BENTHIC ECOLOGY AND BIOTURBATION IN THE COASTAL WATERS OF GOA, INDIA

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GOA UNIVERSITY

by

NIMI ROSIE RODRIGUES, M.Sc.

National Institute of Oceanography

Dona Paula – 403 004, Goa, INDIA.

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STATEMENT

*As required under the university ordinance 0.19.8.(vi), I state that the present thesis entitled "**BENTHIC ECOLOGY AND BIOTURBATION IN THE COASTAL WATERS OF GOA, INDIA**", is my original contribution and the same has not been submitted on any previous occasion. To the best of my knowledge, the present study is the first comprehensive work of it's kind from the areas mentioned.*

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Rodrigues 08/04/04

Nimi R. Rodrigues

CERTIFICATE

*This is to certify that the thesis entitled "**BENTHIC ECOLOGY AND BIOTURBATION IN THE COASTAL WATERS OF GOA, INDIA**", submitted by **Ms. Nimi Rosie Rodrigues** for the award of the degree of Doctor of Philosophy in Marine Sciences, is based on her original studies carried out by her under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.*

Place: Dona Paula

Date: 08 April 2004

Dr. S.N.Harkantra

Research Guide

Scientist

Biological Oceanography Division

National Institute of Oceanography

Dona Paula – 403 004

CERTIFICATE

This is to certify that all corrections and modifications suggested by the referees and the Viva-Voce examination board have been incorporated in the thesis.

(Prof. H. R. V. Reddy)
External Examiner

Professor of Fishery Oceanography
Dept. of Fisheries Environment and Ecology
College of Fisheries
University of Agricultural Sciences
Mangalore – 575 002
Karnataka - INDIA

(S.N.Harkantra)
Research Guide

Scientist
Biological Oceanography Division
National Institute of Oceanography
Dona Paula – 403 004
Goa - INDIA

Date: 08 April, 2004

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To My Mother

List of Tables

List of Figures

CONTENTS

CHAPTER 3
THE ENVIRONMENT

CHAPTER 4
MACROBENTHIC COMMUNITY STRUCTURE

CHAPTER 5
INFLUENCE OF ENVIRONMENTAL PARAMETERS ON THE BENTHIC COMMUNITY STRUCTURE

CHAPTER 6
EFFECT OF ORGANIC ENRICHMENT ON MACROBENTHIC COMMUNITY STRUCTURE

CHAPTER 7
ASSESSMENT OF BIOTURBATION ACTIVITIES

APPENDIX

LIST OF PUBLICATIONS OF THE AUTHOR

PUBLICATIONS FROM THESIS

"The world is a masterpiece.
Every scene is more beautiful
than the finest painting and every
piece displays an intricacy and
harmony finer than Beethoven's
best. The most unique feature
of the earth is it's oceans."

Keith S Stowe

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

It is a well known fact that the sea covers three-quarters of the face of the earth. If a third dimension is added – the sea-bed, it comprises an even greater proportion of the surface of the earth. Most of the sea- bed consists of sediments and only a relatively small portion is rocky or constructed of coral. Sediments are either sandy, silty, clayey or combinations of these three. Hence, different benthic communities are found to inhabit the various types of substratum according to their adaptability.

The diversity of ecosystems of the global world ocean is as much varied if not greater than, as in the terrestrial domain. In a latitudinal axis, the oceanic realm can be broadly divided into boreal, temperate, sub-tropical waters. On the depth scale, the euphotic waters which occupy a thin layer of few dozens of meters thickness but nevertheless support all of the autotrophic production of organic matter, yield progressively to the larger pelagic ecosystem, followed by mesopelagic, bathypelagic and abyssal environments.

Within these broad classes, the diversity is still large and it's extent is a function of the temperature cycle. While the boreal waters are practically monotonic, the temperate waters sustain a relatively larger suite of ecosystems, such as stratified coastal and oceanic waters, permanently well-mixed waters, temperate rocky and sandy beaches, seagrass meadows and estuaries. However, the degree of diversity is the largest in the tropical waters – productive coastal waters and also monsoonal estuaries. Tropical marine ecosystems sustain high levels of biological productivity throughout the year in chronically

nutrient limited situations and are structurally and functionally different, that enables them to harbour a highly varied biodiversity.

The coastal ocean represents an area of transition where land, air and sea interact to form a wide variety of diverse habitats and ecosystems viz. estuaries, coral reefs, sea grass beds, mangrove swamps, creeks, lagoons and bays. In the cosatal ocean, estuaries are regarded as complex ecosystems, involving interactions of physical and bio-geochemical processes both spatially and temporally. They are the most productive ecosystems in the world and act as conduits for dissolved and particulate effluents discharged from centers of population, industries and from land drainage to the adjacent coastal environment. While some components are consumed or retained within the estuarine environment, rest of it are transported into the adjoining coastal waters. The coastal ecosystems are also places of hectic human activity, resulting in interference due to rapid development.

Estuaries, as the transition zones of the world's fresh and marine waters, rank on a landscape scale among the most prominent ecotones on earth. Rapid changes and steep gradients of environmental factors, particularly salinity are the hallmarks of these systems (Schlacher and Wooldridge, 1996). These factors and other biological features of the transition zone between the sea and the freshwater have long attracted the interest of marine biologists. Consequently, the biotic changes and depression of species richness which occur in estuaries are familiar to us all (Boesch, 1977). The restriction of species to particular sections of environmental gradients is then reflected in zonation patterns

(Raffaelli et al., 1991) that are often especially well developed in estuaries (Schlacher and Wooldridge, 1996). Identifying the factors and important processes governing population size and the structure of communities is a central problem in ecology. Studies of estuarine benthic communities have strongly emphasised the role of physical factors. Estuaries are typically characterised as physically controlled, unstable or unpredictable habitats (Schaffner, 1990). Within estuaries, sediment composition and salinity are abiotic factors that can influence benthic community composition. Sediment and salinity distribution are important because of their effects on their ecology, chemistry and physical characteristics of estuaries (Henley and Rauschuber, 1981; Kennish, 1986). Freshwater inflow can regulate the distribution of salinity and sediment transport within estuaries (Bowden, 1967; Kennish, 1986; Jones et al.,1990). The salinity gradient acts as a physiological barrier for stenohaline, marine and freshwater species and places environmental stress on euryhaline organisms. Wider fluctuations of salinity within the middle estuary heightens physiological stress and can result in reduction in the number of species (Sanders et al., 1965). Species diversity has been shown to increase from nearly freshwater at the mouth of the river to seawater (Remane and Schleiper, 1971). However, changes in sediment characteristics, such as sand content and organic matter content also influenced macrofauna communities across the estuarine gradient (Chester et al., 1983; Flint and Kalke, 1985).

One of the aims of benthic ecologist is to understand the ecological processes which is achieved by examining the interrelationship between

environmental parameters and benthic community structure (Holland et al., 1987), anthropogenic impacts (Frouin, 2000) and modelling of the ecosystem (Longhurst, 1978). A better management of living resources in estuaries can be achieved by understanding the ecological processes. Estuaries form an ideal ecosystem in which to observe such interactions due to their wide range of environmental parameters especially salinity and sediment properties (Jones et al., 1990).

India has a long coastline of 7516 km and many rivers through their discharges carry significant quantity of waste laden freshwater into the coastal waters. The amount of pollutants (industrial, sewage and domestic discharge) entering the sea around India is 24×10^9 m^3 (as of 2001). However, this value is expected to increase in the coming years largely due to rapid urbanisation and industrialisation. The pressures on the coastal waters are multifaceted and not only do they interact among themselves to a large extent but also at many levels.

Benthic invertebrates are used extensively as indicators of estuarine environmental status and trends because numerous studies have demonstrated that benthos respond predictably to many kinds of natural and anthropogenic stress (Pearson and Rosenberg, 1978; Dauer, 1993; Tapp et al., 1993; Wilson and Jeffrey, 1994). Many characteristics of benthic assemblages make them useful indicators (Bilyard, 1987), the most important of which are related to their exposure to stress and the diversity of their response. Anthropogenic contaminants often accumulate in sediments where benthos live. Benthic organisms generally have limited mobility and cannot avoid these adverse

conditions (Wass, 1967). This immobility is advantageous in environmental assessments because, unlike most pelagic fauna, benthic assemblages reflect local environmental conditions (Gray and Mirza, 1979). With pollution perturbation of a community, the conservative species are less favoured and are the first casualties while the opportunistic species are more favoured and often become the biomass dominant as well as the numerically dominant (Gray and Mirza, 1979). A further increase in disturbance may lead to elimination of some of the opportunistic species so that the diversity begins to decrease. Organic wastes such as sewage when introduced into the environment may cause changes in the enclosed bays and estuaries (Bozzini, 1975). Benthos appears to respond in a characteristic manner with distance from the source of organic input or enrichment (Pearson and Rosenberg, 1978; Ansari et al., 1984). Monitoring benthic assemblages in such areas is essential to understand complex ecosystems such as those in estuaries, because it provides a mechanism to view community response to disturbance, gives insight about food resource availability and food-web interactions and may be useful for assessing differences in ecosystem structure and function over space and time.

Benthic organisms continuously restructure or bring about mixing of the sediments by means of locomotion, injestion, ejestion and respiration. This process of mixing the sediment grains is referred to as *"bioturbation"* and is recognised as one of the major processes altering the primary structure of sedimentary deposits on millimeter to meter scales. These benthic organisms, play an important functional role in estuaries and other aquatic ecosystems. They

alter geochemical conditions at the sediment-water interface, promote decomposition and nutrient recycling, and transfer energy to other food web components (Rhoads, 1974; Boesch et al., 1976; Aller, 1982; Tenore et al., 1984; Schaffner, et al. 1987). Vertical stratification and redox potential discontinuity (RPD) layers are altered due to the burrowing fauna. New structures such as burrows and tubes are formed. These affect rates of diffusion of dissolved nutrients, gases and synthesis of refractory or inhabitory structural products. The benthic fauna are able to form new potential niches for the enrichment of a variety of physiologically diverse micro-organisms due to irrigation, aeration of sub-surface sediment layers, particle transport as a feature of different feeding habits, excretion of nutrients, metabolites and defecation. Bioturbated structures such as burrow walls and fecal casts have been recognised as potential enrichment sites for the sediment bacteria. Benthic animal activities can influence both the absolute rates and relative balances of sedimentary decomposition reactions, often dramatically affecting net mineralisation and synthesis patterns of new organic and inorganic compounds. Irrigation of sediment during burrowing, feeding and respiration is one particularly important factor controlling diagenetic reactions. By enhancing solute exchange between overlying and pore fluids, irrigation supplies, dissolved reactants from the water column, alters the spatial and temporal distribution of reactions and lowers reaction product build-up in the sediments. The resulting overall increase in the penetration of oxygen in bioturbated surface sediments clearly promotes aerobic metabolism and coupled redox reactions such as nitrification-denitrification (Rhoads, 1974; Jorgensen and

Revsbech, 1985; Andersen and Kristensen, 1991; Pelegri et al., 1994; Mayer et al., 1995). Dominance by different macrobenthic trophic groups suggests differences in food-resource availability and food web interactions and may be indicative of differences in ecosystem-level processes (Commito and Ambrose, 1985; Cohen and Briand, 1990; Diaz and Schaffner, 1990). Benthic community trophic structure is a potentially valuable criterion for integrating and assessing ecological responses along estuarine gradients (Brown et al., 2000).

1.2 SCOPE OF THE STUDY

Ecological studies have a wide range of applications. At first, any ecological study based on spatial and temporal variations will give us a baseline data of that particular area under study. Secondly, this baseline data can be useful in comparing with earlier data, if any, from the same area and thus helps in assessing the changes that have occurred over the time scale. Animal communities with respect to their habitat preferences show variations latitudinally, longitudinally and between different types of water bodies and their varying depths. Not only there are changes between different areas, but the same area exhibits changes in the animal communities during the different seasons. Changes are also due to the various environmental or abiotic factors. Biotic factors such as prey-predator relationship, trophic group ammensalism etc. also play a role in structuring these communities. Knowledge of all these is useful in understanding the natural fluctuations and the changes caused by human / anthropogenic impact. In addition, these studies help us in assessing the ecosystem dynamics and energy flow from one trophic level to the other and also

in resource management. Finally, with the abiotic and biotic data obtained one can arrive to a model, which can be used in predicting any future ecosystem changes or perturbations.

