taxa during this season were Oligochaeta (21%), *Paraprionospio pinnata* (8%) and *Ampithoe* sp. (7%) (Table 3). Among the four genera of amphipods, three were observed during the pre-monsoon season, namely *Ampelisca* sp. (S01, S08), *Ampithoe* sp. (S01, S08) and *Cheirocratus* sp. (S01, S08, S11, S20) with a total abundance of 631 indiv m^{-2} (Fig. 6; Table 3).

Macrobenthic diversity and abundance were at their lowest during monsoon season compared to other seasons with *P. pinnata* and *Ampithoe* sp. contributing 22% and 15% followed by *Ancistrosyllis* sp., *Nereis* sp., Oligochaeta and tanaids, each contributing 11% respectively (Table 3) with a total abundance of 416 indiv m^{-2} (Fig. 4F).

In contrast, during PM II, the abundance (9487 indiv m^{-2}) (Fig. 6B) and biomass (59 797 mg m^2) (Fig. 5A) were maximum compared to other seasons. The most abundant macrobenthos taxa were the Oligochaeta, *Nephtys* sp. and Cirolanid isopod which contributed 19%, 17% and 7% respectively to the total abundance (Table 3). The variation in the diversity and abundance at all the stations were observed during PM II, unlike other seasons when the organisms were reported from few stations. The most abundant polychaetes were *C. capitata* which was observed at S13 and S18 (200 indiv m^{-2}), *C. coasta* observed at S12, S14, S15, S17 and S18 with a total abundance of 200 indiv m^{-2} (Table 3). The *Nephtys* sp. was the second most dominant (1617 indiv m^{-2}) taxon during the PM II season and was observed at most of the stations (Fig. 7). Spionids were the most dominant polychaete family and it was represented by four genera which were reported at many stations such as *P. pinnata* (600 indiv m^{-2}), *Prionospio* sp. (462 indiv m^{-2}), *Polydora kempi* (200 indiv m^{-2}) and *Streblospio* sp. (15 indiv m^{-2}) (Fig. 6). Amphipods found during PM II were *Ampelisca* sp. (S01, S04, S05) with a total abundance of 231 indiv m^{-2}, along with *Ampithoe* sp. and *Cheirocratus* sp. which had similar abundance (169 indiv m^{-2}). The amphipod, *Gammaropsis* sp. was the most abundant (646 indiv m^{-2}) at S05, S08, S10 and S20 (Figs. 4H & 7; Table 3). Oligochaeta was the second most abundant group of annelids observed in Cochin port. They were found during all the seasons and at most of the stations with maximum abundance during PM II with a total count of 1801 indiv m^{-2} (Fig. 6) (S06, S08, S09, S11, S12, S15, S17 and S21) (Table 3). Juvenile fishes (Gobiidae) were also observed during PM II at S08.

3.3. Seasonal variation in macrobenthos diversity

Species diversity index at all the stations was estimated based on Margalef species richness (d), Shannon–Weiner index (H′) and evenness (J′). The maximum number of species were encountered during PM II at S07 (Table 1). The correspondence values of the Shannon–Weiner index (H′) were high during pre-monsoon and PM II, which were 1.77 and 1.92 respectively. During the monsoon season, species diversity was low compared to other three seasons (Table 1), and four species were observed during this season (Table 1). Bray–Curtis similarity index was applied for grouping the stations according to macrobenthic abundance. At 50% similarity level, three and four groups were revealed during PM I and PM II seasons (Fig. 7A–D) respectively. Post monsoon season showed maximum diversity and biomass of macrobenthos with lower DO concentration in near-bottom water (Table 2 and Fig. 8). The group I stations were dominated by *Prionospio* sp. (contribution to abundance — 21.3%), *Ancistrosyllis constricta* (contribution to abundance 2.1%) and *Nephtys* sp. (contribution to abundance 2.6%). In group I (Fig. 7), stations S05, S07, S08, S11 and S18 were closely similar with *Prionospio* sp. being the dominant taxa. In group II (S01, S09, S15 and S20), *Prionospio* sp. was least abundant (11%) compared to Group I and *A. constricta* was the most abundant taxon with 3% contribution to the total abundance respectively (Fig. 7). The group III stations had *Prionospio* sp. as the common organism which contributed 4% to the total abundance. During pre-monsoon season, three groups were reported, group I (S06, S12 and S15), group II (S14 and S17) and group III (S01 and S08) and the organisms which contributed to the total abundance were *Ampithoe* sp. (4.3%), *Ampelisca* sp. (3.1%), *Cheirocratus* sp. (3.6%), *Nephtys* sp. (3.4%), *C. coasta* (3%), Oligochaeta (2.8%), *Streblospio* sp. (3.3%) and *Aricidea* sp. (2.8%) (Fig. 8B). The presence of *Nephtys* sp. and *C. coasta* in all the three stations indicated resemblance in the occurrence of polychaete species in group I stations. In group II, *Nephtys* sp., *Streblospio* sp. and *Aricidea* sp. were common. During pre-monsoon season, group III stations were dominated by amphipods such as *Ampithoe* sp., *Ampelisca* sp. and *Cheirocratus* sp. (Fig. 7B). During the monsoon season, the similarity was least among the stations due to low species diversity and abundance. Only two stations, S02 and S19 showed resemblance owing to the presence of isopods (Fig. 7C). During PMII, the similarity in the stations and the organisms present was higher, and the presence of *P. pinnata* (4.8%), *Nephtys* sp. (4.2%), gastropods (2.8%), *Gammaropsis* sp. (4.7%), *Dendronereis* sp. (4.3%), Oligochaeta (4.8%) and *C. coasta* (3.6%) were responsible for such grouping (Fig. 7D). PM II season had four groups with a 50% resemblance. In group I (S14, S15, S17 and S18), *Nephtys* sp. and *C. coasta* were found in all the stations. Group II (S5, S10 and S21) stations had Nereids, *Dendronereis* sp. and amphipod, *Gammaropsis* sp. in all the stations. The *Nereis* sp. indicated the highest abundance (354 indiv m^{-2}). The group III (S02 and S06) and group IV (S09 and S12) had *Nephtys* sp. which was common to all their stations (Fig. 7D).

The CCA and Redundancy analysis (Fig. 8A–D) indicated sediment characteristics and organic carbon were important in determining the community structure of benthic organisms at the sampling stations during different seasons. Length of gradient value >2 was shown during post-monsoon and pre-monsoon seasons and during monsoon, it was <2. The correlation percentages between macrobenthic abundance and the environmental variables during pre-monsoon were 95%, followed by 82% during monsoon, and 77% and 76% during PM II and PM I respectively. The canonical correspondence analysis for PM I (Fig. 8A) revealed that silt and organic carbon influenced the abundance of the organisms. Sampling stations such as S05, S09, S10, S18 and S20 with high silt and low organic carbon were dominated by sedentary annelids including *Prionospio* sp. and Oligochaeta, while at S08 with higher sand content, *Ancistrosyllis* sp., Tanaidacea and isopods were reported (Table 3). *Prionospio* sp. appeared to be unaffected by changes in environmental variables as they occurred in the majority of the stations during the PMI season. Higher temperatures and salinities (above 28 psu) of bottom water also influenced the abundance of macrobenthos in these stations during PM I.

During PMII (Fig. 8D), the highest abundances were recorded when clay was the dominant sediment. Increased clay and organic carbon content correlated with higher abundance of the organisms. Stations with higher DO, higher temperatures and salinities of 30 psu and above generally correlated with higher abundance. The stations S05, S08, S10, S14, S15 and S17 had higher abundance of *Nereis* sp., *Nephtys* sp., *Dendroneries* sp., *Prionospio* sp., *Polydora* sp., oligochaetes, amphipods (*Gammaropsis* sp.), and cirolanid isopods (Table 3).

Pre-monsoon (Fig. 8B) season showed the highest correlation in diversity of macrobenthos with environmental variables. The

Table 2
Seasonal variation in the salinity, temperature and dissolved oxygen of surface and bottom water at Cochin port (PM I — post monsoon I, Pre-M — pre-monsoon, M – Monsoon, PM II — post monsoon II, S — surface water and B — bottom water).

	Salinity (PSU)								Temperature (°C)								Dissolved Oxygen (mg L^{-1})							
Stations	PM I		Pre-M		M		PM II		PM I		Pre-M		M		PM II		PM I		Pre-M		M		PM II	
	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B
1	30.80	36	18.24	21.6	9.36	22.5	27.09	31.0	29.07	28.1	30.36	29.5	27.04	25.5	30.25	30.3	5.50	8.1	4.30	3.5	2.40	1.0	3.30	3.2
2	20.50	31	14.11	25.4	4.04	8.9	18.86	28.8	28.83	28.5	29.55	29.3	28.01	27.5	29.70	30.6	5.70	3.1	4.70	4.0	3.20	4.1	4.60	3.0
3	22.70	24	18.35	29.1	4.21	4.5	25.26	29.1	28.02	28.6	30.37	28.9	27.37	27.9	30.34	30.5	4.80	3.2	4.20	2.8	4.40	4.6	3.20	3.4
4	27.30	35			7.80	14.6	23.78	32.4	29.30	28.0	29.90	28.4	27.72	24.8	30.33	30.3	5.10	5.3	3.60	3.3	5.10	1.1	4.90	2.2
5	21.00	29	25.61	27.0	6.20	13.2	32.02	32.5	29.23	28.4	30.02	28.9	28.13	24.7	30.20	30.2	6.00	2.4	3.90	4.4	5.50	0.6	4.30	0.8
6	24.90	37	24.38	30.5	8.30	12.5	33.87	34.0	29.25	28.6	29.58	28.5	28.53	24.8	30.38	30.2	7.20	5.0	3.90	2.5	5.60	2.4	2.70	4.4
7	26.70	25	32.54		8.04	10.7	31.70	33.1	29.68	28.5	29.60	28.2	27.32	24.8	30.55	30.5	8.40	5.6	3.90	2.8	1.00	0.5	5.10	1.6
8	23.40	31	18.81	23.8	5.74	22.8	31.70	22.1	29.67	29.1	29.13	28.5	27.34	25.6	30.22	30.2	6.80	3.8	4.20	2.5	2.20	1.0	5.00	2.4
9	24.10	37	21.27	34.6	5.14	23.6	20.02	35.0	30.42	28.1	30.06	28.8	27.23	24.1	29.92	30.1	6.80	5.3	4.20	3.3	2.20	1.1	6.20	3.3
10	25.30	30	15.97	25.5	3.78	9.6	31.91	30.1	29.42	29.1	29.29	28.8	27.54	24.9	30.33	30.4	6.00	4.6	3.60	3.3	2.60	1.7	6.20	4.2
11	30.00	36	17.86	20.8	3.80	34.6	20.10	33.6	28.32	27.5	30.14	29.4	27.46	24.0	30.50	30.2	7.40	3.6	4.20	4.2	5.10	1.6	4.50	4.0
12	19.60	30	17.53	21.4	3.35	32.0	33.24	34.3	28.84	27.0	30.10	29.5	27.55	24.1	29.01	30.2	6.60	3.2	4.00	3.7	5.00	1.7	4.20	3.6
13	14.00	33	18.64	18.7	3.48	34.2	14.49	29.8	29.07	28.0	30.00	30.0	27.39	27.6	29.88	30.5	6.40	4.9	4.00	3.9	4.90	4.0	4.80	1.3
14	9.80	32	14.88	27.7	5.14	33.3	33.23	34.2	29.54	27.8	29.95	28.6	27.74	24.5	30.25	30.4	5.90	3.2	5.50	3.0	4.10	1.5	3.00	1.6
15	15.70	33	17.61		6.15	33.6	23.54	33.5	29.40	27.9	30.34	28.4	27.65	24.1	30.29	30.3	5.90	3.1	5.50	2.7	3.60	1.4	3.30	1.8
16	15.70	36		19.4	6.14		29.49	32.8	31.30	27.1	29.68	29.3	27.50	26.1	30.02	30.3	8.00	3.4	4.20	4.5	2.10	1.8	3.90	2.2
17	32.80	37	13.88	15.1	5.48	13.3	31.76	33.9	29.54	27.0	30.46	28.2	27.23	24.0	30.08	30.2	7.40	3.2	5.60	2.4	2.10	1.3	1.90	2.2
18	32.40	37		34.4	5.60	35.3	32.27	33.8	28.03	26.9	30.19	28.0	27.52	24.0	30.23	30.2	6.40	2.5	5.10	2.4	2.10	0.9	1.60	1.9
19	29.30	36	19.69	19.5	3.18	14.3	19.57	22.6	27.92	27.5	30.33	30.3	27.25	27.2	29.98	30.1	6.40	3.3	4.40	4.6	5.90	2.9	3.20	1.2
20	20.37	24	13.20		4.12	29.7	28.88	33.9	29.36	29.1	30.93	30.1	28.11	24.2	30.52	30.2	6.10	5.4	5.50	5.1	3.50	1.5	3.80	2.3
21	11.20	11	16.79	21.5	2.63	6.4	15.59	18.1	29.34	29.3	30.17	30.0	27.36	27.6	30.51	30.5	5.80	5	4.90	3.7	3.40	3.0	6.60	3.9

stations with the highest abundance of macrobenthic taxa were S6, S8, S12, S13, S15, S17, S20 and S21 (Table 3). In the sediment, sand was present in all the stations which shared the highest abundance with an average organic carbon of 2.5. The organisms found are mostly free-living and active predators such as *Nephtys* sp., and *Syllis* sp. except *Prionospio* sp., which is sedentary. Amphipods such as *Ampelisca* sp., *Ampithoe* sp. Cheirocratus sp., *Gammaropsis* sp. were also reported. Environmental parameters also influenced the distribution and abundance organisms during the monsoon season (Fig. 8C) when lowered temperature, salinity and DO in bottom water occurred, as shown in Table 2. The sediment composition during the previous seasons (PMI and pre-monsoon) had higher sand content compared to monsoon and PM II seasons and this may be due to riverine runoff during the monsoon season thereby influencing the abundance and diversity of the macrobenthic community. During the PM II season, *Paraprionospio* sp. occurred in sandy-silt sediment as they can survive in low DO, nutrients and organic carbon.

4. Discussion

4.1. Temperature, salinity and dissolved oxygen

The fluctuations in physical and chemical variables are often associated with changes in regional climatic and biological activity, alterations in the surface water due to evaporation, freshwater influx, the intensity of solar radiation, as well as cooling and mixing with the ebb and flow from adjoining shallow waters (Kumar and Khan, 2013). Previous studies carried out indicated contamination of Cochin backwaters by anthropogenic pollutants due to poor flushing of sediment, enclosed nature of the estuary and adsorption of pollutants in the sediments leading it into a sensitive ecosystem (Martin et al., 2012; Anu et al., 2014). In the present study, the 21 stations located in all three channels were influenced by the incoming sea water during high tide and outgoing freshwater during the low tide. Water in the Cochin port region derives a large proportion of nutrient load throughout the year from land drainage, agricultural activities and river discharge during the monsoon (Devi et al., 1991; Madhu et al., 2007). Tropic index (TRIX) scores showed that Cochin backwater is highly eutrophic. The hydrography of the Cochin estuary reflected tropical estuarine conditions where seawater temperature gradually increased from post-monsoon to pre-monsoon season, after which a considerable decrease during monsoon was observed. During the monsoon season, stratification intensified owing to increased freshwater influx, which also led to a decrease in salinity from the mouth of the Cochin estuary to upstream. High nutrient supply during monsoonal rainfall is a unique characteristic of an estuary influenced by monsoon (Qasim, 1982). During the non-monsoon period, the freshwater influx to the estuary is reduced, and saltwater intrusion can be seen up to 40 km inland from the mouth (Jacob et al., 2013). As reported in earlier studies, high concentrations of phosphate were observed during the post and pre-monsoon periods from December to April (Sankaranarayanan and Qasim, 1969; Martin et al., 2012). This may be due to the result of high salinity/pH combined with tidal activity during the pre-monsoon, which causes the removal of phosphate from the suspended particles (Martin et al., 2011). Near bottom water had low concentrations of dissolved oxygen compared to the surface waters during day time. This net reduction of oxygen reflected typical tropical estuarine conditions, with salinity stratification during monsoon and partially mixed conditions during non-monsoon seasons.

4.2. Sediment and organic carbon input

The distribution of sediment grain size and organic matter determine metal concentrations as well as anthropogenic pollutants such as total nitrogen (TN) and total phosphorus (TP). They are also in turn correlated with the distribution of rare elements in the sediment (Aloupi and Angelidis, 2001; Liaghati et al., 2003; Rodríguez-Barroso et al., 2010). Sediment texture shows significant fluctuations in their characteristics due to water discharge in riverine and estuarine areas, leading to considerable intermixing of sand, silt and clay (Muraleedharan Nair and Ramachandran, 2002). Even though sediment showed fluctuations in Cochin port, higher percentage of sandy sediment is seen at the bar mouth (sampling stations S07, 08 and 10; see Fig. 1) due to estuarine bed load movement (Nair et al., 1990, 1993; Martin et al., 2012). Higher silty sediment in this estuarine port during pre-monsoon is associated with sedimentation processes leading to the settlement of fine silt particles at the bottom due to weak

Table 3
Variation in the abundance (indiv m^{-2}) of macrobenthos in Cochin port during different seasons (A — Post monsoon I, B — Pre-monsoon, C — Monsoon, Table D — Post monsoon II).

A. Abundance (indiv m^{-2}) of macrobenthic organisms in Cochin port during Post monsoon I.																						
Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Total
Capitella capitata								46														46
Mediomastus sp.							31			31		15										77
Cossura coasta										31										15		46
Dioptara sp.													15		46							62
Glycera sp.										15												15
Nephtys sp.					31			15			15											61
Dendronereis sp.	15				15					31												61
Ancistrosyllis sp.	15							46		124	15									46		246
Pilargis sp.										15												15
Prionospia sp.	92				724	15	339	431	108	1910	231	15	15	15	139	31		647		139		4851
P. pinnata				15																		15
Polydora kempi	15																					15
Oligochaeta	31	15								108			15			93				246		508
Corophium sp.																		15				15
Tanaidacea			31	46				31						15							15	139
B. Abundance (indiv m^{-2}) of macrobenthic organisms in Cochin port during Pre-monsoon.																						
Stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	Total
Capitella capitata													15									15
Cossura coasta						15						31			15		15					77
Goniada sp.													15									15
Nephtys sp.						31				15		62		15	15		92					231
Nereis sp.					15																	15
Owenia sp.															15							15
Aricidae sp.														15			15					30
Ancistrosyllis sp.	31											46										77
Prionospia sp.															31							30
P. pinnata						77									61		46					186
Polydora kempi	15																					15
Streblospio sp.														15			46					61
Syllis cornuta	15																15			15	92	137
Oligochaeta						46						123	293									462
Amphipoda					15	15						31								46		108
Ampelisca sp.	31							15														46
Ampithoe sp.	46							123														169
Cheriocratus sp.	15							92		46												154
Gammaropsis sp.								92													62	154
Cirolanidae																				15		15
Tanaidacea																				46		46
C. Abundance (indiv m^{-2}) of macrobenthic organisms in Cochin port during monsoon.																						
Stations	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	Total
Bivalvia		15																				15
Cossura coasta					15																	15
Nereis sp.																46						46
Ancistrosyllis sp.																			46			46
P. pinnata				62	32																	92
Oligochaeta					15											32						46
Amphipoda					15												15					30
Ampithoe sp.										46									15			61
Gammaropsis sp.																				15		15

(*continued on next page*)

currents (Joy et al., 1990; Menon et al., 2000). Sediment quality is one of the most important factors that determine the spatio-temporal distribution and abundance of benthic organisms. These are related to various properties of sediment such as permeability, penetrability which are in turn controlled by sediment erosion and resuspension, and also the water content in the sediment

Table 3 (*continued*).

D. Abundance (indiv m^{-2}) of macrobenthic organisms in Cochin port during Post monsoon II.

Stations	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	Total
Bivalvia										62												61
Capitella capitata													92					108				200
Cossura coasta												31		62	62		31	15				200
Hesione sp.																	293					293
Nephtys sp.		62		15		77			262	92		92		139	262		416	200				1617
Nereis sp.		46			354						31									46		477
Dendronereis sp.					92					46											62	200
Owenia sp.														31			31					61
Ancistrosyllis sp.	62																					62
Prionospia sp.		31		15										169			185	62				462
P. pinnata		77				200					46			46	108		123					601
Polydora kempi	31													31	92			46				200
Streblospio sp.											15											15
Syllis cornuta	77																			77		154
Oligochaeta						123		169	62		62	277			108		893				108	1802
Amphipoda					15						77				123					123		339
Ampelisca sp.	123			31	77																	231
Ampithoe sp.	46								15								108					169
Cheriocratus sp.	31							92									46					169
Gammaropsis sp.					139			92		323											92	647
Cirolanidae								524		139										15		678
Tanaidacea								385														385

(Sarkar et al., 2005). The present study showed changes in the sediment quality with the seasons, which may have been affected by dredging, tidal flow, sediment erosion and accumulation, currents and monsoon floods. Such changes may have determined the dominance of a particular group of organisms in the sediment in the respective season. Dredging activity in the dock area of Cochin port is of great concern as it leads to turbidity, which reduces productivity affecting greatly the benthic faunal distribution (Rasheed and Balchand, 2001). Dredging activity carried out in the port area and Cochin estuary has had a negative impact on benthic species composition, population density and biomass, resulting in a decrease in diversity (Desprez, 2000; Sarda et al., 2000; Van Dalfsen et al., 2000; Rehitha et al., 2017). The present study showed continuous changes in the silt-clay composition of the bottom sediment across the monsoon season, which in turn, has led to changes in the composition of organic matter in the sediment. The higher silt composition in the sediment comprised of mostly decomposable organic matter, which are the food particles for deposit feeders (Sanders, 1958, 1968; Sanders et al., 1962; Jayaraj et al., 2008). The change in the sediment composition may have led to the eradication of and domination by a few species in some stations and seasons (Figs. 3 and 7).

The organic carbon input into the estuarine sediments is mostly determined by the supply of terrestrial material, the deposition rate of organic to inorganic constituents, primary productivity, and sediment texture (Muraleedharan Nair and Ramachandran, 2002). Organic enrichment observed in the Cochin estuary is a sign of environmental deterioration, possibly leading to a reduction in the diversity of the macrobenthos community (Martin et al., 2011). The build-up of pollutants, contaminated inputs from freshwater and discharge of sewage waste in the estuary all contribute to environmental degradation (Menon et al., 2000). Organic carbon enrichment in the sediments may lead to hypoxia, faunal depletion and ultimately an abiotic environment (Pearson and Rosenberg, 1978). In the present study, even though organic enrichment is observed at various stations and it was in favourable percentage during monsoon season, a decrease in the macrobenthic organisms during monsoon seasons can be attributed to water flow and sediment flushing. The distribution of organic carbon in the sediment is dependent on the sediment grain size and due to the higher surface area of finer sediments, they possess higher organic carbon (Valdés et al., 2005; Rodríguez-Barroso et al., 2010; Paneer Selvam et al., 2012). The present study showed significant spatial variation in the organic carbon content than temporal variation, which may be due to the changes in the sediment constituents in different stations in and around the Cochin port.

4.3. Macrobenthic organisms

Macrobenthic polychaetes comprised the dominant group among the organisms present in Cochin port, and this observation agrees with other locations along the southwest coast of India (Joydas and Damodaran, 2009; Musale and Desai, 2011). Spionids were the most dominant taxa among the polychaetes. Studies on Calcasieu estuary (Louisiana), shows spionids as one of the most dominant taxa throughout the estuary in different seasons (Gaston and Nasci, 1988). The change in the abundance and diversity of benthic organisms such as polychaetes, may be due to the influence of discharge in Cochin backwaters as the amount of organic carbon and organic matter are very high and this leads to eutrophication in the estuary (Devi and Venugopal, 1989; Devi et al., 1991; Geetha et al., 2010). Seasonal variation was also observed in the diversity as the changes in the sediment texture resulted in a qualitative difference in each season (Fig. 2). Influence of waste water has varying effect on the primary producers and consumers with ensuing alterations in food web structure (Geetha et al., 2010). The areas with lower abundance of organisms were mostly dominated by silt and clay sediments, associated with low chlorophyll *a* in both bottom water and sediment. Earlier studies (Cloern, 2001; Bode et al., 2006; Jayaraj et al., 2007; Musale and Desai, 2011) have indicated that clayey and clayey-silt sediments contain a low abundance of organisms, as fine clay particles cause clogging of the feeding apparatus of

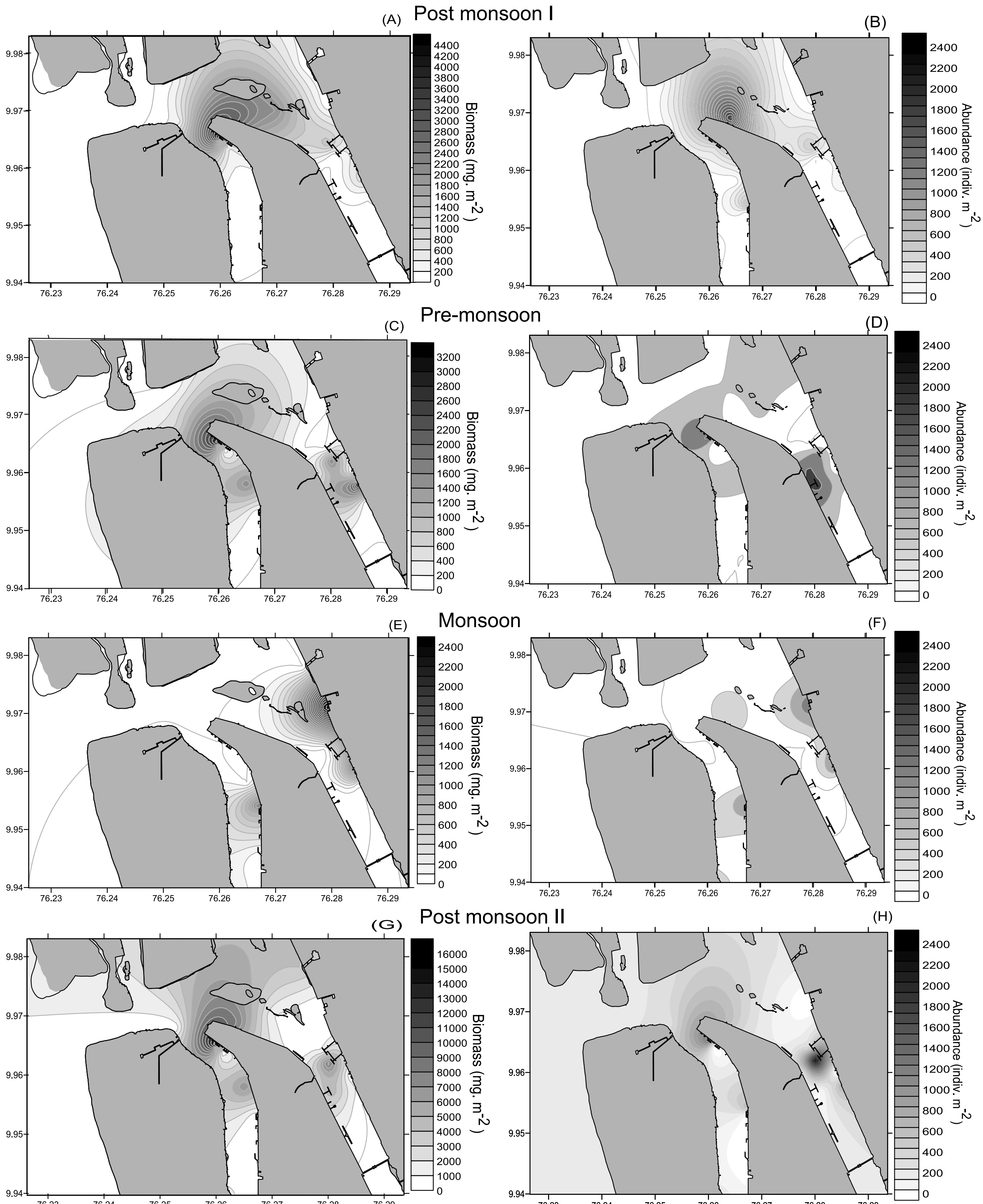

Fig. 4. Distribution of biomass and abundance of macrobenthos in Cochin port during different seasons (A, B) Post monsoon I (C, D) Pre-monsoon (E, F) Monsoon (G, H) Post monsoon II.

the filter feeders. The dominant polychaetes in the present study area were the spionid, *Prionospio* sp., which are deposit feeders preferring fine-grain sediment at shallow depths (Jayaraj et al., 2008).