1.3 REVIEW OF LITERATURE

The Mandovi-Zuari estuarine system is one of the largest riverine network on the West coast of India. The riverine flow contributes substantial amount of organic matter to the adjacent coastal waters, thus influencing the primary productivity and trophic dynamics of the coastal ecosystem. Understanding this system will help to delineate the importance of riverine inputs to the coastal ecosystem.

Extensive studies have been carried out by earlier workers on the environmental parameters such as salinity, pH, temperature and dissolved oxygen of the water in the Mandovi - Zuari estuarine network (Dehadrai and Bhargava, 1972; Singbal, 1973; Parulekar et al., 1973; Goswami and Singbal, 1974; Parulekar and Dwivedi, 1974; Dwivedi et al., 1974; Parulekar et al., 1975; Cherian et al., 1975; Varma et al., 1975; Parulekar et al., 1980; Qasim and Sen Gupta, 1981;Parulekar et al., 1986; Wafar et al., 1997). However, there is no much work done on the sediment characteristics from these two estuaries except for a few studies (Alagarswamy, 1991; Nasnolkar et al., 1996). Also no work has been carried out on the biochemistry of these sediments.

Earlier investigations on the benthos along the Indian coast relate to faunal distribution in relation to salinity incursion and sediment distribution. Also

these studies are basically qualitative and quantitative. These studies carried out covered the annual cycle of environmental and biotic factors in relation to distribution, production, trophic relations and other relevant aspects of the benthic macrofauna (Parulekar, 1973; Parulekar and Dwivedi, 1974; Parulekar et al., 1975; Parulekar et al., 1980; Harkantra et al., 1980; Harkantra and Parulekar, 1984; Parulekar et al., 1986; Ansari et al., 1986; Harkantra and Parulekar, 1994; Mathew and Govindan,1995; Varshney et al.,1998). But there is no much information on community structure analysis and their interaction with the environmental parameters. This work presents the environmental factors (described in Chapter 3) along with the studies on community structure (described in Chapter 4). In addition, species succession of macrobenthos was also studied, the results of which are presented in Chapter 4. The influence of the abiotic factors on the faunal community was studied by using various multivariate techniques and this is described in Chapter 5.

The scientific studies related to the issues mentioned above are scanty and limited. Earlier work on benthos relate to abundance, biomass, diversity, production. The main focus was on the qualitative and quantitative aspects of the benthic fauna. So far, no work had been carried out on the biochemical composition of the sediments from the sites under study. Also macrobenthic species succession was studied using multivariate techniques. In addition, pollution studies were carried out along a gradient of organic enrichment to see the effect of sewage on macrobenthic community. Finally, assessment of bioturbation activities was carried out using chlorophyll *a* as an indicator. Besides

these preliminary studies on nutrient flux in laboratory microcosm and estimation of the sediment reworking rate for the soldier crab, *Dotilla myctiroides* were carried out. All these issues mentioned above have not been studied so far from the coastal waters of Goa.

Hence, in this study an attempt was made to collect extensive benthic data together with other physico-chemical parameters in the Mandovi and Zuari estuaries and adjoining coastal waters. Studies pertaining to the above would significantly contribute to the ecological and biogeochemical understanding of these two estuaries, which are of major importance.

1.4 OBJECTIVES OF THE STUDY

The above mentioned issues in these benthic studies were covered by carrying out the following objectives:

1) To study the influence of environmental parameters on the benthic macrofauna.
2) To study the effect of organic enrichment on macrobenthos.
3) To assess bioturbation activities in the lab as well as in the field.

CHAPTER 2

MATERIALS AND METHODS

2.1. STUDY AREA:

2.1.1 Geographical Features

The state of Goa, having a coastline of about 100 kilometers, lies on the mid-eastern coast of India, between Lat 14°54' N - 15° 48' and Long. 73° 41' E - 74° 21' E **[Fig. 2(a)]**. Among the seven rivers flowing through the plains and hills of Goa, Mandovi and Zuari are of major importance and are called the lifeline of Goa.

River Mandovi originates from the Parva Ghat of the Karnataka part of Sahyadri Hills and after traversing a stretch of about 70 km joins the Arabian Sea through the Aguada Bay near Panaji. Its width at the estuary mouth is about 3.2 km, while upstream it narrows down to about 0.25 km. Large number of tributaries join this river along it's course which is characterized by a number of deltic islands. It is fed by monsoon precipitation from the discharge of a catchment area of about 1150 km^2. The Mandovi basin constitutes about 42% of the land area and covers about 1530 km^2 of the entire state. The occurrence of sandbar near the entrance of the Mandovi in the Arabian Sea has been known for centuries. The mechanism of sand transport, wave action and circulation of Mandovi estuary has been studied by Murty et al., (1976).

River Zuari originates in the Dighi Ghat of the Karnataka part of the Sahyadri Hills and after flowing a zigzag stretch of about 67 km joins the Arabian Sea at Mormugao- Dona Paula point. It's width at the mouth of the estuary is about 5.9 km while upstream it narrows down, and at the upper reaches the

width is less than 1 km. Zuari basin covers an area of about 973 km² and receives discharge from a catchment area of about 550 km².

These two rivers, Mandovi and Zuari are joined by Cumbarjua canal giving rise to a major estuarine system. The area covered by these two river basins is about 69% of the total basin area of the riverine system in Goa. There are a number of iron and manganese mines located along the banks of these two rivers from where bulk of iron ore is transported to Mormugao harbour through these rivers. The banks of both these rivers are provided with thick vegetation of mangrove forest. Geologically speaking, the Mandovi and Zuari river estuaries could be classified as drowned river valley estuaries formed due to the Holocene rise in the Sea level (Anon, 1978). The two river estuaries are rich in resources and are used for fishing activity, practically throughout the year and particularly during the monsoon months when sea –fishing gets suspended.

2.1.2 Climate:

In Goa normally three seasons prevail in a calendar year. They are premonsoon (February – May), southwest monsoon (June-September) and postmonsoon (October – January). The premonsoon season is the warmest period of the year and experiences occasional showers towards the end of May. The average relative humidity is 80%. This season is followed by the southwest monsoon (hereafter referred to as the monsoon season), during which the state receives most of its rainfall, with an average of about 3000 mm. The postmonsoon season is a fair and stable season. Normally, atmospheric temperature shows two peaks, one in October when warm and humid conditions

exist and second in May, which is usually the hottest month of the year. The temperature of seawater varies between 26.5 to 31.0° C. Heavy rainfall, freshwater runoff, sandbar formation in the mouth region of estuary occur during monsoon and is followed by recovery during postmonsoon and stability during pre- monsoon (Qasim and Sen Gupta, 1981). Salinity decreases considerably (3psu) during monsoon due to freshwater runoff and rainfall. The average annual freshwater runoff is 7 km^3 for Mandovi and 9 km^3 for Zuari estuaries (Anon, 1979). The estuaries may be classified as stratified during the monsoon season which gradually evolves towards a well mixed one during the post monsoon period, according to the definition given by Pritchard (1952). It's pre and postmonsoonal flows are regulated by the semi- diurnal tides having amplitude of 2-3 m (average of 2.3m) during spring tides. The currents are mainly influenced by tides during monsoon. Maximum distance of penetration of seawater (0.9×10^{-3}) is about 67 km away from the mouth in May, which comes down to a minimum distance of about 10-11 km in July – August. The estuarine complex is fringed with extensive mangroves (Wafar et al., 1997), which are biologically productive nursery grounds for a variety of commercially important fin and shellfish (Parulekar et al., 1980; Qasim and Sen Gupta, 1981). Earlier work on benthos (Parulekar et al., 1973; Parulekar and Dwivedi, 1974; Parulekar et al., 1975, 1980; Harkantra and Parulekar 1981, 1985) revealed high benthic production consisting of clam beds, polychaetes, other molluscs etc. These estuaries are extensively used for fishing, aquaculture, ore transport, harbour development, water recreation, waste disposal and adjacent land for human

settlements (Parulekar et al., 1980; Qasim and Sen Gupta, 1981; Parulekar et al., 1986).

In Zuari estuary, tides of mixed semidiurnal type with a minimum range of about 2-3 m are encountered causing the exchange of appreciable amount of saltwater into the system from the adjacent sea, the rate of which varies considerably with season (Cherian et al., 1975). During the pre and post-monsoon period the flow is regulated by the tides of semi – diurnal type like that of Mandovi. The freshwater discharge into this estuary during the monsoon season is high. However, the amount of freshwater received by Zuari is less as compared to Mandovi estuary. During post and premonsoon period, the estuary, to a distance of about 14 km is primarily tide- dominated due to meagre or negligible freshwater runoff. Maximum distance of penetration of water of 0.9 x 10^{-3} salinity is reported to a distance of about 65 km away from the mouth during the month of May. It gets reduced to a minimum of about 20 km during June-July following the onset of monsoon. The tidal influence has been recorded upto 41 km.

2.1.3 Station Position:

Six stations, three in Zuari estuary (Z1, Z2, Z3) two in Mandovi (M1, M2) and an offshore station, A, were selected based on the salinity and sediment characteristics **[Fig. 2(a)]**. The positions of the six stations were determined by Global Positioning System (GPS) (Magellan GPS NAV 5000^{TM}, USA).

Station A: is located at 15° 28' .655 N; 073° 44' .024E. it is the offshore station having a mean depth of 15 m and lies at the converging area of Mandovi and

Zuari estuaries in the Arabian Sea. The salinity on an average remains 34.45psu (± 0.83) due to its location in the marine environment. The sediment here is clayey-silt.

Station M1: is located at 15° 30' .123N; 073° 49' .126E. This station remains saline most of the time due to its proximity to the sea, with salinity ranging from 9.1 – 32.5 psu (± 10.15). Mean depth at this station is 3.5 m and the sediment is mostly sandy, sometimes an admixture of sand and mud.

Station M2: is situated further upstream at 15° 30' .323N; 073° 52' .430E. This station also, like M1 remains saline most of the time, with a salinity range of 1.1-33.0 psu (± 12.79). The mean depth at this station is 3 m and the substratum is an admixture of sand and mud.

Station Z1: this station is located at the mouth of the Zuari estuary at 15° 25' .107N; 073° 51' .472E. This station remains saline most of the time with an average salinity of 32.79 psu (± 1.32). The substratum is predominately sandy having a mixture of silt for most of the year. There is an island (St. Jacinto) near this station from where the terrigeneous material also gets deposited. The average depth at this station is 3.5 m.

Station Z2: lies upstream from the mouth of the Zuari estuary at $15^0$25' .107 N; $073^0$51' .472 E and has a mean depth of 3.5 m. The salinity at this station varies from 20.5 – 33.0 psu (± 3.78). The substratum varies from sand to silty sand.

Station Z3: located at 15° 24' .640N; 073° 53' 680E. Salinity varies from 3.0 – 33.0 psu (± 10.34) throughout the year. The bottom is composed of mostly silt with varying combinations of sand and clay to give either sand-silt-clay or sandy-

silt or clayey-silt. A considerable amount of detritus is also found in the sediment that gets from the mangrove swamps. Mean depth at his station is 3 m.

2.1.4 Sampling:

The sampling program was carried out from October 1997 to September 1998. This was designed to cover the three seasons: postmonsoon, premonsoon and monsoon in a complete annual cycle. Monthly sampling was planned at each station. Six stations were sampled monthly except that stations A and Z1 were not sampled in June, July and August due to stormy weather.

There are numerous reports, which illustrate the methodology of benthic sampling and analytical techniques (Holme and McIntyre, 1971; Swartz, 1978), processing and interpretation of benthic data (Vilenkin, 1965; Clifford and Stephenson, 1975; Elliot, 1977) and environmental study (La Fond and Prasad Rao, 1968; Strickland and Parsons, 1972). In the present investigation benthic sampling and environmental parameters were studied using standard methods, which are being widely used.