As observed by Hoey et al. (2004) and Jayaraj et al. (2008), benthic faunal distribution is affected by sediment texture. The *Nephtys* sp. was found in the fine sandy sediment, while *C. coasta* preferred both sandy and muddy sediment due to the availability of food particles and increased organic matter, which increases

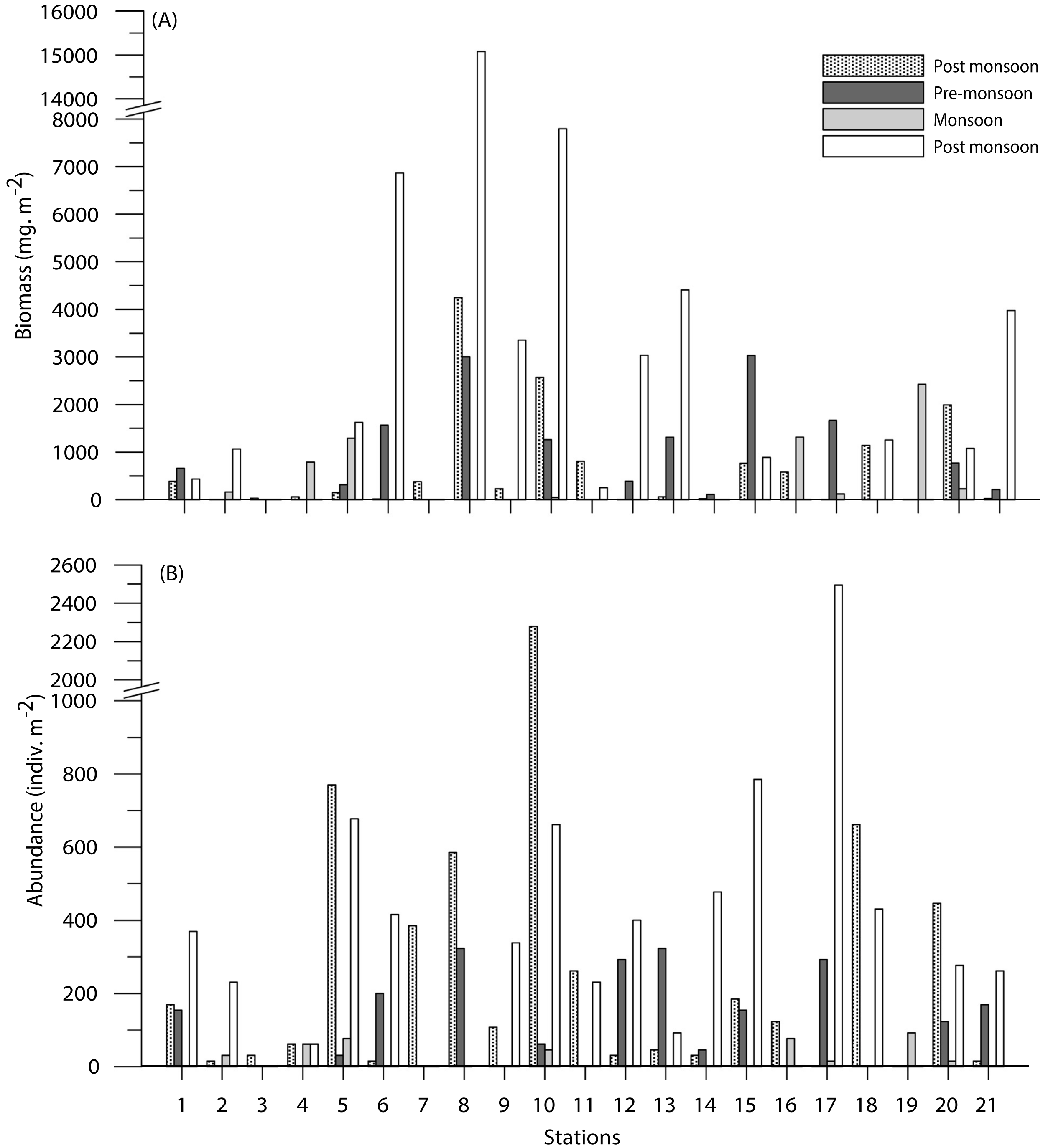

Fig. 5. Seasonal variation in (A) biomass and (B) abundance of total macrobenthic organisms in Cochin port.

their abundance (Lange et al., 2014). Most of the polychaetes such as *C. capitata, Mediomastus* sp., *Prionospio* sp. and *Streblospio* sp. found in the study area are indicator species for anthropogenic pollution and organic enrichment (Sivadas et al., 2010; Balachandar et al., 2016). High organic enrichment may lead to hypoxic conditions, as well as smothering and reduction in the density of organisms, which result in the dominance of the deposit feeders in estuaries (Pearson and Rosenberg, 1978; Ansari et al., 1986; Mojtahid et al., 2008; Martin et al., 2011). Extreme changes in diversity during each season were observed e.g., *Prionospio* sp. was dominant during PM I followed by Oligochaeta during pre and post-monsoon seasons, except monsoon season and during this season *Paraprionospio* sp. was abundant. The dominance of single opportunistic species (*Prionospio* sp.) in the present study area was likely due to the prolonged stress in the environment as observed by Gray (1989). The presence of *Prionospio* sp. shows oxygen depletion and *C. coasta* is an indicator species for sediment instability indicating a disturbed environment (Abdul Jaleel et al., 2014; Rehitha et al., 2017). Most of the above-mentioned organisms are deposit feeders which feed on the freshly settled organic matter on the sediment, as observed by Muniz and Pires (2000) and Dolbeth et al. (2007). The present study shows that the influence of monsoon which brings high freshwater inflow from the catchment area, tidal flow and dredging activity in Cochin port, are major factors influencing the change in the sediment texture and organic matter leading to the change in the species abundance and diversity during different season (Table 3).

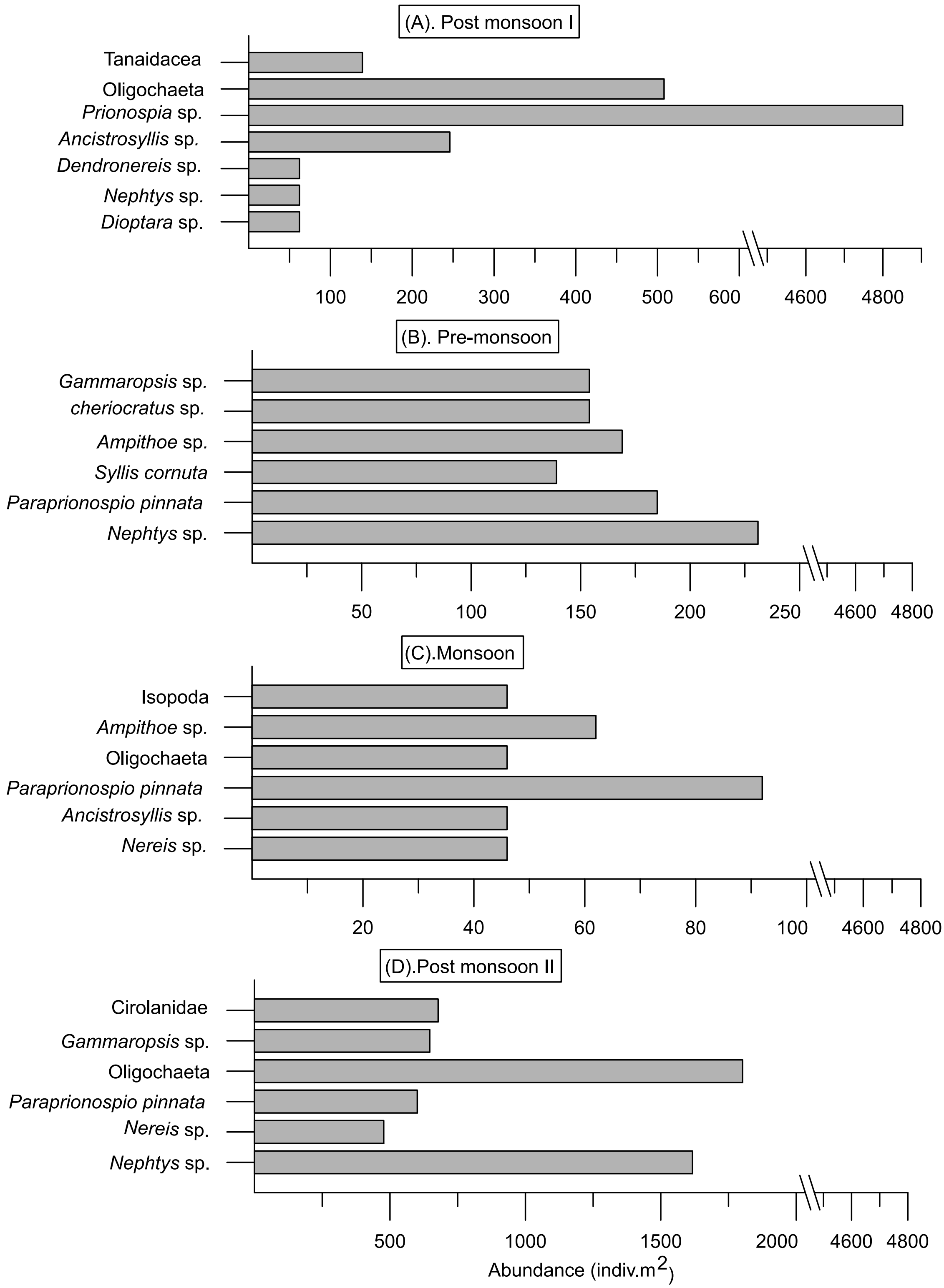

Fig. 6. Seasonal variation in the abundance of macrobenthic organisms during different seasons (A) Post monsoon I (B) Pre-monsoon (C) Monsoon (D) Post monsoon II in Cochin port.

Other macrobenthic organisms observed in Cochin port are the Oligochaeta, crustaceans (amphipods, tanaids and isopods), molluscs, as well as larval and juvenile gobiid fishes. Opportunistic species such as Oligochaeta have shown dominance where dredging is carried out regularly and there is a correspondingly lower concentration of amphipods and polychaetes at these stations (Rehitha et al., 2017). It has been observed that the stable conditions may allow organisms to thrive well, and during unfavourable conditions, may lead to a decline in their density; this coincides with the previous studies (Duineveld et al., 1991; Musale and Desai, 2011). The study indicates that the Cochin port is a stressful environment for the benthic fauna, and this observation is supported by Shannon index (H') and species richness (d) values which are 0.6–1.9. For a healthy environment, H' and

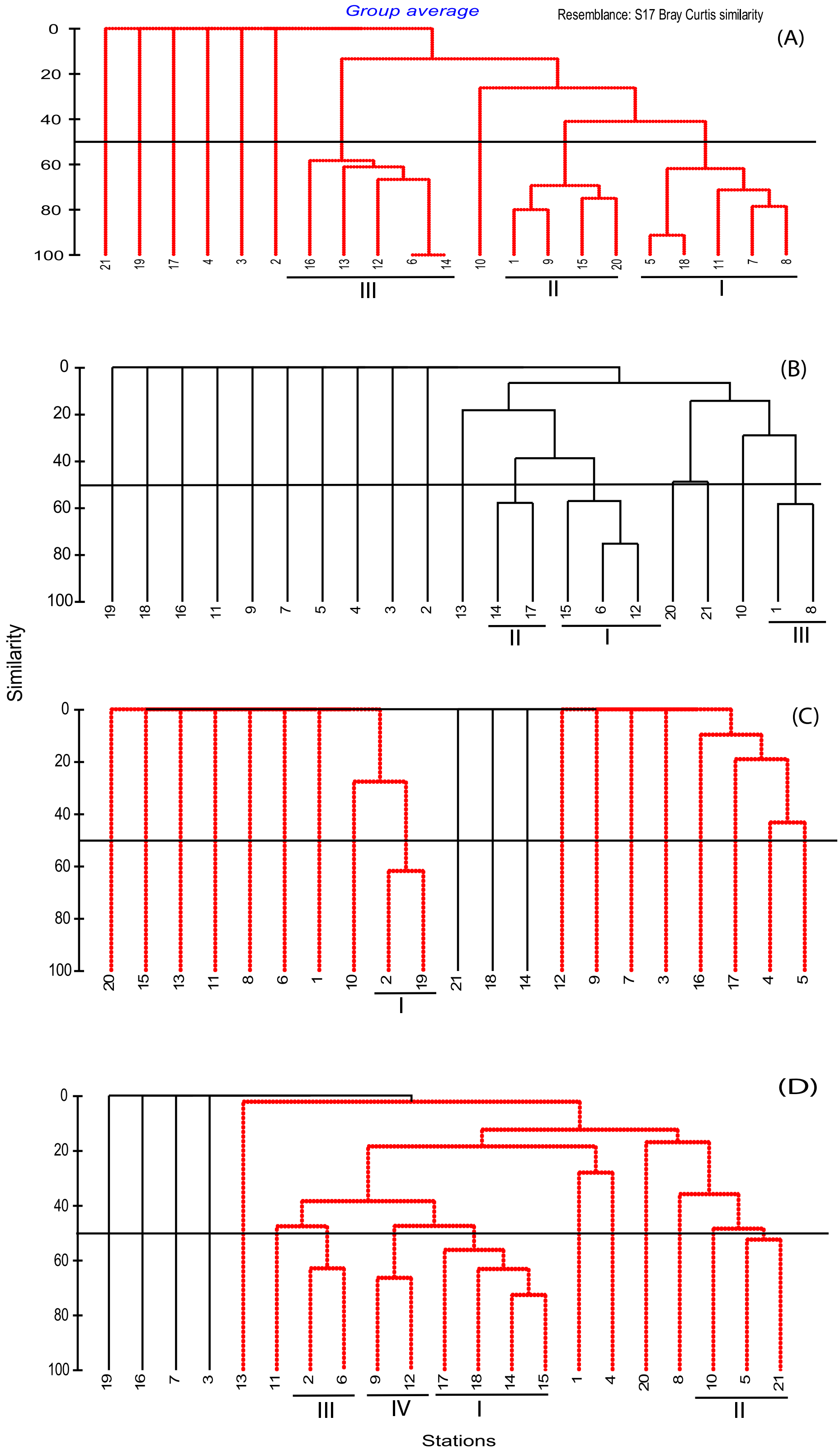

Fig. 7. Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons (A) Post-monsoon I (B) Pre-monsoon (C) Monsoon (D) Post monsoon II. Stations are grouped with respect to their similarity.