2.2. DATA ANALYSES

2.2.1 Objective 1:

To study the influence of environmental variables on benthic macrofauna.

2.2.1(i) Macro fauna:

Duplicate samples were obtained at each station with 0.04 m^2 van Veen grab, having a penetration of 15 cm. The sediment samples from the grab were preserved in 10% Rose Bengal-seawater formalin. Later these sediment samples were sieved through 0.5 mm mesh sieve. Fauna retained on the sieve were transferred into a white enamel tray, half-filled with fresh water. All the stained animals were picked up by means of forceps and stored in transparent plastic bottles containing 5% formalin. Macrofauna were identified upto species level using the available key for polychaetes (Fauvel, 1953), molluscs (Satyamurti, 1956 & Kundu, 1965 a & b), crustaceans and other groups (Barnard, 1935; Gosner, 1971). Food and feeding habits of soft–bottom macroinverterbrates were ascertained from the literature (Fauchald and Jumars, 1979). Numerical abundance of each species was recorded under stereozoom microscope. Population density was converted into nos/m^2.

2.2.1(ii) Biomass estimation of macrofauna

The animals of different size groups were weighed on a microbalance (Sartorius BP 221 S, Germany). The shells of molluscs were removed and crustacean forms were treated with dilute hydrochloric acid (10%) until

effervescence. The animals were then removed and placed on a tissue paper until all the water was absorbed, and then weighed. Due care was taken for incorporating the weight of different size groups while extrapolating the total biomass.

2.2.1(iii) Grain size analysis:

About 25 gm of dried sediment samples was weighed accurately and transferred into a clear 250 ml beaker. The samples were made salt free by repeated washing using distilled water. Approximately 5 ml of 10% sodium hexametaphosphate solution was added to this salt free sediment and disposed overnight. Subsequently, the samples were wet sieved through a 62µm sieve. The sand fraction (62µm) retained on the sieve was dried and weighed. This was later used for separating the different sand fractions on a mechanical shaker. While the mud fraction was collected in a 1000ml beaker, transferred to a 1000ml measuring glass cylinder and subjected to pipette analysis (Folk, 1968), which is based on the classic formula for settling velocities provided by Stokes' law. Percentage distribution of sand, silt and clay fractions in each sample was determined and textured classification was made based on the grain size variation (Folk, 1968). Sand samples were further analysed for medium to very fine sand (Buchanan, 1984). The conventional phi notations (Φ) were used instead of the Wentworth scale. The Wentworth scale can be converted to the phi notation using the formula:

Φ = - log 2 of the particle diameter in mm

The mean grain size and standard deviation (sorting) were calculated by the graphical method (Folk, 1968) using the formulae:

$$\text{Graphic mean} = \frac{16\,\Phi + 50\,\Phi + 84\,\Phi}{3}$$

$$\text{Graphic S.D (Sorting coefficient)} = \frac{84\,\Phi - 16\,\Phi}{4} + \frac{95\,\Phi - 5\,\Phi}{6.6}$$

The analysis was carried out at monthly intervals.

2.2.1(iv) Total Organic Carbon:

Sediment samples were collected at every station and organic carbon was determined using auto analyzer, NCS 2500, Italy. 1 g of the dried (<60° C) and finely powdered sample was treated with dilute hydrochloric acid (1N) to remove all inorganic carbon. This treated sample was used for the analysis. Total organic carbon was expressed as µg/g.

2.2.1(v) Total Organic Nitrogen:

Similarly organic nitrogen was determined using auto analyzer, NCS 2500, Italy, on the same sediment samples used for organic carbon, simultaneously. Total organic nitrogen was expressed as µg/g.

2.2.1(vi) Chlorophyll *a*:

Approximately 1 g of the sediment was used to extract chlorophyll *a* (chl-*a*) by adding 90% acetone in the dark. The fluorescence was measured on a Turner fluorometer, USA. The fluorometer was previously calibrated with standard chl-*a* obtained from Sigma chemicals. Phaeopigments of the samples

were also estimated by acidification with dilute hydrochloric acid (1N). Similarly chl-*a* from the surface and bottom water was also estimated. 500 ml of seawater was filtered on Millipore GF/F filter paper using suction pump. The filter paper along with the retained material (filtrate was transferred to glass vials and covered with Al-foil and stored in refrigerator for extraction, for a period of around 18 hours. (Lorenzen, 1966). The results obtained are expressed in µg/g for sediment. Further, microphytobenthic carbon was calculated by converting chl-*a* concentrations to carbon content (C-chl- *a*) using a conversion factor 40 (De Jonge, 1980).

2.2.1(vii) Proteins:

Proteins were analyzed using the method of Lowry et al., (1951). Appropriate blank and standards (bovine serum albumin) were similarly treated and the absorbance was measured at 750 nm. The concentration was expressed in mg/g.

2.2.1(viii) Carbohydrates:

Carbohydrates were estimated following the method of Kochert, (1978). Appropriate blank and standards (glucose) were similarly treated. The absorbance was measured at 485 nm and the concentration was expressed as mg/g.

2.2.1(ix) Lipids:

Lipids were analyzed using the method of Parsons et al., (1984). Appropriate blank and standards (stearic acid) were treated similarly and the absorbance measured at 440 nm. The concentration was expressed in mg/g.

The principle of this method depends upon the oxidation of lipids by acid dichromate. The oxidation reaction is followed by a decrease in the dichromate colour.

Proteins, carbohydrates and lipids were converted into their carbon equivalents using the conversion factors 0.49, 0.40 and 0.70 respectively (Fabiano et al., 1995). To further investigate the nature of organic nitrogen, protein concentrations were converted to organic nitrogen (N-PRT) by using the conversion factor 6.25 (Fabiano et al., 1995) and were expressed as percentages of ON (N-PRT: ON).

2.2.1(x) Salinity of seawater:

The electrical conductivity ratio of seawater samples was measured in a Guildline "Autosal" model 8400A salinometer (measurement range: 0.005 – 42 psu). The salinity of the sample was calculated using the equation for conversion of conductivity ratio to salinity (Fofonoff, 1983). Low pressurized air forces the saline sample from the sample bottle and through the sampling element, which is called conductivity cell. The sample passes as a continuous flow through the conductivity cell and electrodes implanted in the cell initiate signals that are proportional to the sample's conductivity. Using an internal preset electrical reference to produce an error signal, the instrument provides a numerical radiant, which corresponds in magnitude and direction to the error signal. The display reading provides a valid measurement valve when the internal reference has been preset or standardized against a known external reference.

2.2.1(xi) pH of seawater:

Similarly, water samples from the surface and bottom layers were collected and the pH estimated using a pH meter, LI612, Elico Pvt. Ltd., India.

2.2.1(xii) Dissolved oxygen of seawater:

Bottom water was collected using a Niskin sampler and the oxygen estimated using the Winkler Method (Strickland and Parsons, 1972). Water was carefully collected in standard bottles with Winkler A and B in the field and subsequently titrated with sodium thiosulphate solution in the laboratory using starch as the indicator. The results are expressed in ml/l. A divalent manganese solution (manganous sulphate), i.e. Winkler A followed by a strong alkali (potassium iodide + sodium hydroxide), i.e. Winkler B is added to the sample. The precipitated manganous hydroxide is dispersed evenly throughout the seawater sample that completely fills a stoppered glass bottle. Any dissolved oxygen rapidly oxidizes and equivalent amount of divalent manganese to basic hydroxides of higher valency states. When the solution is acidified in the presence of iodide the oxidized manganese again reverts to the divalent state and iodine, equivalent to the original dissolved oxygen content of water, is liberated. This liberated iodine is titrated with standardized thiosulphate solution.

2.2.1(xiii) Statistical Analyses:

The data obtained from the 12-month study was subjected to statistical analyses. The mean values of various parameters were calculated along with the standard deviations as given in Elliot (1977).

2.2.1(xiii) (a) Mean:

$$\text{Mean } (X) = \frac{x}{n}$$

2.2.1 (xiii) (b) Standard Deviation:

$$\text{Standard deviation } (S.D) = \frac{(x - x)^2}{n - 1}$$

Where 'x' is the observation and 'n' is the number of observations.

2.2.1 (xiii) (c) Species Diversity:

Species diversity was computed using the Shannon-Wiener Index (Pielou, 1975). This was originally proposed by Shannon (Shannon and Weaver, 1963).

(Species diversity) $H' = - pi \log_2 pi$

Where 'pi' is the proportion of individuals belonging to 'i' th species and 's' is the number of species. Species diversity has species evenness and a species richness component.

2.2.1 (xiii) (d) Species evenness:

Evenness (J) was computed as $J = \frac{H}{\log_2 s}$ (Pielou, 1966)

Where $H = \frac{H'}{H' \text{ max}}$ and 's' the number of species.

Such method has been used by several authors like Sanders (1968), Heip and Engels (1974) and Parulekar et al. (1980).

2.2.1 (xiii) (e) Species Richness:

Species richness was calculated as suggested by Margalef (1958).

(Species richness) SR = (s – 1) / ln N

Where 's' is the number of species and "'N' is the total number of individuals in a collection.

2.2.1 (xiii) (f) Index of Dominance:

This was calculated as, Dominance (D) = J (evenness) – 1.

2.2.1 (xiii) (g) Two-way analysis of variance:

Two–way ANOVA tests were carried out to see any significant differences between stations and seasons. This was computed using MINITAB-Release 8.3 (MINITAB Inc., 1991). Further, one-way Tukey's HSD multiple comparison was used when significance was detected ($P<0.05$).

2.2.1(xiii) (h) Linear Multiple Regression:

The best multiple linear regression models (Draper and Smith, 1981; Wiesberg, 1985) were used to assess the relative significant influencing environmental parameters on the benthic community structure such as species diversity, total wet biomass and total population and to construct the predictive

models. The three types of regression methods available; forward, backward and stepwise do not always agree on the best model, especially when multicollinearity exists. The regression explaining the greatest amount of variation with all the parameters coefficient significant were presented as the best fit based on maximum R^2 and minimum Mallows' Cp (Helsel and Hirsch, 1992). The total data of four sites were first anlaysed to give regression model. However, it did not give any significant regression and variation was very low. Moreover, ANOVA revealed significant differences of environmental parameters among the sites. Hence, it was decided to perform this analysis on the data set of each site separately.

All the raw data were log transformed into log 10(x+ 1) and percentage values were transformed into arcsine (Bakus, 1990) before any statistical analyses.

2.2.1 (xiii) (i) Cluster Analysis (CNESS):

A new faunal distance matrix, Chord Normalised Expected Species Shared (CNESS) was used for clustering and to study the species succession. The statistical programme COMPAH 96 (Combinatorial Polythetic Agglomerative Hierarchical Clustering) (Gallagher, 1996) was used for the purpose. The results were expressed in the form of dendrograms.

2.2.1(xiii) (j) Principal Component Analysis - Hypergeometric (PCA-H):

Principal Component Analysis – Hypergeometric (PCA-H) was used to examine the relationship among the macrobenthos and other parameters. Species versus month matrix was arranged for each sites as there was significant difference in environmental parameters and community structure such as Shannon-Weiner's diversity index, total population and wet biomass. Actual mean density data and species which has contributed more than 2% of the samples were considered for the analysis (Trueblood et al., 1994). Sample size (m) was determined as half of the total sample population.

2.2.2 Objective 2:

Evaluation of changes in benthic fauna due to organic enrichment

A section of a beach near site M1 if the Mandovi estuary, receiving domestic sewage through a 'nullah' was sampled from March 2000 – May 2000. Sampling areas each covering an area of 1 m^2 was sub sampled at 5 points (4 at the corners and 1 at the center of each point). The sampling areas were placed around 10m apart from each other from the low tide to the high tide zone (i.e. along the organic enrichment gradient). A total of 4 sampling areas were covered: 3 sample sites and 1 reference site.

2.2.2 (i) Macrofauna:

Macrofauna was sampled using a PVC core having an internal diameter of 20 cm and penetration depth of 15cm. The sediment was preserved with 10% seawater Rose Bengal-formalin. Later the sediment was washed and the fauna retained on the sieve was transferred to an enamel tray from where they were picked and transferred to vials containing 5% formalin. This fauna was later identified using the keys for the literature mentioned in the earlier section of this chapter.

2.2.2 (ii) Biomass of fauna:

Wet weight of individual's species was estimated following the method described in the earlier sections.

2.2.2 (iii) Water characteristics:

Interstitial water was collected from the depressions formed as a result of the core insertion in the sediment for obtaining macrofauna. Water was analysed for salinity, pH, dissolved oxygen and BOD_5. All the parameters were analysed using standard techniques. Biological oxygen demand was estimated after 5 days in order to check the biological activity. Oxygen bottles were filled with seawater from the surface, capped and covered with a black paper or cloth and kept in a cool environment. After 5 days the oxygen from these bottles was fixed by adding sodium thiosulphate and was estimated by Winkler's method. The

difference in the amount of dissolved oxygen obtained was a result of the biological activity.

2.2.2 (iv) Sediment characteristics:

Sediment parameters such as temperature, grain size, organic carbon, chlorophyll *a*, were estimated using the standard methods explained earlier.

The data thus obtained was analysed for the Abundance Biomass Comparison (ABC) Curves (Warwick, 1986) and dendrograms using the statistical programme PRIMER-v5 (Plymouth Routines In Multivariate Ecological Research) (Clarke and Gorley, 2001). Also the Species Abundance Biomass (SAB) Curves (Pearson and Rosenberg, 1978) were drawn to summarise the changes in the basic faunal parameters occuring along the gradient of organic enrichment.

2.2.3 Objective 3:

Assessment of bioturbation activities

2.2.3 (i) Vertical trend of chlorophyll *a* in the sediment:

Station A was selected for the study as these stations had more of clayey substratum. This enabled us to obtain the core easily. Core samples were obtained by operating a gravity corer having a length of 50 cm and an internal diameter of 4.5-cm. After retrieval of the core, the temperature of the sediment

was recorded and subsequently the core was sectioned at every 2 cm interval. All the samples were stored frozen until extraction. Later the sections were analyzed for chlorophyll *a* using the method explained in the previous sections of this chapter.

2.2.3 (ii) Nutrient flux experiments:

Microcosm experiments to compare the nutrient values in sediment-overlying waters were carried out following the method of Kristensen and Blackburn, 1987 to suit our experiments. The uppermost ~ 5 cm of the sediment surface was collected and sieved through a 500 micron mesh in order to remove the macrofauna and larger particles (shells and gravel). Simultaneously soldier crabs, *Dotilla myctiroides* having a carapace length of 120mm were collected (form Zuari estuary) and kept separate from the sediment. Tanks containing the sieved sediment to a depth of ~ 15 cm and the crabs were transported to the laboratory for further treatment. Since the objective of the study was to examine the flux rates, meiofaunal organisms present in the sediment were killed before the start of the experiment. These small animals were killed by freezing the sediment for 48 hours at –20°C before further use. Microscopy on sediment samples before and after the freezing procedure revealed that live larvae and meiofauna had disappeared following the treatment. After thawing, the sediment was homogenised by handmixing in the transport-tanks and compaction was allowed to proceed. Aquarium tanks of size 40x 25x 25 cms were used for the study. 8 individuals each were kept in two tanks, one containing sediment and

water (35 psu) and other containing only water. Similar tanks only with water, but without the animals, were kept as controls. Nitrate was estimated from water column (Grasshoff, 1983) after definite intervals of time.

2.2.3 (iii) Sediment reworking rate:

To study the sediment-reworking rate of the soldier crab, *Dotilla myctiroides*, an intertidal area of a small beach was selected. The crabs were monitored and the reworking rate (*in vivo*) was worked out according to Rowden and Jones (1993).

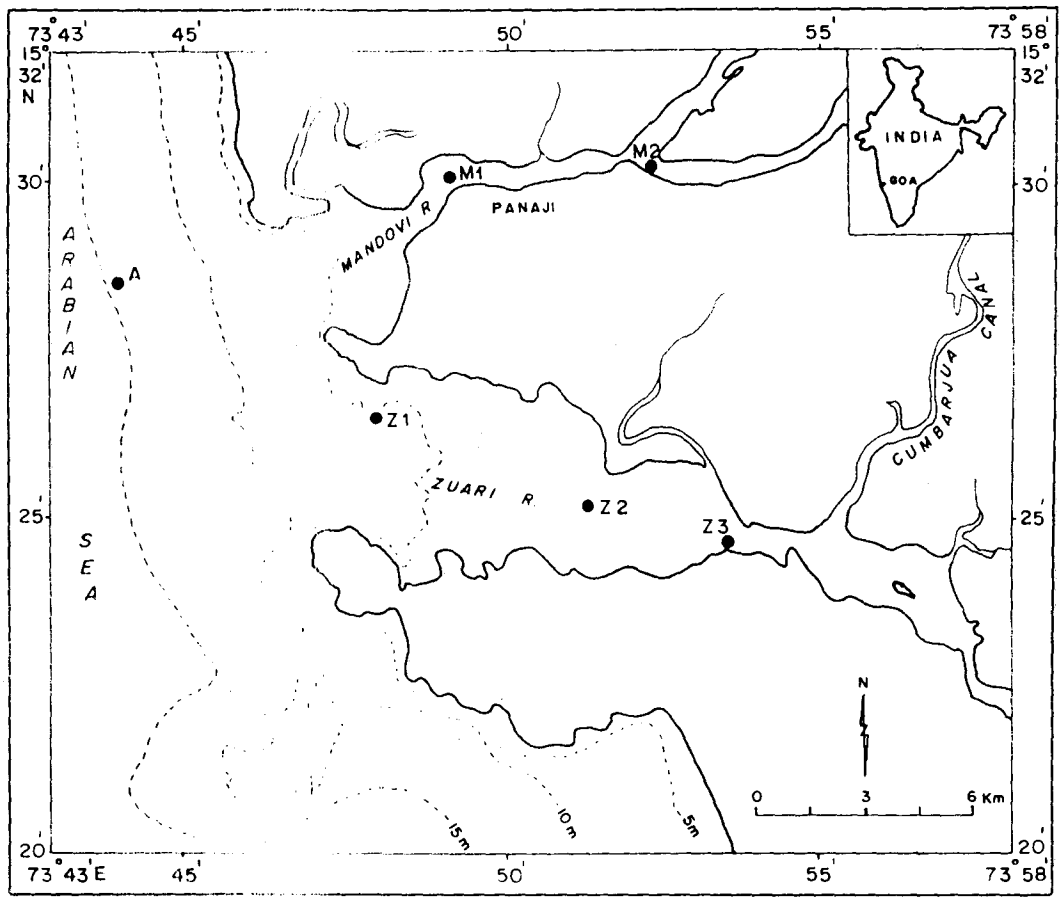


Fig. 2 (a) Map showing the six different study sites in the two estuaries, Mandovi and Zuari

CHAPTER 3

THE ENVIRONMENT

3.1 INTRODUCTION

The estuary and its adjacent coastal waters display great variability in terms of physical and biogeochemical forcings. The estuarine environment has a free connection with the open sea at one end and the river at the other end, and hence can exhibit variability in the magnitude of these forcings. Temporally, they respond to a combination of parameters in a variable fashion. These temporal variations interact, however, with spatial variations, which are also important determinants of system processes and structure. The spatial and temporal variability within the estuaries reflect changes that have occurred and are occurring simultaneously over a continuous range of different spatial and temporal scales. Basically, estuaries are considered to be the most geochemically and biologically active areas of the biosphere where rapid changes in salinity, temperature, nutrients, sediment load etc. occur. This variability has strong effects on the composition and dynamics of the biota. Many estuarine characteristics are shared with the adjacent coastal waters and the combination of their characters makes each ecosystem unique. Although research has led to the formulation of a number of generalizations regarding their structure and function, their uniqueness is largely determined by the set of physical, chemical, biological and geomorphological features influencing the system.

Studies have been carried out by earlier workers on the environmental parameters such as salinity, pH, temperature and dissolved oxygen of the water in the Mandovi - Zuari estuarine network (Dehadrai and Bhargava, 1972;

Singbal, 1973; Parulekar et al., 1973; Goswami and Singbal, 1974; Parulekar and Dwivedi, 1974; Dwivedi et al., 1974; Parulekar et al., 1975; Cherian et al., 1975; Varma et al., 1975; Parulekar et al., 1980; Qasim and Sen Gupta, 1981; Parulekar et al., 1986; Wafar et al., 1997). However, there is no much work done on the sediment characteristics from these two estuaries except for a few studies (Alagarsamy, 1991; Nasnolkar et al., 1996). Also no work has been carried out on the biochemistry of these sediments. Hence this detailed study was carried out on the sediment characteristics along with the hydrological parameters to assess the influence of these factors on the benthic community structure.

3.2 RESULTS

3.2.1 Bottom water characteristics

Tables 3 (a) to **3 (f)** give the monthly variations of hydrological parameters such as temperature, pH, salinity and dissolved oxygen at different sites over the study period.

3.2.1. (i) Temperature:

The bottom water temperature varied from 26.0^0 C in July at site M1 to 33.0^0 C in November at site A. At all the six sites there was a progressive increase in temperature from February to May followed by a decline during peak monsoon months and again an increase thereafter. The annual variation in temperature at all the sites was from $5 - 7^0$ C.

3.2.1. (ii) pH :

pH of the bottom water showed the lowest value of 7.51 in July at site M1 and the highest value of 8.19 in November at site A.

3.2.1. (iii) Salinity :

Salinity variation among the sites in the estuarine system was very large and it fluctuated in accordance with the freshwater influx into the system. From February to May the two estuaries simply become an extension of the sea with salinity reaching 35.5 psu. The lowest salinity of 1.1 psu was recorded at site M2 in July whereas the highest of 35.5 psu was recorded at sites A and Z1 in May.

3.2.1. (iv) Dissolved oxygen:

The lowest dissolved oxygen concentration was observed at site Z1 in March with a value of 3.42 ml/l. While the highest of 5.85 ml/l was observed at site Z3 in August. The average oxygen concentrations in both the estuaries increase with distance from the mouth upstream.

Table 3 (a5) reveals the annual and seasonal variations of the above mentioned parameters at sites M1, M2, Z2 and Z3 (As there was no data during June, July, August and September for sites A and Z1, ANOVA and Tukey test were not carried out). There was significant annual and seasonal variation in these parameters among the seasons and the sites as revealed by ANOVA and Tukey test. In general the salinity was significantly lower during monsoon and the upstream sites, compared to the premonsoon and postmonsoon seasons (Tukey test).

3.2.2 Sediment characteristics

Tables 3 (g) to **3 (l)** summarise monthly variations of sediment characteristics such as sand, silt, clay fractions, mean grain size, sorting coefficient and sediment texture at different sites during the period of study.

3.2.2. (i) Mean grain size:

The mean grain size ranged from 1.4 Ø in July at site M1to 5.7 Ø at site A in September showing muddy to sandy substrata.

3.2.2. (ii) Sorting coefficient (S.D.):

Sediment sorting coefficient varied from 0.37 Ø at M2 during the month of January to 1.88 Ø at site Z3 during March showing poorly sorted to well sorted sediments (Folk, 1968).

3.2.2. (iii) Sand:

Percentage of sand varied between 1.4% at site A during December to 99.2% at site M1 in July.

3.2.2. (iv) Silt:

Silt percentage ranged between 0.6% at M1 in July to 69.7% at site A in October.

3.2.2. (v) Clay:

Clay percent ranged from 0.1% at M1 in June to 39.48% at Z1 in March. Based on these percentages, five different types of substrata were identified. The muddy regions varied from clayey silt to sand-silt-clay. The type of sand in the sandy regions varied from medium to very fine sand.

Tables 3(a5) and **3(a6)** show the seasonal and annual mean grain size and sediment sorting at four different sites (M1, M2, Z2 and Z3). The mean grain size values varied significantly between the season and sites (ANOVA). Site M2 had significantly coarser particles than the other sites (Tukey test). Similarly, during monsoon, the mean grain size was significantly higher than the other seasons (Tukey test). Similarly sediment sorting showed significant variations between the seasons as well as sites (ANOVA). Site Z2 had significantly high values than the other sites.