d should be in the range of 2.5–3.5 (Magurran and Anne, 1988). Previous studies by Jayaraj et al. (2008) and Musale and Desai (2011) showed that *Prionospio* sp. was found in high numbers along the southwest coast of India especially off Cochin estuary and Cochin port which is organically polluted (Remani et al., 1983). Several studies on southwest coast showed higher benthic biomass and abundance (Neyman, 1969; Harkantra et al., 1980; Parulekar et al., 1982; Jayaraj et al., 2007). Pillai (2001) has described 30 species belonging to 25 genera of polychaetes in Cochin estuary, but the present study showed 21 polychaete taxa

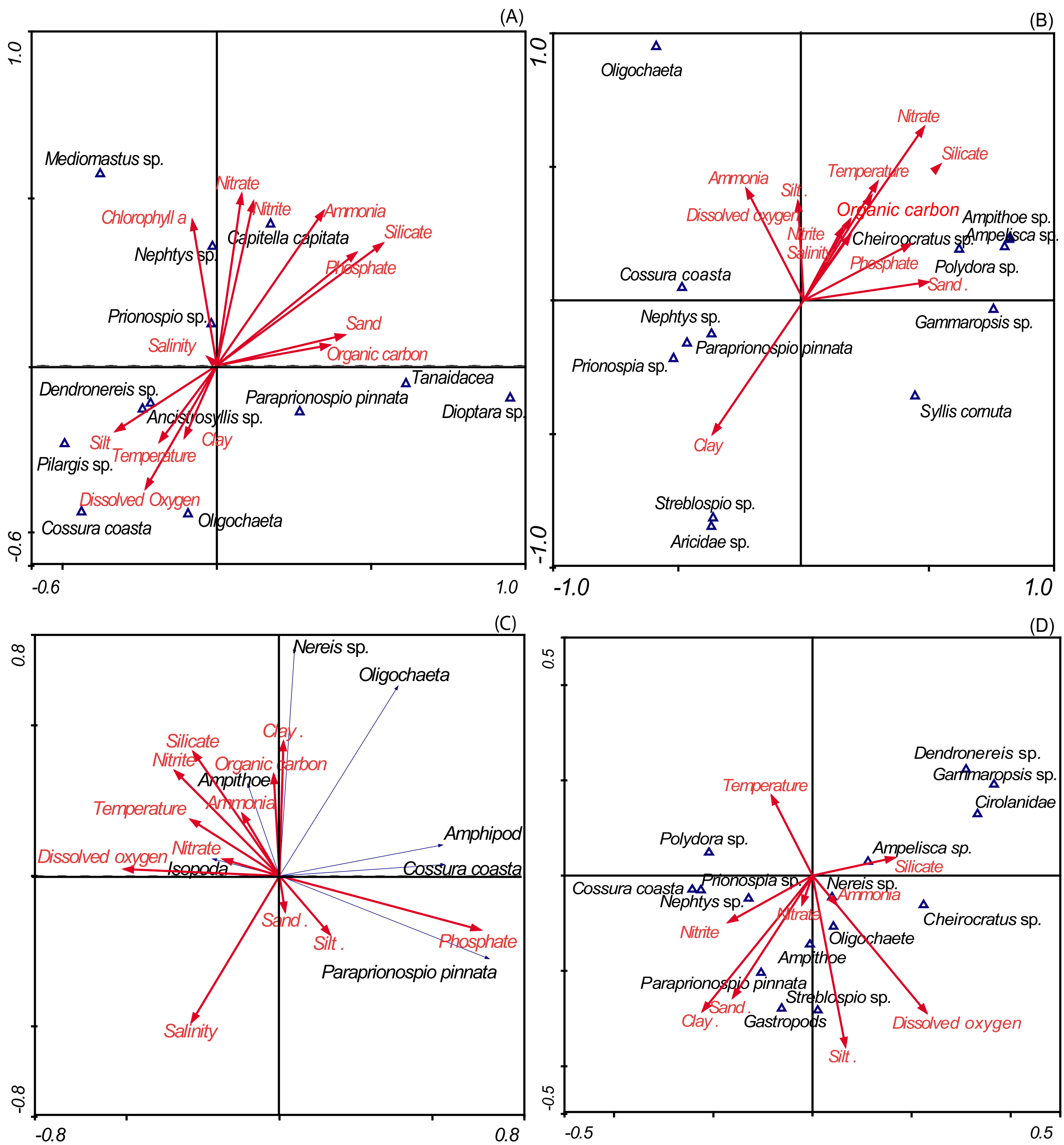

Fig. 8. CCA and RDA plots to illustrate the correlation between environmental parameters and species diversity during different seasons (A) Post monsoon I (B) Pre-monsoon (C) Monsoon (D) Post monsoon II at Cochin port.

in the study stations which indicates to decreased diversity in Cochin estuary. The observed drastic changes in diversity and density, which may be due to the high organic carbon content and the influence of anthropogenically deposited effluents. Cochin estuary is influenced by petroleum hydrocarbons and dissolved and suspended organic matter in the surface and subsurface waters. These wastes get flushed out during monsoon season except the bar mouth (port area) were they accumulate the waste from the estuary (Menon et al., 2000). As described by Martin et al. (2011) the above mentioned anthropogenic activities have affected the benthic organisms and lead to the survival of the tolerant species.

5. Conclusions

The study provided information on the community structure and diversity of macrobenthos in Cochin port. A significant spatio-temporal variation in the abundance and macrobenthic community structure across the year was observed. The diversity and community structure of macrobenthos in the port region were considerably lower compared to other areas of the backwaters indicating that the study area is under stress. A strong seasonal variation in the abundance of macrobenthos, which is highest during PM II and lowest during monsoon season was observed. Such seasonal variation can be attributed to the river run off during the monsoon and reverting back to the normal condition during the non-monsoon months. A seasonal change in the macrobenthic diversity and shifts in the dominance of macrobenthos was prominent, PM I is dominated by *Prionospio* sp. and *Ancistrosyllis* sp. which were replaced by *Ampithoe* sp. during pre-monsoon and monsoon, and subsequently replaced by Cirolanidae during PM II season. Oligochaeta is found during all the seasons. This study provides a complete database on the diversity of macrobenthos in Cochin port with regard to changes in the benthic ecology, and is a baseline for future studies.

Data availability

All data generated or analysed during this study are included in this manuscript and data is also provided as supplementary data file.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical approval

No animal testing was performed during this study.

Sampling and field studies

All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the acknowledgements.

Data availability

All data generated or analysed during this study are included in this manuscript and data is also provided as supplementary data file.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2020.101075.

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Spatio-temporal variation in the macrobenthos of Paradip port, east coast of India

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The spatio-temporal variation in the abundance and community structure of macrobenthic invertebrates, which are useful ecological indicators, was assessed along with associated environmental settings and sediment characteristics in Paradip port, Odisha along the east coast of India. The Paradip port is a coastal port directly connected to the Bay of Bengal and is influenced by tropical monsoons. The maximum diversity and abundance of macroinvertebrates was reported during monsoon season, whereas it was minimum during post-monsoon and pre-monsoon and attributed to higher organic carbon in the sediments. The sediment characteristics (sediment composition and total organic carbon) were the major factors influencing the abundance and community composition of benthic organisms. Silty-sand was dominant throughout the port environment. The polychaetes were the dominant macrobenthos organisms followed by Pantopoda and Crustaceans. Organically rich and sandy-silt sediments have led to the dominance of pollution indicator taxa such as *Tharyx* sp., *Prionospio* sp., *Cossura* sp., *Magelona* sp. and *Mediomastus* sp. The multivariate index of trophic state indicated good water quality in near bottom water; however, high organic carbon load in the sediments could have resulted in a stressed environment. This study will serve as a baseline for future studies on the diversity of macrobenthic invertebrates and benthic ecology of the monsoon influenced coastal habitats, especially in a busy port subjected to rigorous physical and anthropogenic stress.

Keywords: Coastal port, macrobenthos, polychaetes, spatio-temporal variation, species diversity.

THE benthic fauna are an important link in the food web and are useful both ecologically and economically. Benthic organisms play a major role in the marine community with their involvement in mineralization, sediment mixing, oxygen flux, nutrient cycling and in the recovery of organic matter[1]. They are used as bio-indicators for pollution monitoring studies owing to their short life cycles and limited mobility, tertiary-level feeders and food for several bottom-dwelling higher invertebrates and fishes[2]. Polychaetes are the most abundant and dominant groups in the benthic community which contribute to 80% of total macrobenthic population. They are being used for biomonitoring organic pollution and to check the quality of the marine environment[3].

Ports are considered as the lifeline of a country's economic development and port areas are one of the highly disturbed coastal habitats due to heavy traffic owing to shipping and also human activities[4]. Since they are often located in the coastal environments, port areas are subjected to various forms of anthropogenic stressors such as untreated sewage or municipal run-off, terrestrial run-off during monsoon, and port-related activities such as dredging, oil spill, petroleum effluents, out-fall of a variety of cargo handled by the port, etc.[5]. Port waters are often characterized by low dissolved oxygen and the presence of pollutants in the sediments and water[5–8]. As harbour areas have empty niches, they are prone to marine bioinvasion especially due to discharge of ship ballast water[9,10], as the empty niches are formed due to instability of the equilibrium between the origination and extinction of the benthic community[11]. Bioinvasion is of global concern due to its adverse effect on biodiversity and ecosystem functioing[12].

The distribution and community of macrobenthic organisms depend on the interaction between the physical, chemical and biological variables in both water column and sediments. So to study the diversity and abundance of macrobenthic organisms, it is important to assess the factors affecting the benthic community mainly sediment characteristics such as texture, organic content and food availability. The present study was carried out to observe the spatio-temporal variation in the macrobenthic diversity and abundance, and to examine the impact of sediment characteristics and environmental parameters on macrobenthos in a dynamic port environment situated along the east coast of India.

Material and methods

Study area

Sampling in Paradip port was carried out during August 2014 (monsoon I–MI), December 2014 (post-monsoon – PM), May 2015 (pre-monsoon – Pre-M) and August 2015 (monsoon II – M II) representing different seasons. This

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is a major port along the east coast of India in Odisha (20°15′N, 86°40′E; Figure 1). The port is influenced by the south–west monsoon (June–September) and receives 75–80% of rainfall during these months, and remaining during the northeast monsoon (October–December). On the east coast, this port manages a large amount of trade of the country. Even though this is a natural deep water port, artificial bunds (breakwaters) were built to reduce the severe wave intensity in the port; thus it resembles an artificial lagoon. The breakwaters are: (1) south breakwater with a length of 1217 m and (2) north breakwater with a length of 538 m. It is a major port that handles various cargo such as crude oil, petroleum, oil and lubricants (POL), iron ore, thermal coal, chrome ore, coking coal, manganese and other ores, fertilizer raw materials and containers, etc. The samples were collected from 22 stations in accordance to berths, and Table 1 provides their details.

Sampling and analysis

The near-bottom sea-water samples were collected (in triplicate) for the analysis of chlorophyll *a*, salinity, dissolved oxygen (DO), temperature and nutrients using Niskin water sampler and analysed using standard protocols[13]. Nutrients such as nitrate (NO_3), phosphate (PO_4), nitrite (NO_2), ammonium (NH_4) and silicate (SiO_4) were analysed using SKALAR SANplus analyzer. Sediment samples were collected in triplicate from an average depth of 13–16 m using a van Veen grab (0.04 m^2). The sediment samples were washed separately through a 500 μm nylon mesh in the field and then preserved in 10% formaldehyde in sea water containing rose Bengal stain before transferring them in a plastic container.

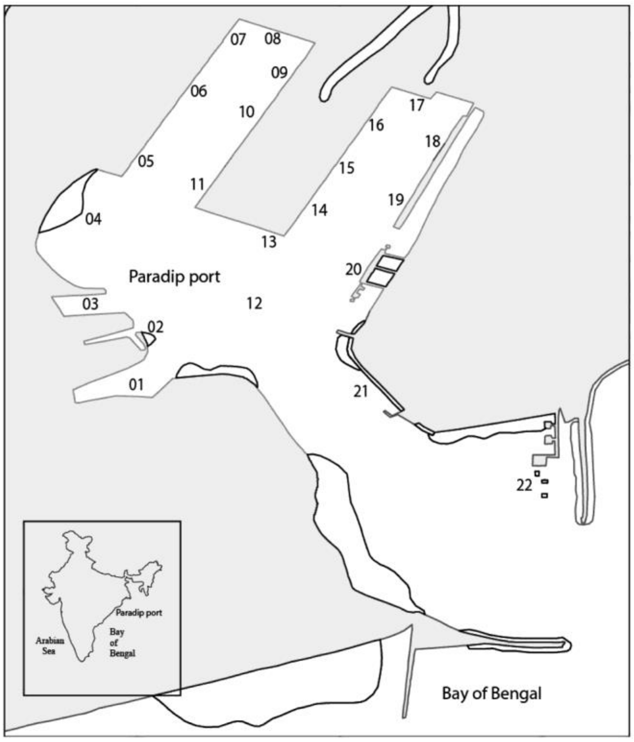

Figure 1. Map showing the sampling stations in Paradip port. S01, Boat Basin; S02, Slip Way; S03, Deep Sea Trawler Berth; S04, Area Adjacent to Fertilizer Berths; S05, Fertilizer Berth-I; S06, Fertilizer Berth-II; S07, Multipurpose Berth; S08, North Quay-II; S09, Central Quay-III; S10, Central Quay-II; S11, Central Quay-I; S12, Turning Circle; S13, South Quay; S14, East Quay-I; S15, East Quay-II; S16, East Quay-III; S17, North Quay-I; S18, Coal Berth-Il S19, Coal Berth-II; S20, Iron Ore Berth; S21, Stone Pitching Side and S22, Oil Berth.