3.2.3 Chemical composition of the sediments

Tables 3 (m) to **3 (r)** summarise the data for the total organic carbon, total organic nitrogen and the ratio of these two obtained at the six sites over the study period.

3.2.3.i) Total organic carbon (TOC):

Total organic carbon varied from 485.0 μg/g at site M1 in September to 85931.0 μg/g at Z1 during October.

3.2.3.(ii) Total organic nitrogen (TON):

The total organic nitrogen varied between 104.0 μg/g at M1 in August and 2893.0 μg/g at Z2 in the month of July.

The ratio of total organic carbon to total organic nitrogen (C/N) always remained above 2.88 (at site M1 in March) and never exceeded 18.23 (also at site M1 but in December).

Regression between mean grain size and TOC and TON showed that there was significant variation. Between mean grain size and TOC it was 45.18% and between mean grain size and TON it was 48.04% **[Fig. 3(f)]**.

3.2.4 Microphytobenthos

Tables 3(s) to **3(x)** show the values of the microphytobenthos and the ratios associated with it at the six sites during the study period.

3.2.4 (i) Chlorophyll *a*:

Microphytobenthic biomass measured as chlorophyll *a* ranged from 0.0921μg/g at site A during November to 5.378 μg/g at Z3 in September. C-Chl - *a* accounted for a very small percentage of total organic carbon ranging between 0.014 % at A in November and 9.029 % at M1 in October, with an average percentage of 1.25%. But it accounted for the dominant fraction of C-BPF, and this ranged from 0.88% in September to 82.07% at Z2 in December.

3.2.5 Biochemistry of the sediments

Tables 3 (y) to **3 (a4)** summarize the data for biochemical components in the sediments at different sites during the study period.

3.2.5. (i) Proteins (P):

Protein values ranged from 5.17 μg/g at M1 in August to 33.30 μg/g at Z3 in October.

3.2.5. (ii) Carbohydrates (C) :

Carbohydrate content in the sediments showed the lowest value of 126.4 μg/g at Z1 in October and the highest value of 2486.5 μg/g at Z2 in July.

3.2.5. (iii) Lipids (L):

Maximum lipid content was observed to be 153.60 μg/g at Z1 in December and the minimum was 40.90 μg/g at A in September.

Graphs of linear regression revealed that maximum variation was found to occur between proteins and organic carbon (54.72%), while the minimum was seen between lipids and organic carbon (10.79%). Proteins showed a higher variation when associated with total organic carbon (54.72%), while on the other hand carbohydrates showed a better variation with total organic nitrogen (50.51%). Lipids however, did not exhibit a good variation with carbon as well as nitrogen **[Fig. 3 (e)]**.

3.2.5. (iv) Carbon of the Biopolymeric Fraction (C-BPF):

The sum of the protein, carbohydrate and lipid carbon was referred to as the biopolymeric fraction and was utilised to estimate the fraction potentially available for benthic consumers. C-BPF usually accounted for a very small percentage of organic carbon with a minima of 112.42 μg/g at Z1 in November and a maxima of 1177.68 μg/g at A in May. Of all the six sites, site A, on an

average had the highest amount of C-BPF (609.07 C μg/g) while the lowest was found at site M2 (245.32 C μg/g). The amount of C-BPF at M1, Z1, Z2 and Z3 was 263.32, 359.04, 328.87 and 448.53 C μg/g respectively.

3.2.5. (v) C-BPF : TOC ratio:

The C-BPF:TOC ratio or the Food Index ranged from 0.15 at Z1 in September to 28.30 at M1 also in September. The average C-BPF:TOC ratios for the six sites – A, M1, M2, Z1, Z2 and Z3 were calculated to be 2.72, 12.95, 10.04, 5.10, 2.52 and 2.21 respectively. These ratios indicated that C-BPF on annual average accounted for very small fraction of the total organic carbon, ranging from 2.21 to 12.95, with an average ratio of 5.92.

3.2.5. (vi) Complex organic matter (COM):

Complex organic matter or COM ranged between 347.7 μg/g at M1 in September to 85718 μg/g at Z1 in October and it represented the largest pool for organic carbon (94.08 % on average).

3.2.5. (vii) Nitrogen of the protein (N-P):

N-protein values varied from 0.019 % at site Z1 in December to 5.728% at site Z3 in October. It accounted for 0.099, 0.549, 0.526, 0.218, 0.231 and 0.187 % on an average, of the total organic nitrogen (N-Protein:TON) at sites A, M1, M2, Z1, Z2 and Z3 respectively. It ranged from 0.008 % at Z1 in December to 1.24% at M2 in May.

3.2.5. (viii) Protein : Carbohydrate ratio (P-C):

Carbohydrate concentrations always exceeded that of protein and this ratio ranged from 0.14 at Z1 in December to 13.91 in February also at the same site.

3.3 DISCUSSION

Hydrographical properties of the estuarine waters of Goa have been studied fairly extensively in the past and there is a great deal of information available on seasonal changes in temperature, salinity, dissolved oxygen (Rao et al., 1969; Murty and Das, 1972; Varadachari et al., 1974; Cherian et al., 1975; Verma et al., 1975; Murty et al., 1976; Anon, 1978; Verlencar, 1982). A review of these studies in the estuarine system have been presented by Qasim and Sen Gupta, 1981. However, there is no work done on the chlorophyll and biochemistry of the sediments from these two estuaries.

The most important feature emerging from these studies is that the environmental features in the estuarine complex of Goa were found to be fairly regular and followed a regular seasonal cycle.

It seemed that the water temperature was controlled mainly by climatologically conditions, because of the shallowness of these estuaries and their proximity to land that permitted water to change temperature rapidly in response to variations in atmospheric temperature. The low temperature recorded during the monsoon period could be attributed to intrusion of cold

upwelled water. Earlier studies have reported the intrusion of cold upwelled water in Zuari and Mandovi estuary from July to October (Sankaranarayanan and Jayaraman, 1972; Verlencar, 1982).

There were no marked seasonal fluctuations in the pH. The carbon dioxide – calcium carbonate system regulates the level of hydrogen ion concentration and since the oxygen and carbon dioxide in seawater undergo constant and intensive biological and chemical transformations, the fluctuations in the pH values were very much sinusoidal.

Intense precipitation and land runoff during monsoon period brings about large changes in hydrographical features particularly salinity. Thus salinity variations were mainly attributed to the southwest monsoon rains, riverine flow and tidal mixing (Qasim and Sen Gupta, 1981; Shetye et al., 1995). In the summer months (premonsoon season) the estuary was dominated by high salinity neritic waters. This season of stability was followed by a period of transition (monsoon season) that prevailed from the time when the first arrivals of freshwater displaced the neritic waters. Then followed the recovery phase (post monsoon season) when there was a reduction in fresh water discharge and the neritic component took it's place by intruding into the estuary to a large extent.

The appearance of salinity gradient during the monsoon period and it's disappearance in the following post monsoon period is a regular phenomenon observed on the west coast of India (De Souza et al., 1981; Verlencar, 1982; Nair et al., 1984). In the post monsoon period the mixing of water is due to the

formation of internal waves and other water mixing forces such as wind and tidal currents (Qasim and Sen Gupta, 1981). These forces are also responsible for the development of a longitudinal salinity gradient in the two estuaries (Anon, 1978). During the fair season (post and premonsoon) the diurnal variation in physico-chemical properties of Mandovi estuary are reported to be controlled by tidal flow (Singbal, 1973). Thus during the fair season, a strong longitudinal salinity gradient develops from mouth towards upstream.

The concentration of dissolved oxygen is influenced by biological and physico-chemical processes. The gross factors controlling it's solubility are temperature, salinity and humidity (Verlencar, 1982). Dissolved oxygen variations are also dependant on the mixing process. Decreasing salinity increases the solubility of oxygen in water, which probably appears to be the main cause for the increase in the concentration of dissolved oxygen upstream (Qasim and Sen Gupta, 1981). In the present study, lowest value of dissolved oxygen was seen at the offshore site A where salinity was the highest. High values of dissolved oxygen observed in the monsoon months were probably due to the higher oxygen solubility as a result of heavy precipitation and almost freshwater conditions of the two estuaries associated with low salinity and low temperature of the overlying water. High percentage of oxygen saturation has also been observed by others in Mandovi and Zuari (Singbal, 1976; Qasim and Sen Gupta, 1981) during the southwest monsoon. But the higher oxygen concentration in the later postmonsoon months and summer were due to the higher rate of primary production. Dehadrai and Bhargava (1972) reported oxygen concentration from

4.1 – 5.3 ml/l in Mandovi – Zuari estuaries of Goa. They also concluded that the decrease in oxygen concentration during March – April could be related to high temperature and high salinity of the water.

Sediment granulometry is important for the biological constituents of the environment in general and benthos in particular. Sediment characteristics of both the estuaries have been studied in detail earlier (Parulekar and Dwivedi, 1974; Parulekar et al., 1975; Parulekar et al., 1980; Shirodkar, 1984). Parulekar et. al. (1980) have reported sediment of three size categories in the present study area. The categories are < 0.062 mm, 0.062 – 0.125 mm and > 0.125 mm. The mean grain size of the present study falls within these categories. The median grain size can act as an important factor only if large differences occur (Coull, 1970). Mean grain size and sediment sorting distribution is a function of hydrodynamic regime. Well sorted sediments occur in high energy areas and they offer small ranges of grain sizes whereas the poorly sorted sediments occur in low energy areas. In the present study the sorting coefficient indicated poorly to well sorted sediments. In an earlier study, Parulekar et al. (1975) reported moderately to well sorted sediment in Zuari estuary. The change may be the effect of increased human activity including sand excavation and mining reject deposition round the year. Basically, variations in the longitudinal distribution of sediment reflect the characteristic feature of tidal current at the bottom level in the two estuaries.

Organic carbon in the present study was not influenced by the seasonal variation. However, spatial variation was evident (ANOVA). Sites in Zuari estuary

and Arabian sea had higher values (Tukey HSD). This is largely due to the terrigenous input and sedimentation process. In this study high organic carbon concentrations were observed at Z1 (Zuari estuary) during monsoon (85931 µg/g). High values during monsoon is attributed to terrestrial runoff (allochthonous) which is brought by heavy downpour. The results of organic carbon concentrations in Mandovi estuary are comparable to earlier studies carried out (Shirodkar and Sen Gupta, 1985; Alagarsamy, 1991; Nasnolkar et al., 1996). Shirodkar (1984) suggested that sediment organic carbon in Mandovi estuary is a contribution from the land drained sources. Low values of organic carbon is due to oxygenation (Paropkari, 1979). The seasonal variation in sediment organic carbon of the two estuaries in the present study could be attributed to the oxidation and decaying of the dead organisms in the sediment during the dry season and land drainage during the monsoon season. Fine grain sediment with high organic carbon of the present study corroborates earlier reports (Parulekar et al., 1980; Shirodkar, 1984). It is due to the fact that fine particles have increased surface area per unit weight for adsorption of organic matter. The concentration of organic carbon in marine surface sediments varies depending on the extent of supply of organic matter. The nearshore sedments usually have considerably higher organic carbon content.

Nitrogen is commonly thought to be the limiting factor of the detritus food chain (Tenore, 1988; Carey and Mayer, 1990). It's regulatory role in secondary production has long been recognised. It is probably the major regulatory nutritional factor in most detrital based systems, providing cellular structural

materials. Nitrogen is a more conservative element in cellular structure than carbon and hydrogen components of organic compounds. Amino acids which make up the protein molecules account for about one quarter of the particulate organic carbon and half of the particulate organic nitrogen in surface waters. After sinking to the sea floor, particulate amino acids can provide energy and nitrogen to benthic organisms. They are more labile than other carbon compounds and hence contribute a smaller percentage to total particulate organic carbon (Lee, 1988). Total organic nitrogen was influenced by spatial and temporal variation largely due to seasonal overlying primary productivity and terrigenous input. Total nitrogen concentrations in the Mandovi estuary were much lower than those observed in previous study (Nasnolkar et al., 1996). Such low values could be due to due to loss of nitrogen during particle sedimentation.

C:N ratio was influenced by the spatio-temporal variations. On the whole there were large variations in the elemental ratios. These C:N ratios suggest that phytoplankton accounted for an important fraction of the particulate organic matter that settled down to the sea floor. Also the high average ratio (10.13) indicates a preferential loss of nitrogen particle during sedimentation. This could confirm that nitrogen recycling from the sinking organic material is more rapid than that of carbon (Treguer et al., 1990). This also indicates that the sediment is of recent origin. Due to high fluid energy, the surface sediments are constantly disturbed leading to their limited burial (Metzler and Smock, 1990; Zavattarelli, 1986). C:N ratio is generally used to identify the source of organic matter in the sediment and it suggests the phytoplankton contribution of particulate organic

matter (POM) that settle down to the sea floor. Transk has attributed C:N ratio of more than 12 as terrigenous material whereas a ratio of 10 is indicated as indicator of marine nature of the organic matter (Sardessai, 1989). These results of the relative carbon and nitrogen content confirm the authocthonous nature of the organic matter.

Data on the distribution of organic carbon and it's constituent fractions provide useful information about the amount, nature and the source of organic matter in the sediments. The total organic matter was evaluated through the sum of it's three principal biochemical components (proteins, carbohydrates, lipids). These three main components of the organic matter do not account for the total organic fraction, yet they form a substantial portion (Gordon, 1970; Tenore, 1985; Fichez, 1991). Biochemical composition of organic matter seems to be quite different from one coastal area to another, but is usually characterised by small amounts of total lipids and also by large quantities of proteins which may exceed carbohydrate concentrations (Sargent et al., 1983; Fabiano and Danovaro, 1994). In this study, concentrations of carbohydrates exceeded that of proteins and lipids. However, since carbohydrate analysis involves acidification and partial hydrolysis of complex organic compounds and geopolymers able to react with various reagents (Cawet, 1981), carbohydrate content and the biopolymeric fraction (BPF) may have been overestimated. Also, lower values of energy-rich (lipids) and easily hydrolysable (proteins) compounds suggest their preferential utilisation by the benthic deposit feeders (Bhosle and Dhople, 1988).

In the studied sediments protein:carbohydrate (P:C) ratio was very low (on average 0.029). As proteins are more readily utilised than carbohydrates (Newell and Field, 1983) and are rapidly bound into refractory compounds, such low values would confirm the role of labile proteins as a potentially limiting element for consumer growth in the two estuaries (Tenore et al., 1984; Jumars and Wheatcroft, 1989).

The BPF is assumed to account for the labile and easily degradable fraction. High concentration of C-BPF was found at site A, having a clayey silt bottom. This was supported by the fact that highest macrofaunal density, on an average, was also found at this site. The carbon component of this fraction (C-BPF) accounts for only 6.83%, on average, of the total organic carbon. Results of the present study confirm the hypothesis put forth by Mare (1942), and corroborated by several authors (Hargrave, 1970; Yingst, 1976; Tenore and Hanson, 1980), that only 5 – 15% of sediment detritus is available at any one time as food for benthic consumers. The percentage of C-BPF reported in this area is lower than that reported by Fabiano et al. (1995) from the Mediterranean Sea.

Although the C-BPF was higher at site A (offshore, marine site), food quality was better at site M1, as seen from the high C-BPF:TOC ratio of 12.95, on an average. This suggests an increase in the proportion of the labile material quality at site M1 (shallow, estuarine site). This could be attributed to the terrestrial run-off and subsequent settling of this material at site M1 and also to the productivity of the water column.

Two-way ANOVA showed that there was significant difference in the protein, lipid, organic carbon and total nitrogen concentrations between sites. Differences in sediment texture could be a major factor for this significant difference, besides chlorophyll *a* and primary productivity (Krishna Kumari et al., 2002).

Algae are often important contributors to organic carbon and nitrogen pools (Mayer et al., 1988). Chlorophyll *a* values can be used to give an approximate estimate of the amount of living carbon contained in algae in the sediment of shallow estuarine areas. Low concentrations of chlorophyll *a* were reported in the present study (0.0433 µg/g – 1.111 µg/g wet weight). The very low contribution of C-Chl-*a* to the C-BPF (on average 5.025%), suggest that the labile organic matter is mostly of phytoplanktonic origin (Bhaskar et al., 2000; Krishna Kumari et al., 2002). This result is in accordance with those reported by Mayer et al. (1995) who presented evidence indicating that deposition of planktonic material was the major source of organic matter.

Table 3 (a): Environmental parameters for the bottom water at site A.

MONTHS	Temperature (^{0}C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	30.0	7.84	34.6	4.90
November	33.0	8.19	34.1	3.91
December	29.9	7.94	35.2	5.36
January 1998	28.0	8.15	35.0	5.50
February	28.1	7.82	35.0	4.85
March	30.0	7.86	35.0	3.42
April	28.5	7.89	35.0	5.04
May	32.0	7.78	35.5	4.80
June	26.4	7.64	34.0	4.10
July	26.3	7.65	33.0	3.90
August	26.2	7.69	34.0	4.20
September	26.1	7.65	33.0	4.20
$\bar{x}$	28.70	7.84	34.45	4.51
SD (±)	2.31	0.18	0.83	0.64

Table 3 (b): Environmental parameters for the bottom water at site M1.

MONTHS	Temperature (^{0}C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	31.5	7.99	29.0	3.99
November	30.0	8.13	30.0	3.71
December	30.1	7.87	32.0	5.36
January 1998	27.0	7.95	31.0	5.72
February	29.0	7.81	32.0	4.91
March	31.4	7.84	32.5	3.83
April	30.5	7.83	32.0	5.16
May	29.5	7.81	32.5	5.16
June	27.4	7.78	12.0	5.45
July	26.0	7.51	9.1	5.28
August	26.8	7.81	12.0	5.58
September	29.0	7.22	10.5	4.97
$\bar{x}$	29.01	7.79	24.55	4.92
SD (±)	1.83	0.23	10.15	0.69

Table 3 (c): Environmental parameters for the bottom water at site M2.

MONTHS	Temperature (^{0} C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	32.0	7.56	21.6	3.99
November	30.5	7.91	24.7	4.70
December	30.0	7.65	26.7	5.76
January 1998	27.5	7.59	31.0	5.51
February	29.4	7.33	30.0	4.31
March	32.0	7.61	30.0	3.75
April	29.5	7.66	33.0	4.80
May	32.5	7.69	32.0	4.68
June	26.9	7.80	5.5	5.57
July	26.5	7.75	1.1	4.92
August	28.8	7.62	4.5	5.71
September	29.0	7.57	3.0	5.44
$\bar{x}$	29.55	7.64	20.25	4.92
SD (±)	1.98	0.14	12.79	0.68

Table 3 (d): Environmental parameters for the bottom water at site Z1.

MONTHS	Temperature (^{0}C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	31.0	8.02	31.0	3.68
November	30.8	8.18	32.0	3.29
December	29.2	7.95	31.0	4.64
January 1998	27.0	8.10	33.0	3.24
February	28.5	7.72	33.5	4.43
March	30.5	7.69	34.0	3.48
April	31.6	7.84	34.0	4.44
May	30.0	7.85	35.5	4.44
June	26.4	7.7	32.0	4.10
July	26.3	7.76	32.5	4.10
August	26.2	7.73	33.0	4.15
September	26.1	7.74	32.0	4.09
$\bar{x}$	28.63	7.85	32.79	4.00
SD (±)	2.13	0.16	1.32	0.47

Table 3 (e): Environmental parameters for the bottom water at site Z2.

MONTHS	Temperature (^{0}C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	32.0	7.91	30.8	4.42
November	30.5	8.1	31.7	3.81
December	28.8	7.9	31.5	5.76
January 1998	27.5	8.06	32.0	3.48
February	29.8	7.80	32.0	4.25
March	31.2	7.84	32.5	3.75
April	3.0	7.86	32.0	3.96
May	31.0	7.77	33.0	3.84
June	27.0	7.83	27.5	4.58
July	27.2	7.87	20.5	4.80
August	29.0	7.79	25.0	4.08
September	26.5	7.71	28.0	3.96
$\bar{x}$	26.95	7.87	29.70	4.22
SD (±)	7.76	0.11	3.78	0.61

Table 3 (f): Environmental parameters for the bottom water at site Z3.

MONTHS	Temperature (^{0}C)	pH	Salinity (psu)	Dissolved Oxygen (ml/l)
October 1997	32.0	7.72	25.0	4.14
November	31.0	7.94	30.0	3.48
December	29.0	7.82	32.0	5.50
January 1998	26.8	7.89	32.0	5.44
February	30.4	7.59	29.0	4.19
March	32.0	7.65	33.0	3.47
April	33.0	7.66	31.0	4.44
May	31.0	7.48	33.0	4.32
June	26.2	7.67	23.0	4.21
July	27.0	7.32	7.0	4.44
August	29.5	7.88	3.0	5.85
September	27.8	7.43	17.0	5.37
$\bar{x}$	29.64	7.67	24.58	4.57
SD (±)	2.28	0.19	10.34	0.78

Table 3 (g): Sediment characteristics at site A.

MONTHS	Sand %	Silt %	Clay %	Mean grain size (Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	1.6	69.7	28.7	6.0	0.73	Clayey silt	-
November	1.5	69.5	29.0	5.9	0.72	Clayey silt	-
December	1.4	69.3	29.3	6.1	0.74	Clayey silt	-
January 1998	1.7	68.9	29.4	6.0	0.73	Clayey silt	-
February	1.8	67.5	30.7	6.2	0.72	Clayey silt	-
March	1.9	68.5	29.6	6.0	0.73	Clayey silt	-
April	1.7	68.4	29.9	6.2	0.70	Clayey silt	-
May	1.8	68.3	29.9	6.1	0.71	Clayey silt	-
June	16.8	60.0	23.2	6.0	0.73	Clayey silt	-
July	15.9	61.0	23.1	5.9	0.74	Clayey silt	-
August	16.5	62.4	21.1	6.1	0.72	Clayey silt	-
September	17.1	60.8	22.1	5.7	0.73	Clayey silt	-
$\bar{x}$	6.64	66.2	27.2	6.0	0.72		
SD (±)	7.34	3.87	3.60	0.14	0.01		

Table 3 (h): Sediment characteristics at site M1.

MONTHS	Sand %	Silt %	Clay %	Mean grain size Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	89.4	6.5	4.1	2.63	1.0	Sandy	Fine sand
November	90.6	7.9	1.5	2.60	0.9	Sandy	Fine sand
December	88.3	4.8	6.9	2.64	1.1	Sandy	Fine sand
January 1998	87.1	5.5	7.4	2.62	1.0	Sandy	Fine sand
February	80.56	8.75	10.69	3.27	1.44	Sandy	Very fine sand
March	81.23	7.62	11.15	3.28	1.43	Sandy	Very fine sand
April	82.69	6.38	10.93	3.25	1.45	Sandy	Very fine sand
May	79.54	5.19	15.27	3.26	1.44	Sandy	Very fine sand
June	98.8	1.1	0.1	1.5	0.9	Sandy	Medium sand
July	99.2	0.6	0.2	1.4	1.0	Sandy	Medium sand
August	98.6	1.02	0.38	1.6	1.1	Sandy	Medium sand
September	98.7	0.98	0.32	1.5	1.0	Sandy	Medium sand
$\bar{x}$	89.56	4.69	5.74	2.46	1.14		
SD (±)	7.68	3.00	5.36	0.76	0.22		

Table 3 (i) : Sediment characteristics at site M2.