Laboratory analysis involved the sorting of macrobenthic organisms from the sediment samples that were sieved through a 500 μm metal sieve. The macrobenthic fauna collected were preserved in plastic vials containing 10% formaldehyde solution for further microscopic analysis. Polychaetes (Phylum–Annelida) were identified to the highest taxonomic level (genus or species), with the help of available identification keys[14–16] and other macrobenthos were identified up to group, family or genus levels. Numerical abundance of each species was expressed as number per square metre. Biomass was determined using wet weight method and expressed as milligram per metre square[17]. Total carbon (TC) and inorganic carbon (IC), and percentage composition of sediments (sand, silt and clay) that are expressed as the percentage of sediment dry weight were determined using CHNS Analyser (Vario MICRO Select, Germany) and pipette analysis respectively[18,19]. The total organic carbon (TOC) content was obtained by the difference between TC and IC (TOC = TC–IC)[20].

Number of individuals or specimens (*N*), number of species (*S*), total abundance (*A*), Margalef species richness (*d*), Pielou's eveness (*J*′) and Shannon index (*H*′) using log2 scale were used to determine the environmental and ecological assessment of macrobenthic organisms in each station. PRIMER-v5 was used to determine the similarity of species diversity in macrobenthic polychaetes by Bay-Curtis similarity index (ref. 21). Canonical correspondence analysis (CCA) and redundancy analysis were performed to evaluate the relationship between environmental variables and different groups of macrobenthos. The multivariate index of trophic state (TRIX) method was used to evaluate the trophic status of Paradip port[22]. This allows us to determine the water quality and also the relationship between trophic status of near bottom water and sediments.

TRIX was calculated as

$$\mathrm{TRIX} = \frac{(\log_{10}(\mathrm{chl}\ a \times \mathrm{a\%O_2} \times \mathrm{DIN} \times \mathrm{DIP}) + k)}{m,\ \text{of DO saturation (abs}\ |100 - \%\mathrm{O_2}| = \%\mathrm{O_2})},$$

where chl *a* is in mg m^{-3}, a%O_2 is absolute value of the percentage of DO saturation (abs |100 – % O_2 = %O_2), DIN is dissolved inorganic nitrogen including NO_3, NO_2,

Table 1. Paradip port stations and their locations.

Station no.	Station	Latitude	Longitude
1	Boat Basin	20°16′07.6″N	86°40′03.1″E
2	Slip Way	20°16′12.1″N	86°40′07.4″E
3	Deep Sea Trawler Berth	20°16′18.3″N	86°40′02.4″E
4	Area Adjacent to Fertilizer Berths	20°16′27.8″N	86°40′02.9″E
5	Fertilizer Berth-I	20°16′38.1″N	86°40′06.2″E
6	Fertilizer Berth-II	20°16′45.3″N	86°40′11.2″E
7	Multipurpose Berth	20°16′52.7″N	86°40′14.8″E
8	North Quay-II	20°16′54.0″N	86°40′19.4″E
9	Central Quay-III	20°16′50.2″N	86°40′19.1″E
10	Central Quay-II	20°16′43.2″N	86°40′15.5″E
11	Central Quay-I	20°16′35.3″N	86″40′11.6″E
12	Turning Circle	20°16′15.2″N	86°40′15.5″E
13	South Quay	20°16′27.3″N	86°40′14.2″E
14	East Quay-I	20°16′30.5″N	86°40′22.5″E
15	East Quay-II	20°16′37.9″N	86°40′26.3″E
16	East Quay-III	20°16′46.7″N	86°40′29.7″E
17	North Quay-I	20°16′46.1″N	86°40′35.6″E
18	Coal Berth-I	20°16′38.7″N	86°40′34.9″E
19	Coal Berth-II	20″16′30.3″N	86°40′29.0″E
20	Iron Ore Berth	20°16′23.4″N	86°40′25.5″E
21	Stone Pitching Side	20°16′08.8″N	86°40′30.0″E
22	Oil Berth	20°15′52.6″N	86°40′43.1″E

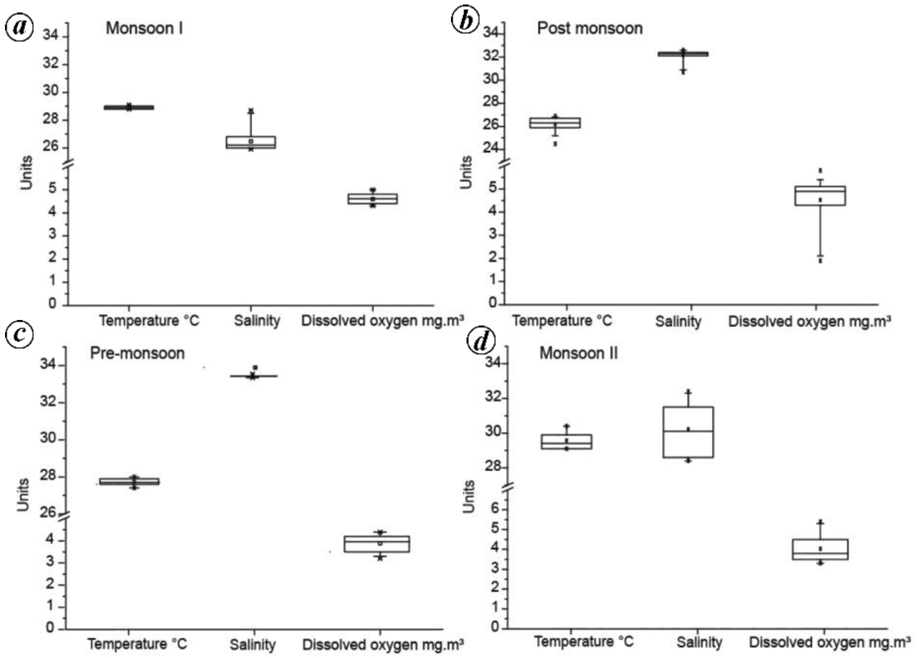

Figure 2 *a–d*. Seasonal variations in the bottom-water parameters, temperature (°C), salinity and dissolved oxygen (mg m^3) at Paradip port.

NH_4 in mg m^{-3}, DIP is dissolved inorganic PO_4 in mg m^{-3}, constants k – 3.5 and m – 0.8 are scale values.

Results

Environmental parameters

Table 2 and Figure 2 show the variations in near-bottom environmental parameters such as temperature, salinity and dissolved oxygen. The near-bottom sea-water temperature during different seasons ranged between 26.2° ± 0.6° and 29.7° ± 0.45°C (Table 2 and Figure 2 *a–d*).

The salinity of near-bottom water varied with seasons; it was low (26.5 ± 0.7 and 30.2 ± 1.4 during M I and M II respectively) during monsoon compared to non-monsoon season (32.1 ± 0.5 and 33.9 ± 0.04 during PM and Pre-M respectively; Table 2 and Figure 2 *a–d*). The near-bottom

Table 2. Variations in temperature, salinity and dissolved oxygen in near bottom water at Paradip port at different stations during different seasons

Station	Temperature (°C)				Salinity				Dissolved oxygen (mg l^{-1})			
	M I	PM	Pre-M	M II	M I	PM	Pre-M	M II	M I	PM	Pre-M	M II
1	28.9	26.0	27.9	30.4	25.9	30.7	33.8	28.4	5.0	5.0	4.4	5.2
2	28.9	26.1	27.7	30.4	26.0	30.9	33.8	28.6	5.0	3.7	4.4	5.3
3	28.9	26.1	27.8	30.2	26.0	31.2	33.8	28.4	4.8	4.3	4.4	5.4
4	28.9	25.2	27.4	29.2	26.9	32.4	33.9	29.8	4.6	4.6	4.2	4.0
5	28.9	24.5	27.6	29.1	26.8	32.4	33.9	30.1	4.4	4.0	3.5	3.8
6	29.0	26.4	27.8	29.1	26.0	32.5	33.9	30.6	4.3	1.9	4.2	3.6
7	28.8	26.4	27.8	29.4	26.1	32.3	33.9	30.1	4.4	5.2	4.2	3.6
8	28.9	26.1	27.9	29.4	26.0	32.1	34.0	29.3	4.6	5.3	4.3	3.7
9	28.9	26.2	27.9	29.4	26.0	32.3	33.9	29.7	4.4	5.1	4.2	3.9
10	28.8	26.6	27.7	29.1	26.0	32.4	33.9	32.4	4.4	2.1	3.5	3.3
11	28.8	25.9	27.6	29.1	26.8	32.4	33.9	32.1	4.7	4.4	3.4	3.4
12	29.0	25.4	27.6	29.6	28.7	32.6	33.9	28.4	4.9	5.8	4.0	4.3
13	28.8	25.8	27.4	29.1	28.5	32.6	33.9	32.3	4.8	3.4	4.2	3.8
14	28.8	25.5	27.9	29.1	26.9	32.2	33.9	32.2	4.6	4.4	3.9	3.3
15	29.0	26.7	28.0	29.4	26.4	32.5	33.8	31.4	4.3	4.8	3.9	3.4
16	29.0	26.8	27.7	29.6	26.3	32.3	33.9	31.6	4.4	4.9	3.2	3.3
17	29.1	26.7	28.0	29.4	26.4	32.3	33.9	31.5	4.5	4.8	3.6	3.5
18	28.8	26.7	27.7	29.6	26.1	32.1	33.9	31.4	4.6	5.1	3.8	3.5
19	28.8	26.9	27.6	30.3	26.0	32.6	33.9	29.9	4.9	5.1	3.8	4.8
20	28.8	26.7	27.9	29.9	26.0	31.9	33.9	28.6	4.3	5.4	3.4	4.2
21	28.9	26.6	27.7	29.9	26.3	32.1	33.9	29.7	4.6	5.1	3.6	4.5
22	29.0	26.3	27.6	29.9	26.2	32.4	33.9	28.4	4.5	5.0	3.3	4.8
Minimum	28.8	24.5	27.4	29.1	25.9	30.7	33.8	28.4	4.3	1.9	3.2	3.3
Maximum	29.1	26.9	28.0	30.4	28.7	32.6	34.0	32.4	5.0	5.8	4.4	5.4
Mean	28.9	26.2	27.7	29.6	26.5	32.1	33.9	30.2	4.6	4.5	3.9	4.0
SD	0.09	0.60	0.17	0.44	0.76	0.52	0.04	1.43	0.22	0.99	0.39	0.68

M I, Monsoon I; Pre-M, Pre-monsoon; PM, Post-monsoon and M II, Monsoon II.

DO ranged from 3.9 ± 0.3 to 4.5 ± 0.9 mg l^{-1} during the study (Table 2 and Figure 2 *a*–*d*). The concentration of bottom-water nutrients varied with the seasons and stations (Supplementary Figure 1). The tidal range at Paradip port is from 0.2 to 3.5 m and the maximum wave height is 5.3 m. TRIX analysed for the bottom water during the study was 1.8 ± 0.8, indicating high state of water quality with low eutrophication. TRIX scores ranged from 0.07 to 3.39 during all the seasons indicating healthy bottom-water conditions.

The sediment texture was composed of sand, silt and clay and it varied spatio-temporally within the port (Figure 3 *a*–*d*). In general, silt was the dominant component (59.0% ± 26.8%), followed by sand (37.3% ± 26.3%) and clay (2.8% ± 9.5%) during all seasons in most of the stations. The sand content was comparatively higher during Pre-M. The silt content showed wide fluctuation and ranged from 5.3% to 94.6% (Figure 3 *b*). The percentage of clay was minimum when compared to sand and silt and it ranged from 0.3% to 3.8% (Figure 3 *a*–*d*). Overall, the sediment texture at Paradip port was dominated by silt, followed by silty-sand and sandy-silt, and few stations were dominated by sand (Figure 3 *e*). TOC in the sediments ranged from 0.5% at S06 to 31.6% at S04. During M I (Figure 4 *a*–*d*), the average TOC was maximum (5.6% ± 7.4%) while it was minimum (1.8% ± 1.8%) during M II. During PM and Pre-M, the TOC content was 4.1% ± 5.6% and 3.7% ± 2.3% respectively (Figure 4 *a*–*d*).

The sediment chlorophyll *a* during M I, PM, Pre-M and M II was 0.22 ± 0.1, 2.9 ± 1.2, 1.6 ± 0.7 and 1.4 ± 0.8 mg m^{-2} respectively (Figure 4 *a*–*d*). The sediment chlorophyll *a* was maximum during PM followed by Pre-M, indicating that the chlorophyll *a* content was higher during non-monsoon season (Figure 4 *a*–*d*).