MONTHS	Sand %	Silt %	Clay %	Mean grain size (Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	97.2	1.5	1.3	2.37	0.39	Sandy	Fine sand
November	96.8	2.0	5.2	2.40	0.38	Sandy	Fine sand
December	97.3	2.1	0.6	2.36	0.39	Sandy	Fine sand
January 1998	97.5	1.6	0.9	2.38	0.37	Sandy	Fine sand
February	96.09	3.0	0.91	2.2	0.68	Sandy	Fine sand
March	96.53	2.9	0.57	2.1	0.69	Sandy	Fine sand
April	94.25	3.56	2.19	2.3	0.67	Sandy	Fine sand
May	97.12	1.4	1.48	2.2	0.68	Sandy	Fine sand
June	98.4	1.0	0.6	1.77	0.59	Sandy	Medium sand
July	97.6	0.98	1.42	1.75	0.60	Sandy	Medium sand
August	98.2	0.95	0.85	1.76	0.59	Sandy	Medium sand
September	98.0	1.1	0.9	1.77	0.58	Sandy	Medium sand
$\bar{x}$	97.08	1.84	1.41	2.11	0.55		
SD (±)	1.11	0.88	1.28	0.27	0.13		

Table 3 (j): Sediment characteristics at site Z1.

MONTHS	Sand %	Silt %	Clay %	Mean grain size (Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	76.8	4.0	19.2	4.03	1.11	Sandy	Very fine sand
November	75.9	3.6	20.5	4.01	1.12	Sandy	Very fine sand
December	77.8	5.1	17.1	4.02	1.10	Sandy	Very fine sand
January 1998	76.4	4.7	18.9	4.03	1.11	Sandy	Very fine sand
February	41.85	20.95	37.2	5.1	1.45	Sand-silt-clay	Very fine sand
March	40.96	19.56	39.48	5.0	1.46	Sand-silt-clay	Very fine sand
April	41.36	20.84	37.8	5.2	1.44	Sand-silt-clay	Very fine sand
May	41.0	20.0	39.0	5.1	1.45	Sand-silt-clay	Very fine sand
June	84.8	10.0	5.2	3.5	0.88	Silty sand	Very fine sand
July	85.3	11.2	3.5	3.4	0.87	Silty sand	Very fine sand
August	82.6	8.7	8.7	3.5	0.88	Silty sand	Very fine sand
September	83.7	9.3	7.0	3.3	0.89	Silty sand	Very fine sand
$\bar{x}$	67.37	11.49	21.13	4.18	1.14		
SD (±)	19.53	6.97	13.93	0.72	0.24		

Table 3 (k): Sediment characteristics at site Z2.

MONTHS	Sand %	Silt %	Clay %	Mean grain size (Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	88.3	8.0	3.7	3.0	0.78	Sandy	Fine sand
November	89.3	9.5	1.2	2.9	0.79	Sandy	Fine sand
December	88.1	8.6	3.3	3.1	0.77	Sandy	Fine sand
January 1998	87.3	7.1	5.6	3.0	0.78	Sandy	Fine sand
February	60.8	17.87	21.33	4.23	1.77	Silty sand	Very fine sand
March	61.2	18.64	20.16	4.22	1.76	Silty sand	Very fine sand
April	62.3	19.23	18.47	4.24	1.77	Silty sand	Very fine sand
May	59.8	16.25	23.95	4.23	1.78	Silty sand	Very fine sand
June	90.8	8.0	1.2	3.0	0.78	Silty sand	Fine sand
July	90.3	8.5	1.2	2.9	0.79	Silty sand	Fine sand
August	90.5	8.4	1.1	3.0	0.77	Silty sand	Fine sand
September	91.0	8.0	1.0	3.1	0.78	Silty sand	Fine sand
$\bar{x}$	79.97	11.50	8.51	3.41	1.11		
SD (±)	14.05	4.87	9.38	0.60	0.48		

Table 3 (I): Sediment characteristics at site Z3.

MONTHS	Sand %	Silt %	Clay %	Mean grain size (Ø)	Sorting coefficient (Ø)	Sediment texture	Type of sand
October 1997	32.6	34.2	33.2	5.4	1.53	Sand silt clay	-
November	31.5	33.5	35.0	5.3	1.54	Sand silt clay	-
December	33.8	35.24	30.96	5.5	1.55	Sand silt clay	-
January 1998	32.5	34.7	32.8	5.4	1.53	Sand silt clay	-
February	35.9	27.6	36.5	5.2	1.87	Sandy silt	-
March	34.8	26.4	38.8	5.1	1.88	Sandy silt	-
April	35.6	27.9	36.5	5.2	1.86	Sandy silt	-
May	34.9	26.8	38.3	5.3	1.87	Sandy silt	-
June	18.5	51.5	30.0	5.4	1.53	Clayey silt	-
July	18.3	51.3	30.4	5.3	1.52	Clayey silt	-
August	18.2	51.4	30.4	5.5	1.54	Clayey silt	-
September	18.0	51.0	31.0	5.4	1.53	Clayey silt	-
$\bar{x}$	29.69	37.62	33.65	5.33	1.64		
SD (±)	7.83	10.57	3.24	0.12	0.16		

Table 3 (m): Chemical composition of the sediments at site A .

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	23811	2553	11.3002
November	18971	1649	11.5045
December	25747	2536	10.1526
January 1998	18687	2093	8.9283
February	21177	2009	10.5410
March	24603	2512	9.7941
April	20597	2202	9.3537
May	23012	2304	9.9878
June	–	–	–
July	–	–	–
August	–	–	–
September	17801	1954	9.1100
$\bar{x}$	21600.67	2201.33	10.07
SD (±)	2830.91	307.75	0.90

Table 3 (n): Chemical composition of the sediments at site M1 .

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	504	609	11.9193
November	8771	571	15.3607
December	11013	604	18.2334
January 1998	1846	420	14.4212
February	5761	473	12.1797
March	7441	298	2.8859
April	10704	852	12.5633
May	11528	917	12.5714
June	885	192	4.6093
July	638	527	10.1859
August	559	104	5.3750
September	485	424	5.1052
$\bar{x}$	5011.25	499.25	10.45
SD (±)	4654.35	239.62	4.86

Table 3 (o): Chemical composition of the sediments at site M2.

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	3930	378	6.4089
November	4927	592	8.3226
December	1279	230	5.5608
January 1998	1680	311	5.4019
February	1231	162	7.5987
March	5476	524	10.4503
April	1256	284	12.1591
May	2434	168	14.4880
June	11981	900	13.3122
July	2146	352	6.0965
August	1249	127	9.8346
September	8635	711	12.1448
$\bar{x}$	3852.00	394.91	311.33
SD (±)	3429.82	240.58	3.19

Table 3 (p): Chemical composition of the sediments at site Z1 .

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	85931	487	8.6246
November	1352	216	6.2592
December	1591	236	6.7415
January 1998	42726	323	7.2600
February	65196	2005	9.3700
March	26632	2259	11.7892
April	7685	1054	7.2912
May	6218	1008	6.1686
June	–	–	–
July	–	–	–
August	–	–	–
September	1132	140	8.0857
$\bar{x}$	26495.89	858.66	7.95
SD (±)	31532.73	796.69	1.78

Table 3 (q): Chemical composition of the sediments at site Z2.

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	4460	723	16.0429
November	24613	1658	14.8449
December	3729	534	6.9831
January 1998	20895	1601	13.0512
February	5807	419	13.8591
March	10891	916	11.8897
April	10124	941	10.7587
May	10267	985	10.4233
June	11935	2614	13.7817
July	41453	2893	14.3287
August	27845	2515	11.0715
September	25849	2404	10.7524
$\bar{x}$	16489.0	1516.91	12.31
SD (±)	11591.94	888.55	2.48

Table 3 (r): Chemical composition of the sediments at site Z3.

MONTHS	TOC µg/g	TON µg/g	C/N
October 1997	30822	2435	13.1141
November	23028	1565	14.7143
December	27186	1967	13.8210
January 1998	36050	2620	13.7595
February	20144	1704	11.8215
March	26185	2002	13.0794
April	13737	1537	8.9375
May	21509	2513	8.5590
June	11302	2310	13.1418
July	17230	1052	16.3783
August	27090	2499	10.8403
September	13782	1070	12.8803
$\bar{x}$	22338.75	1939.5	12.58
SD (±)	7519.22	555.45	2.25

Table 3 (s): Microphytobenthos in the sediments at site A

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	0.542	16.26	0.125	3.75
November	0.0921	2.76	0.014	1.025
December	0.271	8.13	0.031	2.45
January 1998	1.289	38.67	0.206	12.10
February	0.888	26.64	0.125	7.28
March	0.66	19.8	0.080	3.127
April	0.501	15.03	0.072	1.318
May	0.708	21.24	0.092	1.80
June	–	–	–	–
July	–	–	–	–
August	–	–	–	–
September	0.239	7.17	0.040	0.883
$\bar{x}$	0.57	17.3	0.08	3.74
SD (±)	0.36	11.01	0.05	3.70

Table 3 (t): Microphytobenthos in the sediments at site M1

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	1.517	45.51	9.029	33.06
November	1.68	50.4	0.574	19.93
December	1.626	48.78	0.442	14.035
January 1998	1.547	46.41	2.514	27.73
February	0.802	24.06	0.417	6.24
March	0.466	13.98	0.1878	10.94
April	2.115	63.45	0.592	14.519
May	2.868	86.04	0.746	15.47
June	0.717	21.51	2.430	9.975
July	0.2056	6.168	0.96	2.422
August	0.638	19.14	3.42	13.55
September	1.326	39.78	8.20	28.97
$\bar{x}$	1.29	38.76	2.45	16.40
SD (±)	0.76	22.88	3.05	9.36

Table 3 (u): Microphytobenthos in the sediments at site M2

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	1.084	54.12	1.377	38.19
November	1.68	50.4	1.022	33.72
December	3.794	113.82	8.899	56.24
January 1998	3.615	108.45	6.455	57.34
February	0.997	29.91	2.429	15.58
March	2.276	68.28	1.246	31.35
April	2.688	80.64	6.420	46.88
May	3.262	97.86	4.020	32.51
June	0.645	19.35	0.1615	4.73
July	0.1418	4.254	0.198	1.053
August	0.248	7.44	0.5956	4.096
September	0.39	11.7	0.135	3.04
$\bar{x}$	1.73	53.85	2.74	27.06
SD (±)	1.34	40.00	2.99	20.86

Table 3 (v): Microphytobenthos in the sediments at site Z1

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	1.192	35.76	0.0416	16.79
November	1.192	35.76	2.644	31.809
December	1.517	45.51	2.860	34.41
January 1998	0.888	26.64	0.0623	18.28
February	0.552	16.56	0.0254	15.82
March	0.487	14.61	0.0548	1.689
April	0.86	25.8	0.335	3.712
May	0.537	16.11	0.259	1.93
June	–	–	–	–
July	–	–	–	–
August	–	–	–	–
September	0.179	5.37	0.474	4.138
$\bar{x}$	0.82	24.68	0.75	14.28
SD (±)	0.42	12.73	1.14	12.56

Table 3 (w): Microphytobenthos in the sediments at site Z2

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	2.601	78.03	1.749	20.57
November	1.463	43.89	0.178	24.30
December	3.685	110.55	2.964	82.07
January 1998	2.384	71.52	0.342	21.78
February	1.181	35.43	0.610	17.32
March	1.95	58.5	0.537	16.90
April	2.868	86.04	0.849	27.18
May	2.86	85.8	0.835	25.24
June	0.932	27.96	0.234	12.67
July	0.354	10.62	0.0256	2.47
August	0.968	29.04	0.104	6.01
September	2.904	87.12	0.337	14.90
$\bar{x}$	2.01	60.37	0.73	23.31
SD (±)	1.02	30.71	0.84	20.16

Table 3 (x): Microphytobenthos in the sediments at site Z3

MONTHS	Chl-a µg/g	C-Chl a µg/g	C-Chl a:TOC %	C-Chl a:C-BPF %
October 1997	1.626	48.78	0.158	7.499
November	1.68	50.4	0.218	23.93
December	2.059	61.77	0.227	18.51
January 1998	2.157	64.71	0.179	11.939
February	0.899	26.97	0.133	5.46
March	1.528	45.84	0.175	9.217
April	2.509	75.27	0.547	16.89
May	2.33	69.9	0.324	14.39
June	1.434	43.02	0.380	16.22
July	0.7887	23.661	0.137	4.71
August	3.37	101.1	0.373	24.16
September	5.378	161.34	1.170	29.93
$\bar{x}$	2.14	64.39	0.33	15.23
SD (±)	1.23	37.17	0.29	7.97

Table 3 (y): Biochemistry of the sediments at site A.