Seasonal variation in the abundance of macrobenthic organisms

The macrobenthic organisms in Paradip port comprised Annelida (Polychaeta and Oligochaeta), Arthropoda (Pantopoda, Amphipoda and Isopoda), Mollusca (Bivalvia) and Echinodermata (sea anemones and brittle stars). The polychaetes were the most common and abundant organisms during all seasons. Among the 30 macrobenthic forms, 20 were polychaetes contributing more than 70% to the total macrobenthic abundance. Polychaetes belonging to genera *Mediomastus* and *Cossura* were observed during all seasons. The maximum abundance of macrobenthos was during M I (1893 no. m^{-2}), followed

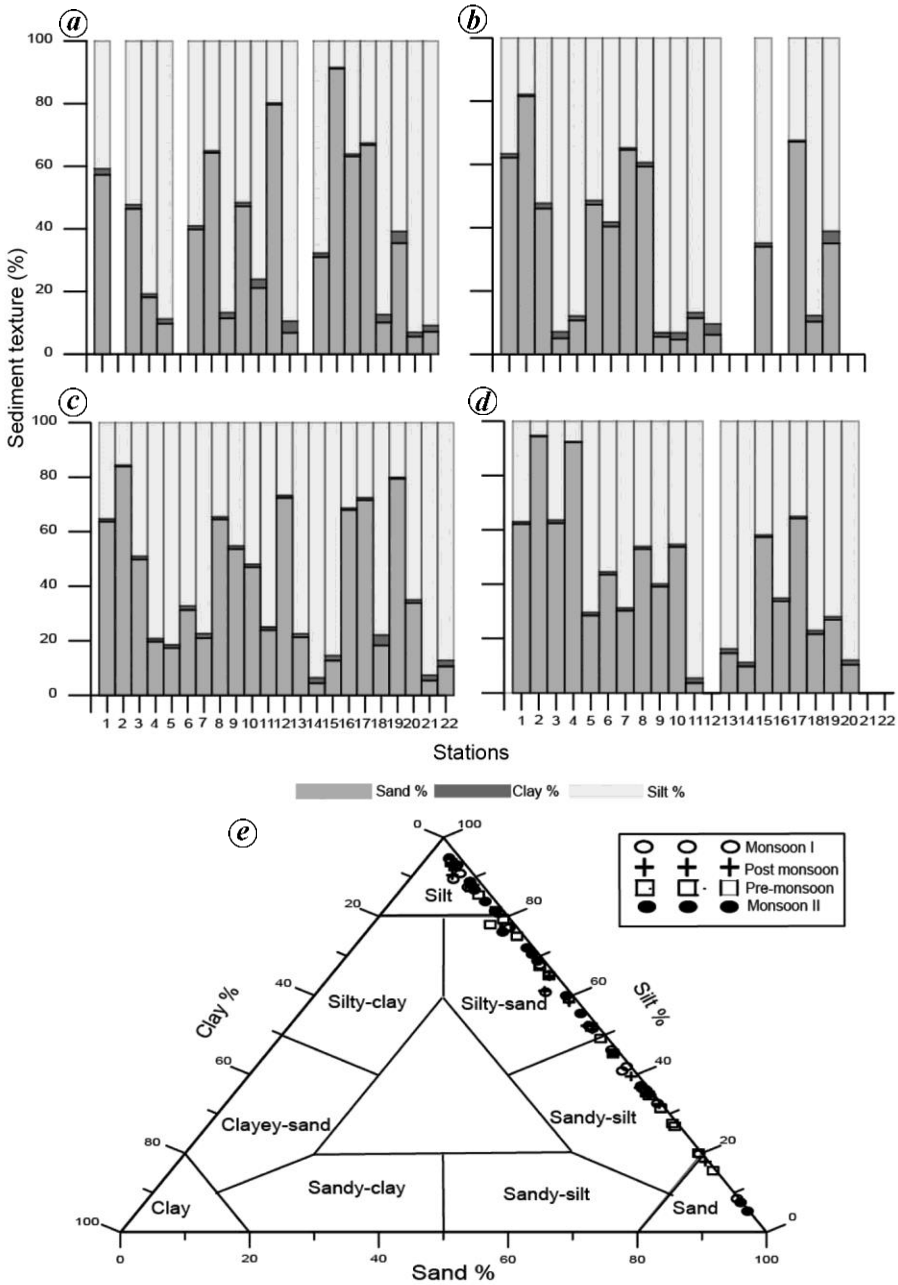

Figure 3. Variations in the sediment characteristics during different seasons: ***a***, monsoon I; ***b***, post monsoon; ***c***, pre-monsoon; ***d***, monsoon II. ***e***, Ternary plot at Paradip port.

by M II (1444 no. m^{-2}), PM (922 no. m^{-2}) and Pre-M (767 no. m^{-2}) seasons (Table 3). During M I, maximum abundance of macrobenthos was at stations S06 (323 no. m^{-2}) and S11 (446 no. m^{-2}); during PM at station S04 (122 no. m^{-2}); during Pre-M at S18 (216 no. m^{-2}) and during M II at S12 (324 no. m^{-2}; Table 3). The biomass was maximum during M I (12,313 mg m^{-2}), followed by M II (9528 mg. m^{-2}), PM (3596 mg m^{-2}), and it was minimum during Pre-M season (3050 mg m^{-2}).

The maximum biomass during M II was 5085 mg m^{-2} at S11 and minimum was 10.7 mg m^{-2} at S15 (Table 3). During PM and Pre-M seasons, the biomass was higher at S04 (980 mg m^{-2}) and S18 (1562 mg m^{-2}), and low at S15 (47 mg m^{-2}) and S07 (25 mg m^{-2}; Table 3).

During MI, the maximum abundance of polychaetes was contributed by the Cirratulidae, *Tharyx* sp. (447 no. m^{-2}), followed by *Mediomastus* sp. (292 no. m^{-2}) and *Cossura* sp. (232 no. m^{-2}) along with organisms belonging to order Pantopoda (185 no. m^{-2}; Figure 5 *a*). The abundance of *Prionospio* sp. during this season was 155 no. m^{-2} (Figure 5*a*). *Tharyx* sp. contributed 21% to total macrobenthic abundance, with 14.1% by *Mediomastus* sp. and 11.2% by *Cossura* sp. (Figure 5 *a*). Among the non-polychaete taxa, Pantopoda contributed 9% followed by

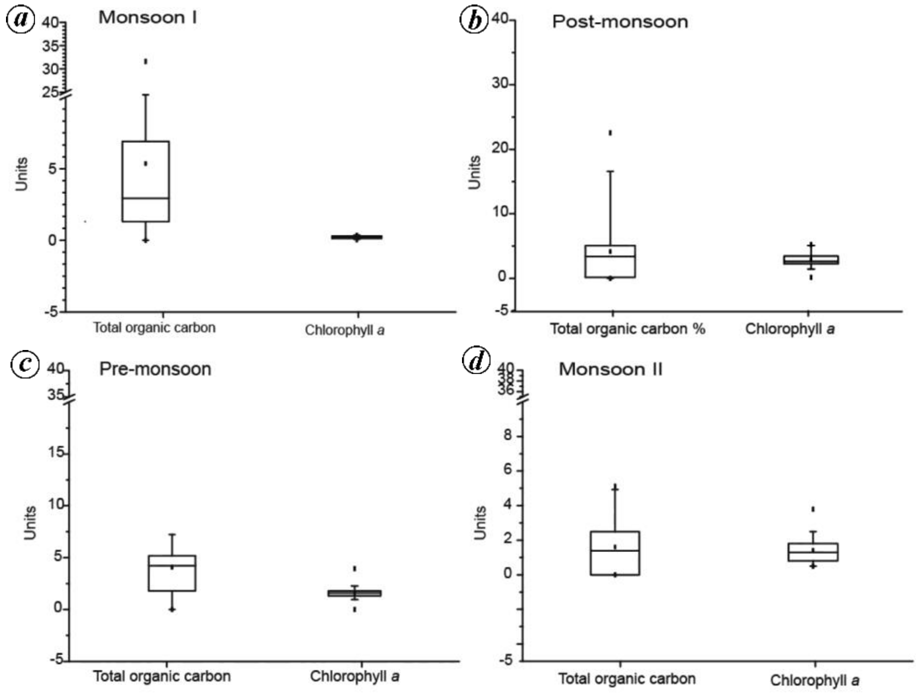

Figure 4 *a–d*. Seasonal variations in the total organic carbon (%) and sediment chlorophyll *a* (mg m^{-2}) at Paradip port during different seasons.

Nototropis sp. and Iospilidae (2.9% and 2.2% respectively) to the total macrobenthos abundance (Figure 5 *a*). Stations S11, S06 and S08 showed higher abundance of macrobenthos, and Pantopoda was observed only at S11. At stations S02, S12, S18, S21 and S22, macrobenthos were not reported. Compared to M I, during PM the abundance of macrobenthos was less and the community was dominated by *Tharyx* sp. (at stations S01, S04, S12, S17 and S22) and *Cossura* sp. (at stations S04, S09, S12 and S14) with an abundance of 200 and 184 no. m^{-2} respectively (Figure 5 *b* and Table 3). The polychaetes *Cossura longocirrata*, *Magelona* sp. and *Mediomastus* sp. contributed considerably to the total abundance of macrobenthos (Table 3). The abundance and diversity of macrobenthos was minimum during Pre-M compared to other seasons. The most abundant group was Cirolanidae (215 no. m^{-2}) at S18. Among the polychaetes, *Nephtys* sp. was dominant (169 no. m^{-2}) followed by *Cossura* sp. (38 no. m^{-2}; Figure 5 *c* and Table 3). The other polychaetes found were *Kirkegaardia* sp., *Tharyx* sp., *Magelona* sp., *Diopatra* sp. and *Prionospio* sp. (Table 3 and Figure 5 *c*). Monsoon seasons were more productive in terms of occurrence of macrobenthos compared to non-monsoon seasons in Paradip port. *Tharyx* sp. was the most abundant during M II with a total abundance of 339 no. m^{-2} and found in S10, S11, S12, S15, S16 and S17, followed by *Mediomastus* sp. (168 no. m^{-2}) and *Maldane* sp. 169 no. m^{-2} (Figures 5 *d* and 6). The other common Polychaetes were *Cossura longicerrata* – 123 no. m^{-2}, *Lumbrineries* sp. – 123 no. m^{-2}, *Prionsopio* sp. – 61 no. m^{-2}, *Melinna* sp. – 46 no. m^{-2}, *Megalona* sp. – 77 no. m^{-2}, *Glycera* sp. – 61 no. m^{-2} and *Paraonis* sp. – 61 no. m^{-2} (Figures 5 *d* and 6).

Variation and species diversity in macrobenthos

Margalef species richness (*d*), Shannon-Weiner index (*H*′) and evenness (*J*′) were used to calculate species diversity index at the stations. The maximum number of species were encountered during M I, and the correspondence values of the Shannon–Weiner index (*H*′) during M I and M II are 1.9 and 1.5 followed by Pre-M (1.3) and PM (1.3) season respectively. Post-monsoon showed low species diversity and abundance compared to the other three seasons (Table 3 and Figures 5 and 6). Bray–Curtis similarity index at 50% similarity level, M I and M II showed two and three groups, and the diversity and abundance were higher during the monsoon season compared to the other seasons (Table 4). Monsoon season showed maximum diversity and biomass of macrobenthos with high temperature and low salinity in near-bottom water compared to the other seasons (Tables 2 and 3; Figure 2). During M I, high diversity and least similarity among stations was observed (Table 4). The group I stations were dominated by *Prionospio* sp. (contribution to abundance – 7.5%) and in group II, *Tharyx* sp. was abundant with 21.7% contribution to the total abundance while the other abundant species were *Mediomastus* sp. and *Cossura* sp. contributing 14.1% and 11.2% respectively

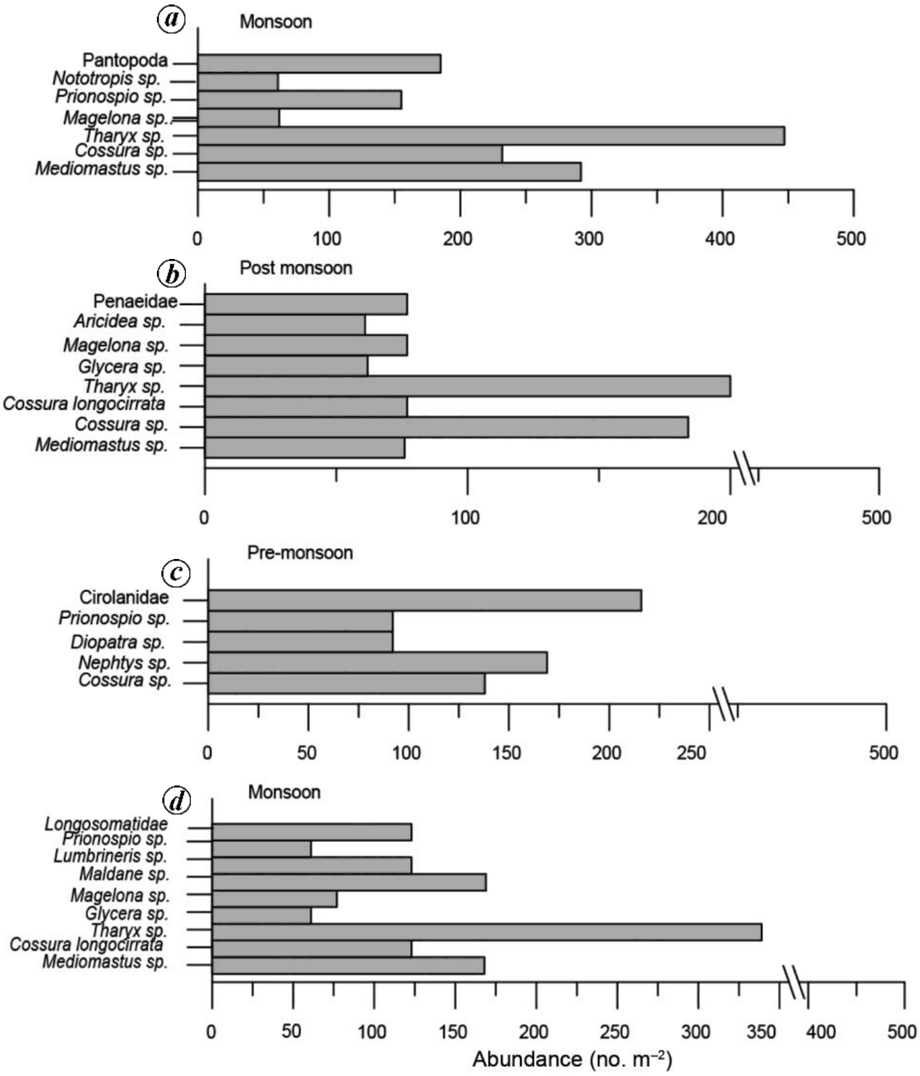

Figure 5 *a*–*d*. Seasonal variation in the abundance (no. m^{-2}) of dominant macrobenthic taxa at Paradip port.

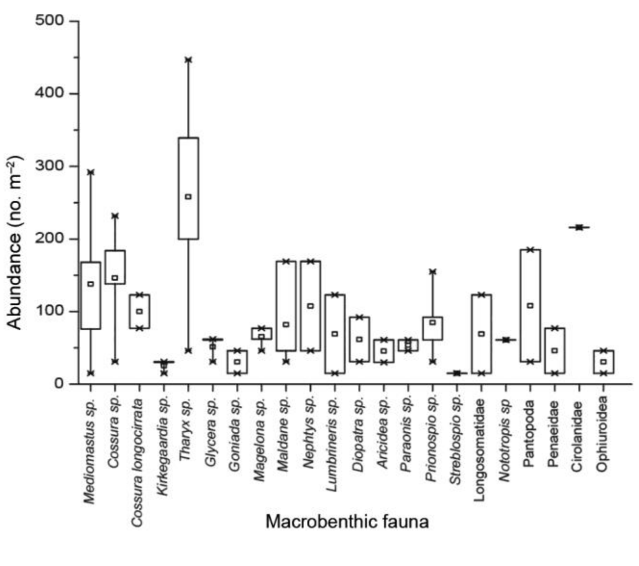

Figure 6. Box-plots depecting the abundance (no. m^{-2}) of dominant macrobenthos at Paradip port.

(Figure 7 *a*). During PM season, the similarity of organisms and their average abundance in groups I to IV was dominated by *Tharyx* sp. (20%), *Cossura* sp. (18.4%), *Mediomastus* sp. (7.6%), *Nephtys* sp. (4.6%) and *Magelona* sp. (7.7%; Figure 7 *b*). In the case of Pre-M season, average similarity among groups I, II and III was 36.6%, 61.5% and 50% respectively (Figure 7 *c*). During M II, three groups were observed, with group I (stations S09, S11, S15 and S17), group II (stations S03 and S13) and group III (stations S01 and S08) having similarity of 66.6%, 66.6% and 54.9% respectively (Figure 7 *d*).

CCA and redundancy analysis indicated sediment characteristics and TOC to play an important role in influencing the community structure of benthic organisms during different seasons at different stations (Figure 8 *a*–*d*). Length of gradient value >2 was obtained during MI and M II seasons and during PM and Pre-M season it was <2. The correlation percentage between macrobenthic abundance and the environmental variables during M I and

Table 3. Variation in the abundance of macrobenthos in Paradip port at different stations during different seasons

Organisms/stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Monsoon I																							
Hesione sp.											31												31
Mediomastus sp.				31	77	92		15			46								31				292
Cossura sp.	139							31			62												232
Kirkegaardia sp.			31																				31
Tharyx sp.						231	108	62	46														447
Glycera sp.								31															31
Goniada sp.				46																			46
Magelona sp.					62																		62
Maldane sp.										31									15				46
Lumbrineris sp.			15																				15
Diopatra sp.											31												31
Aricidea sp.								15					15										30
Paraonis sp.								15			15								31				61
Eteone sp.													15										15
Ancistrosyllis sp								15															15
Prionospio sp.			62					31	31											31			155
Streblospio sp.					15																		15
Iospilidae																46							46
Nototropis sp.									15		15					31							61
Pantopoda											185												185
Isopoda											46												46
Total	139	0	108	77	154	323	108	215	92	31	431	0	30	0	0	77	0	0	77	31	0	0	1893
Biomass (mg/m^2)	964	0	416	243	512	2640	677	837	231	52	5086	0	104	0	11	279	54	0	132	85	0	0	
Post-monsoon																							
Mediomastus sp.	15				15										31					15			76
Cossura sp.				31	15				31		15	31		31	15		15						184
Cossura longocirrata														46							31		77
Tharyx sp.	31			46								31				15	46					31	200
Glycera sp.		31																		31			62
Magelona sp.																				15	31	31	77
Nephtys sp.																15						31	46
Aricidea sp.		46		15																			61
Prionospio sp.			31																				31
Pantopoda																				31			31
Penaeidae									46										31				77
Total	46	77	31	92	30	0	0	0	77	0	15	62	0	77	46	30	61	0	31	92	62	93	922
Biomass (mg/m^2)	178	259	84	980	185	0	0	70	218	0	48	260	0	315	47	182	216	0	59	450	184	271	

(*Contd*)

Table 3. (*Contd*)

Organisms/stations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Pre-monsoon																							
Cossura sp.				31							15			46			15			31			138
Tharyx sp.																	46						46
Magelona sp.				46																			46
Nephtys sp.				31			15			31		46		15			31						169
Diopatra sp.	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77	0	92
Prionospio sp.										15	15						31						61
Cirolanidae																		215					215
Total	0	0	0	108	15	0	15	0	0	46	30	46	0	61	0	0	123	215	0	31	77	0	767
Biomass (mg m^2)	0	0	0	196	19	0	25	94	0	132	29	58	0	120	0	0	515	1562	0	70	238	0	
Monsoon II																							
Sipuncula				31																			31
Melinna sp.		46																					46
Mediomastus sp.	31		15		15		31	46					15					15					168
Cossura longocirrata				31						15				15				62					123
Tharyx sp.									31		46	139			31	15	77						339
Glycera sp.		46											15										61
Magelona sp.					31									46									77
Maldane sp.					108		15					31				15							169
Lumbrineris sp.		31			62					15					15	0							123
Eunice sp.							46																46
Paraonis sp.	15											31											46
Prionospio sp.		31			15										15								61
Longosomatidae												123											123
Acantharia											31												31
Total	46	154	15	62	231	0	92	46	31	30	77	324	30	61	61	30	77	77	0	0	0	0	1444
Biomass (mg m^2)	114	1167	90	139	1498	0	251	122	61	48	1524	2879	52	124	171	116	760	422	0	0	0	0	

Table 4. Number of species (S), number of specimens (N), Margalef species richness (d), Pielou's evenness (J'), Shannon index (H), of macrobenthic organisms during different seasons at Paradip port

	Monsoon I						Post-monsoon						Pre-monsoon						Monsoon II				
Stations	S	N	d	J'	H'(loge)	Stations	S	N	d	J'	H'(loge)	Stations	S	N	d	J'	H'(loge)	Stations	S	N	d	J'	H'(loge)
1	1	139	0	****	0	1	2	46	0.2612	0.9109	0.6314	1	0	0	****	****	0	1	2	6	0.5454	0.9919	0.6875
2	0	0	****	****	0	2	2	77	0.2302	0.9724	0.6741	2	0	0	****	****	0	2	4	15	1.118	0.9989	1.385
3	3	108	0.4272	0.8657	0.9511	3	1	31	0	****	0	3	0	0	****	****	0	3	1	3	0	****	0
4	2	77	0.2302	0.9724	0.6741	4	3	92	0.4423	0.9183	1.009	4	3	108	0.4273	0.9821	1.079	4	2	7	0.517	1	0.6931
5	3	154	0.3971	0.8554	0.9397	5	2	30	0.294	1	0.6931	5	0	0	****	****	0	5	5	18	1.387	0.9866	1.588
6	2	323	0.1731	0.8619	0.5975	6	0	0	****	****	0	6	0	0	****	****	0	6	0	0	****	****	0
7	1	108	0	****	0	7	0	0	****	****	0	7	1	15	0	****	0	7	3	10	0.8644	0.9922	1.09
8	8	215	1.303	0.9326	1.939	8	0	0	****	****	0	8	0	0	****	****	0	8	1	4	0	****	0
9	3	92	0.4423	0.9183	1.009	9	2	77	0.2302	0.9724	0.6741	9	0	0	****	****	0	9	1	3	0	****	0
10	1	31	0	****	0	10	0	0	****	****	0	10	2	77	0.2302	0.971	0.673	10	2	6	0.5808	1	0.6931
11	8	431	1.154	0.8329	1.732	11	1	15	0	****	0	11	2	31	0.2918	1	0.6931	11	2	7	0.5026	0.9979	0.6917
12	0	0	****	****	0	12	2	62	0.2423	1	0.6931	12	1	46	0	****	0	12	4	17	1.066	0.9894	1.372
13	2	30	0.294	1	0.6931	13	0	0	****	****	0	13	0	0	****	****	0	13	2	6	0.5808	1	0.6931
14	0	0	****	****	0	14	2	77	0.2302	0.9724	0.6741	14	2	62	0.2427	0.8113	0.5623	14	2	7	0.5277	0.9817	0.6805
15	0	0	****	****	0	15	2	46	0.2612	0.9109	0.6314	15	0	0	****	****	0	15	3	9	0.9078	0.9952	1.093
16	2	77	0.2302	0.9724	0.6741	16	2	30	0.294	1	0.6931	16	0	0	****	****	0	16	2	6	0.5808	1	0.6931
17	0	0	****	****	0	17	2	61	0.2433	0.8047	0.5578	17	4	123	0.6232	0.9528	1.321	17	1	4	0	****	0
18	0	0	****	****	0	18	0	0	****	****	0	18	1	216	0	****	0	18	2	7	0.5164	0.9729	0.6744
19	3	77	0.4604	0.9569	1.051	19	1	31	0	****	0	19	0	0	****	****	0	19	0	0	****	****	0
20	1	31	0	****	0	20	4	92	0.6635	0.9554	1.325	20	1	31	0	****	0	20	0	0	****	****	0
21	0	0	****	****	0	21	2	62	0.2423	1	0.6931	21	0	0	****	****	0	21	0	0	****	****	0
22	0	0	****	****	0	22	3	93	0.4412	1	1.099	22	0	0	****	****	0	22	0	0	****	****	0

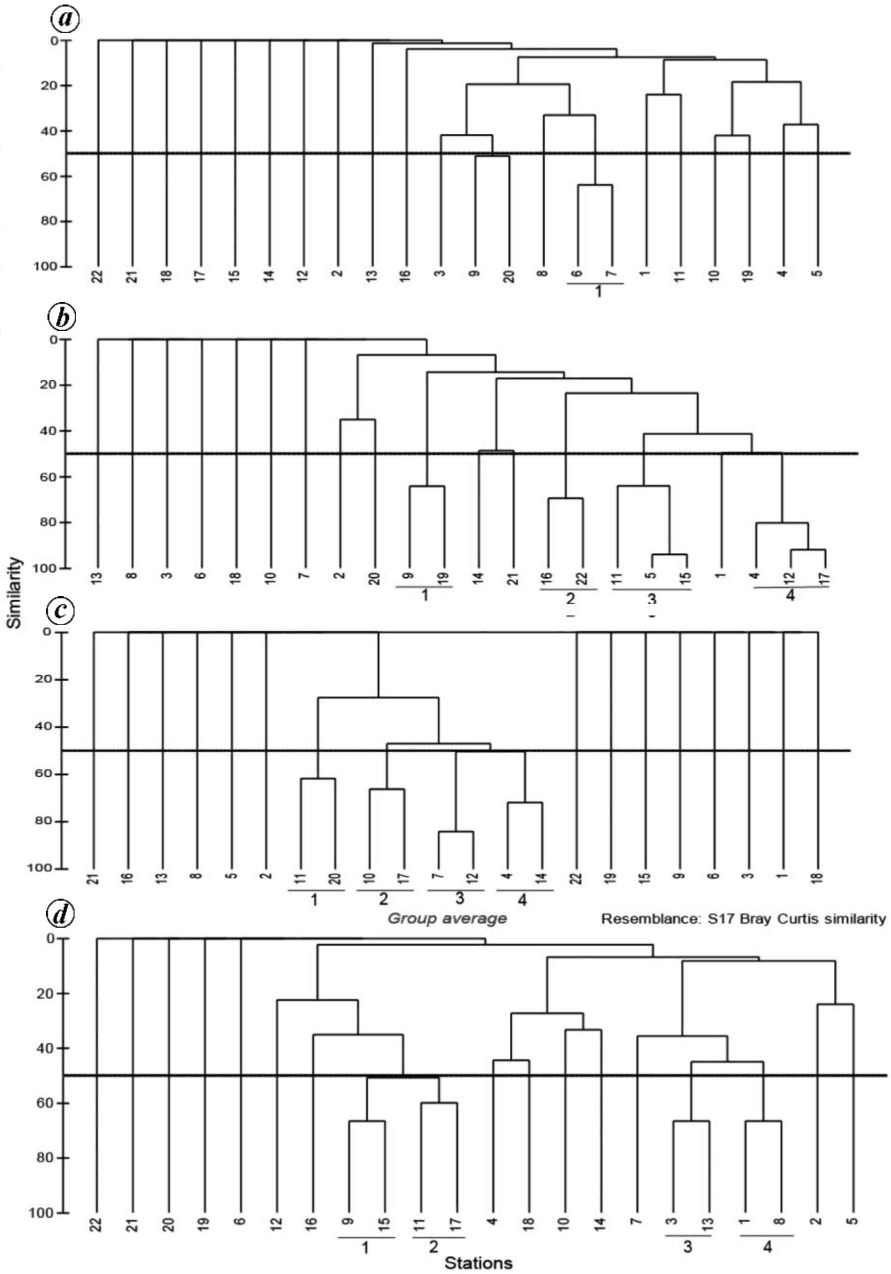

Figure 7. Dendrogram for hierarchical clustering of macrobenthic polychaetes with Bray–Curtis similarity indices during different seasons: (***a***) monsoon I, (***b***) post-monsoon, (***c***) pre-monsoon and (***d***) monsoon II.

M II was 81.4 and 96.7, and during PM and Pre M it was 92.6 and 82.8 respectively. CCA indicated that during MI (Figure 8 *a*) sand, near-bottom water temperature and TOC influenced the abundance of organisms such as *Prionospio* sp., *Lumbrineris* sp. and *Kirkegaardia* sp., whereas silt, organic nitrogen and DO positively influenced *Goniada* sp., *Magelona* sp., *Cossura* sp. and *Streblospio* sp. The polychaetes *Mediomastus* sp. and *Eteone* sp. were not influenced by the environment variables. During PM season, *Tharyx* sp., Penaeidae and *Aricidea* sp. were positively influenced by silt, DO and salinity. *Mediomastus* sp., *Magelona* sp., *Glycera* sp. and Pantopoda were found to survive well in clayey sediment and in low DO, salinity and silt content (Figure 8 *b* and Table 3). The redundancy analyses during Pre-M showed that sand and bottom-water temperature positively influenced *Tharyx* sp., *Prionospio* sp. and *Nephtys* sp., and they were negatively influenced by TOC, organic nitrogen, silt and chlorophyll *a* (Figure 6 *c* and Table 3). The polychaetes *Magelona* sp. and *Cossura* sp. thrived well in high organic carbon and nitrogen-rich silty or sandy sediments. The CCA plot during M II showed that silt, chlorophyll *a*, organic nitrogen and silicate contributed to higher abundance of *Tharyx* sp., *Maldane* sp., *Paraonis* sp.,

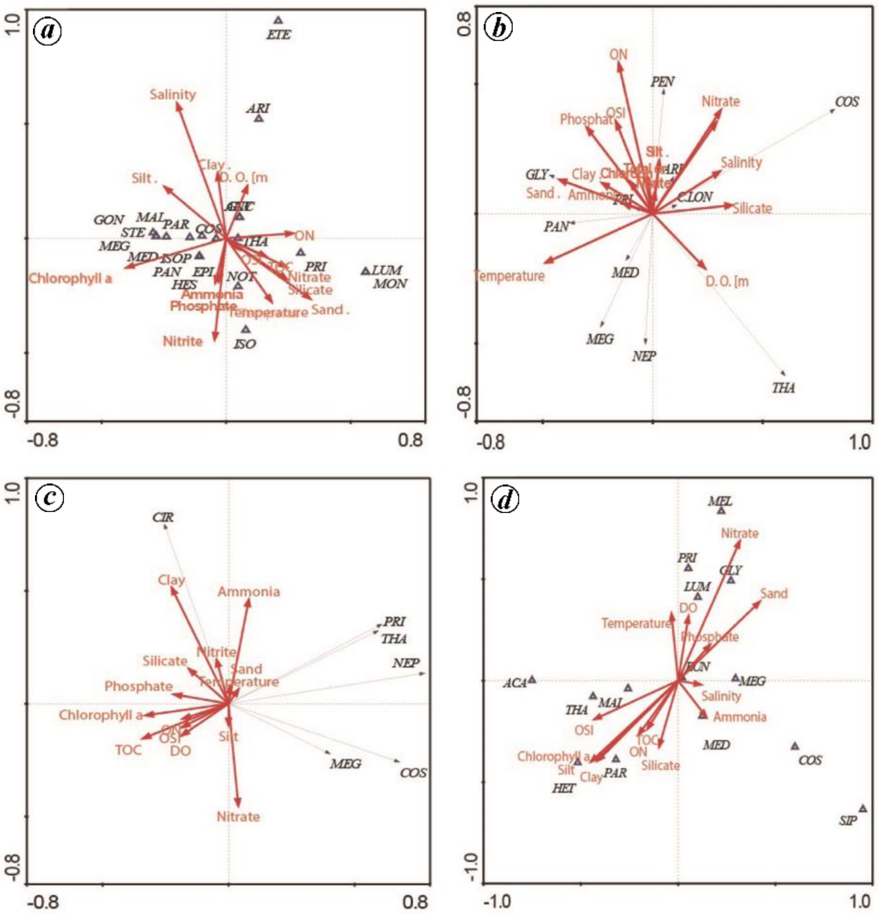

Figure 8. Canonical correspondence analysis (CCA) and RDA plots illustrating the correlation between environmental parameters and sediment characteristics and macrobenthos species during different seasons: (***a***) monsoon I, (***b***) post-monsoon, (***c***) pre-monsoon and (***d***) monsoon II at Paradip port. (ANC, *Ancistrosyllis* sp.; ARI, *Aricidea* sp.; COS, Cossura sp.; C.LON, *Cossura longocirrata*; ETE, *Eteone* sp.; EUN, *Eunice* sp.; EPI, *Diopatra* sp.; GLY, *Glycera* sp.; GON, *Goniada* sp.; HES, *Hesione* sp.; LUM, *Lumbrineris* sp.; MAL, *Maldane* sp.; MED, *Mediomastus* sp.; MEG, *Magelona* sp.; MEL, *Melinna* sp., MON, *Kirkegaardia* sp.; NEP, *Nephtys* sp.; NOT, *Nototropis* sp.; PAR, *Paraonis* sp.; PRI, *Prionospio* sp.; STR, *Streblospio* sp.; THA, *Tharyx* sp.; ACA, *Acantharia*, CIR, *Cirolanidae*; HET, Longosomatidae; ISO, Iospilidae; ISOP, Isopoda; PAN, Pantopoda; PEN, Penaeidae and SIP, Sipuncula; ON, Organic nitrogen (%); OSI, Organic sediment index (%); DO, Dissolved oxygen (mg m) and TOC, Total organic carbon (%)).

Longosomatidae and Acantharia, while Errantiate polychaetes, *Glycera* sp., *Lumbrineris* sp. and *Melinna* sp. could adapt to sandy sediments with high temperature and DO (Figure 8 *d* and Table 3).

Discussion

Studies on the biodiversity of benthic organisms from the tropical regions are limited when compared to higher altitudes[23] and the same is true for Paradip port situated on the east coast of India[24]. The study of macrobenthic organisms is important to understand and establish a database for the region to improve our understanding on distribution, abundance, diversity and other characteristics of macrobenthic organisms in the marine environment[25], as they play an important role in the food web dynamics and ecological functioning of the benthic ecosystems. The changes occurring in these parameters can lead to disturbance in the benthic faunal diversity and abundance. In the present study, macrobenthic community structure and abundance varied with the seasons, associated with changes in salinity (lower in monsoon and higher in non-monsoon seasons), temperature, DO and sediment characteristics. The sediment quality is the most important parameter for seasonal and spatial distribution and diversity of benthic organisms. The various properties related to sediment quality are permeability, penetrability that is controlled by erosion, resuspension and water content in the sediments[26]. The sediment quality in Paradip port indicated that there were limited changes in the spatio-temporal variation in the sediment texture which was mostly dominated by silt followed by sand with minimum contribution of clay. The TRIX analysis for bottom water showed that the near-bottom water quality was also good and rich in organic matter, indicating healthy bottom-water conditions[27]. There was a wide range in salinity variation (25–34) during the non-monsoon and monsoon seasons, resulting in the euryhaline species such as Cossuridae and Cirratulidae to adapt and survive during monsoon and stenohaline organisms such as isopods and crustaceans (Penaeidae) during the non-monsoon seasons. The near bottom sea-water nutrients were higher during pre-monsoon (summer) than in the other seasons due to gradual increase in temperature[28]. The present study area also showed increased nutrient levels during pre-monsoon compared to monsoon and post-monsoon seasons.

The organic carbon enrichment was high in Paradip port especially during M I and PM and it was low during Pre-M and M II, and such an increase in organic carbon in the sediments leads to hypoxic conditions as well as a decrease in the abundance and diversity of benthic organisms[29]. The stations with high organic content in the study area were either dominated by the indicator species or had lower abundance of macrobenthos. The distribution of organic carbon also varied in the surface sediments with stations along with changes in the sand-silt content, as organic carbon content was high in silt-dominated areas. The finer silt particles accumulated higher organic carbon content due to the lack of disturbance in the sediments. There was a dominance of subsurface dwelling polychaetes, which are biological indicators of high organic matter in the sediments. This high organic matter content may be due to plant material and faeces that settle down, and such organic matter is removed from the water column and at the sediment–water interface by the benthic fauna. The deposited organic material either becomes part of particulate organic matter, which is taken in by benthic fauna or directly ingested by deposit feeders[30]. The temporal changes such as salinity, sediment size gradient and other environmental stresses associated with organic carbon enrichment lead to the succession of different species[31]. The present study also showed changes in the diversity pattern of macrobenthos due to seasonal variation along with increased organic carbon input. The most common organisms reported were *Tharyx* sp., *Prionospio* sp., *Cossura* sp. and *Magelona* sp. in Paradip port, and these are called opportunistic species and are well-known pollution indicators[32]. These organisms are mostly found in stations with high organic carbon in the sediments, indicating that they may be surface or subsurface deposit feeders[33]. An earlier study indicated higher abundance of *Prionospio* sp. in a semi-polluted (moderate organic carbon) region of the Visakhapatnam harbour[5]. It has been reported that *Prionospio* sp. and few other species burrow in sand and are capable of constructing tubes in which they hide and which also protects them from predators, indicating their subsurface deposit-feeding habit[34]. With regard to properties of sediment dynamics, it has been suggested that high silt-clay fraction in the sediments contains more food particles which are commonly composed of decomposable organic constituents and sustain deposit-feeding benthic organisms[5,27,35,36]. Organisms belonging to *Cossura* sp. are mostly burrowers in the soft sediment dominated by high silt.

Higher abundance of deposit feeders belonging to genus *Cossura* was reported in a high silt area at Visakhapatnam port[5]. *Prionospio* sp. has been reported as an indicator of organic enrichment in subtidal areas, which is an inhabitant of the subsurface region of the sediments[7]. An earlier study has reported that subsurface deposit-feeding polychaetes such as *Mediomastus* sp., *Tharyx* sp. and *Cossura* sp. are capable of feeding on freshly settled organic carbon and on aged organic matter in the sediments[37]. The *Magelona* sp. is a subsurface deposit feeder and its feeding activity usually occurs below the surface[38]. Spatial variation in the benthic community is observed mostly in the estuaries and bays, under extreme or abnormal circumstances of organic matter overloading in the coastal waters leading to disturbance in the faunal community[39]. They are also mostly deposit feeders and are present in sandy-silt sediments with high total organic carbon, as observed in *Mediomastus* sp.[38].

Similar conditions were observed in the Paradip port and *Mediomastus* sp. which is one of the most abundant sedentary polychaetes present in the fine-grained sandy habitats dominated by silt with high organic matter. The individuals of *Mediomastus* sp. were present during all the seasons. These are non-selective feeders as they engulf food directly from the sediments[40] and this may be related to less disturbance in the sediments as they are observed during all the seasons. *Cossura* sp. is a stress-tolerant macrobenthic polychaete which is a suspension feeder and prefers sandy and fine silty sediments. It is a burrower which prefers soft sediments with high silt, as reported earlier[41]. The other dominant polychaete, *Nephtys* sp. found during all the seasons is an active predator that prefers fine sandy sediments, and studies have reported higher abundance of these organisms in fine sandy sediments[40,41]. The hypoxia and pollution-tolerant polychaetes *Tharyx* sp. and *Prionospio* sp., which are deposit feeders were observed during all the seasons, thus indicating the health of the ecosystem. Even though *Tharyx* sp. is a selective feeder which inhabits the mud-coloured tubes, it is found in highly polluted areas[16].

During monsoon season, the observed high organic carbon content can be attributed to collapse and sinking of phytoplankton from the surface waters[42]. The presence of Spionidae, *Prionospio* sp. and Cossuridae, *Cossura* sp. in the sediments shows sediment instability and disturbed environment, and both these species are deposit feeders that feed on fresh surface organic matter[43,44]. The diversity of macrobenthos is limited in Paradip port, as high organic matter content promotes the abundance of tolerant species and lowers the abundance of sensitive species[29], and this leads to reduction in their diversity and abundance. There is also another possibility of macrobenthic assemblages in high organic carbon sediments, where black carbon contributes more to organic carbon content present in the sediments[45]. The presence of indicator species of pollution, viz. *Prionospio* sp., *Streblospio* sp., *Mediomastus* sp. and *Tharyx* sp. in this study indicates that they thrive in low oxygen and high organic load[46].

Lumbrineris sp. are carnivores or carrion feeders and they prey on other polychaetes, Nemertea, Crustacea and Bivalvia[16]. It is possible that disturbance in the surface sediments during monsoon season may lead to the exposure of burrowing organisms and this may be the reason for observing *Lumbrineris* sp. during the monsoon season. The *Magelona* sp. is also found during all seasons. Studies on *Magelona* indicate that they are non-selective surface deposit feeders and also alter their feeding mode to suspension feeding[16]. In respect to their non-selective feeding behaviour and the presence of sufficient organic matter in the study area, *Magelona* sp. is present during all the seasons despite variations in its abundance. There is a difference in species abundance and diversity in accordance to the seasonal changes in Paradip port, with higher abundance during the monsoon season[23]. The life cycle of a tropical macrobenthic organism integrates with the monsoon and this results in seasonal differences in occurrence and abundance of such organisms. A previous study on Indian ports shows reduction in the macrobenthic species composition, density and biomass due to dredging and anthropogenic activities, as observed in Cochin port[47]. In Visakhapatnam port, a coastal ecosystem, the macrobenthic community composition varied due to various levels of pollutant accumulation in the sediments spatially showing the difference in benthic community in the port ecosystem[5]. The loss of macrobenthic communities and their rapid recovery in these stations are due to the migration of these fauna from the nearby sediment patches that are not leading to reclamation of macrobenthos under suitable conditions, as observed in Cleveland Bay[48].

The previous studies showed that due to variations in the sediments, the macrobenthic populations increased or decreased in the small port ecosystems as observed in the present study. The presence of higher organic carbon in sediments also causes a depletion in the species diversity, abundance and biomass[49], resulting in proliferation of opportunistic species. The present study shows higher organic carbon in the study area leading to the depletion in diversity and also survival of pollution-tolerant species, albeit their count. The present study also showed that the Paradip port environment is influenced by seasonal variation mostly brought in by the monsoons and anthropogenic activities: however, healthy bottom-water quality and high amount of organic load accumulated in the sediments lead to the survival and proliferation of indicator macrobenthos species.

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