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	16.50	622.0	110.0	433.37	1.79	2.414	0.083	1.84	23377.6
November	15.50	491.4	120.0	269.18	1.41	2.480	0.150	3.15	18701.8
December	10.70	637.7	102.0	331.72	1.28	1.712	0.067	1.67	25415.2
January 1998	11.30	583.6	115.0	319.48	1.70	1.808	0.086	1.93	18367.5
February	10.10	2421.7	53.10	365.92	1.72	1.616	0.080	1.24	20811.0
March	16.20	1320.0	59.4	633.17	2.57	2.592	0.103	1.22	23969.8
April	12.90	2725.0	61.80	1139.58	5.53	2.064	0.093	0.47	19457.4
May	19.10	2808.6	64.12	1177.68	5.11	3.056	0.130	0.68	21834.3
June	–	–	–	–	–	–	–	–	–
July	–	–	–	–	–	–	–	–	–
August	–	–	–	–	–	–	–	–	–
September	12.60	609.9	40.90	811.60	3.40	2.640	0.103	0.94	16989.4
$\bar{X}$	13.87	1357.7	80.70	609.07	2.72	2.26	0.099	1.46	20991.5
SD (±)	3.07	1004.7	30.54	355.78	1.61	0.48	0.02	0.80	2858.6

Table 3 (z): Biochemistry of the sediments at site M1.

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	12.2	149.4	107.60	137.64	27.30	0.836	0.960	3.50	366.3
November	13.10	399.0	124.00	252.82	2.88	2.096	0.367	3.28	8518.1
December	30.50	590.0	138.00	347.55	3.15	4.880	0.807	5.16	10665.4
January 1998	24.9	185.2	131.00	167.31	9.06	0.499	0.614	1.68	1678.6
February	17.60	736.3	117.20	385.18	6.68	2.816	0.590	2.39	5375.8
March	22.6	905.0	136.00	127.71	14.85	0.441	0.140	3.54	7313.2
April	21.70	854.0	121.10	437.00	4.08	3.472	0.400	2.54	10267.0
May	25.80	1142.7	123.10	555.89	4.82	4.128	0.450	2.25	10972.1
June	7.46	315.6	126.00	215.62	24.36	0.384	0.200	0.76	669.3
July	9.56	405.5	125.40	254.66	4.74	1.529	0.290	2.35	383.3
August	5.17	141.5	117.20	141.17	25.25	0.827	0.790	3.65	417.8
September	5.83	274.5	138.00	137.30	28.30	0.932	0.980	6.16	347.7
$\overline{X}$	16.36	508.22	125.38	263.32	12.95	1.90	0.54	3.10	4747.95
SD (±)	8.63	333.03	9.23	139.60	10.40	1.56	0.28	1.47	4550.95

Table 3 (a1): Biochemistry of the sediments at site M2

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	7.21	146.3	113.80	141.71	3.60	1.153	0.305	4.92	3788.2
November	5.41	143.0	128.0	149.45	3.03	0.865	0.146	3.78	4777.5
December	9.32	260.0	134.00	202.37	15.82	1.491	0.648	3.58	1076.6
January 1998	5.53	242.0	128.0	189.11	11.25	0.884	0.284	2.28	1490.8
February	5.65	256.8	87.7	191.87	15.58	0.904	0.558	2.20	1039.1
March	10.40	382.4	85.30	217.77	3.97	1.664	0.317	2.71	5258.2
April	6.12	272.7	85.59	171.99	13.69	0.979	0.815	2.24	1084.0
May	13.11	581.2	88.69	300.99	12.36	2.097	1.240	2.25	2133.0
June	17.90	795.9	116.30	408.54	3.40	2.864	0.318	2.24	11572.4
July	7.03	823.8	101.40	403.94	18.82	1.124	0.319	0.85	1742.0
August	8.36	225.0	125.00	181.60	14.53	1.337	1.050	3.71	1067.4
September	14.40	746.0	112.70	384.59	4.45	2.304	0.320	1.92	8250.4
$\bar{X}$	9.20	406.2	108.87	245.32	10.04	1.47	0.52	2.72	3606.63
SD (±)	4.03	257.7	18.40	101.03	5.91	0.64	0.34	1.08	3372.07

Table 3 (a2): Biochemistry of the sediments at site Z1.

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	6.79	126.4	108.40	212.92	3.01	2.304	0.281	5.37	85718.0
November	5.30	148.3	129.90	112.42	8.31	0.172	0.079	2.06	1239.5
December	4.90	137.4	153.00	132.22	8.31	0.019	0.008	0.14	1458.7
January 1998	8.90	128.0	128.80	145.72	0.34	0.424	0.440	6.95	42580.2
February	6.19	1015.5	119.70	104.62	0.16	0.990	0.290	13.91	65091.3
March	14.10	1904.5	137.00	864.61	3.24	2.256	0.099	0.74	25767.3
April	12.80	1498.0	127.90	695.00	9.04	2.048	0.190	0.85	6990.0
May	17.00	1847.2	124.20	834.15	13.41	2.720	0.360	5.16	5383.8
June	–	–	–	–	–	–	–	–	–
July	–	–	–	–	–	–	–	–	–
August	–	–	–	–	–	–	–	–	–
September	9.36	228.2	124.00	129.77	0.15	1.086	0.220	5.37	1002.2
$\bar{X}$	9.48	781.5	128.1	359.04	5.107	1.33	0.21	4.50	26136.7
SD (±)	4.26	786.06	12.21	333.65	4.80	1.01	0.14	4.31	31614.5

Table 3 (a3): Biochemistry of the sediments at site Z2.

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	18.20	1184.0	101.8	379.17	2.98	3.280	0.410	3.04	4080.8
November	24.80	207.5	112.00	180.55	0.73	3.968	0.230	11.95	24432.4
December	17.8	193.2	77.39	134.69	3.61	1.056	0.190	3.41	3594.3
January 1998	15.00	616.2	106.40	328.31	1.57	2.400	0.140	2.43	20566.6
February	22.05	304.5	111.50	204.53	3.52	1.529	0.360	3.13	5602.4
March	15.50	614.6	132.40	346.11	3.17	2.480	0.270	2.52	10544.8
April	14.70	557.4	123.40	316.54	3.12	2.352	0.240	2.63	9807.4
May	24.10	621.0	113.80	339.87	3.31	3.856	0.390	3.88	9927.1
June	10.88	322.8	123.00	220.55	1.84	1.740	0.200	3.37	11714.4
July	26.90	2486.5	80.50	429.19	2.43	4.304	0.140	1.08	41023.8
August	12.20	1085.4	109.7	482.45	1.73	1.952	0.077	1.12	27362.5
September	19.72	1239.0	113.30	584.57	2.26	3.155	0.130	1.59	25264.4
$\overline{X}$	18.48	786.00	108.76	328.87	2.52	2.67	0.23	3.34	16160.0
SD (±)	5.13	647.73	16.17	131.09	0.90	1.03	0.10	2.85	11521.5

Table 3 (a4): Biochemistry of the sediments at site Z3.

MONTHS	P µg/g	C µg/g	L µg/g	C-BPF Cµg/g	C-BPF:TOC %	N-P %	N-P:TON	P:C	COM
October 1997	33.30	1328.7	98.45	650.48	2.48	5.728	0.280	2.38	30171.5
November	24.70	1201.3	90.39	210.54	0.91	3.952	0.250	7.30	22817.4
December	21.90	805.0	115.00	333.63	1.22	3.504	0.170	3.61	26852.3
January 1998	19.70	1316.0	84.70	541.98	1.50	3.152	0.120	1.49	35508.0
February	12.20	1140.3	107.6	493.14	2.44	1.952	0.114	1.06	19650.8
March	16.50	986.8	69.0	497.30	1.89	2.640	0.130	1.67	25687.7
April	18.70	922.4	96.32	445.55	3.24	2.992	0.190	2.02	13291.4
May	26.10	1029.7	87.00	485.57	2.25	4.176	0.160	2.53	21023.4
June	11.96	423.0	128.80	265.22	2.34	1.913	0.222	2.82	11036.7
July	17.68	1096.5	77.68	501.63	2.91	2.828	0.260	1.61	16728.3
August	15.27	993.2	98.74	418.40	1.54	2.443	0.097	1.53	26671.6
September	17.80	1123.6	115.50	539.01	3.91	2.848	0.260	1.58	13242.9
$\bar{X}$	19.65	1030.5	97.43	448.53	2.21	3.17	0.18	2.46	21890.1
SD (±)	6.10	244.87	17.17	124.54	0.86	1.06	0.06	1.67	7481.5

- Not sampled due to bad weather

Table 3 (a5): Seasonal environmental parameters - Mean and Standard Deviation at different sites. * P< 0.05; ** P< 0.01; *** P< 0.001; **** P< 0.0001. (ns) - Not significant. Superscripts refer to Tukey's HSD test, where the values with same letter in each column are not different at the 0.05 significance level. (1- Post -monsoon, 2- Pre-monsoon, 3- Monsoon)

		SITES							
		M1		M2		Z2		Z3	
Variables	Season	Mean ($\bar{x}$)	SD ($\pm$)	Mean ($\bar{x}$)	SD ($\pm$)	Mean ($\bar{x}$)	SD ($\pm$)	Mean ($\bar{x}$)	SD ($\pm$)
Temperature	1	26.91(ns)	1.04	28.18(ns)	1.12	29.51(ns)	1.09	28.84(ns)	2.30
	2	26.91	1.07	28.18	1.12	28.84	1.09	30.9	1.14
	3	26.91	1.07	29.51	1.12	30.19	1.17	30.9	1.41
Salinity	1	***30.9^{b}	1.07	***26.3^{c}	1.12	****31.62^{b}	1.02	****28.84^{b}	3.30
	2	28.18^{b}	1.47	22.9^{b}	1.99	30.9^{b}	1.04	29.51^{b}	1.91
	3	12.3^{a}	1.28	3.38^{a}	2.34	24.54^{a}	1.17	13.18^{a}	9.14
DO	1	*4.07^{a}	1.05	5.75(ns)	1.90	**3.63^{a}	1.17	4.46(ns)	1.30
	2	4.07^{a}	1.23	4.36	1.12	4.07^{b}	1.12	4.07	0.43
	3	4.67^{b}	1.04	5.01	1.14	4.16^{b}	1.09	4.46	0.77
pH	1	**7.58^{b}	1.04	7.24(ns)	1.07	7.58(ns)	1.07	***7.41^{c}	0.09
	2	6.76^{a}	1.05	6.45	1.14	6.91	1.12	6.45^{a}	0.83
	3	6.6^{a}	1.04	6.76	1.09	7.24	1.04	7.07^{b}	0.28
Chlorophyll a	1	**1.49^{a}	1.23	1.25(ns)	2.34	*2.73^{b}	1.51	1.07	0.26
	2	1.48^{a}	1.81	1.99	1.73	2.04^{b}	1.58	1.9	0.74
	3	2.08^{b}	4.57	1.99	2.29	1.17^{a}	2.08	2.13	2.06
Mn. Gr.Sz.	1	***2.68^{b}	0.2	****2.39^{c}	0.10	****3.05^{a}	0.39	*5.31^{b}	0.08
	2	3.01^{c}	0.51	2.04^{b}	0.23	4.0^{b}	0.33	5.20^{b}	0.08
	3	1.56^{a}	0.27	1.79^{a}	0.38	3.23^{a}	0.72	4.67^{a}	0.08
Sed.Sort.	1	***1.04^{b}	0.16	****0.42^{a}	0.09	***0.82^{a}	0.29	****1.57^{b}	0.009
	2	1.29^{c}	0.16	0.67^{c}	0.04	1.66^{b}	0.28	1.81^{c}	0.008
	3	0.93^{a}	0.19	0.59^{b}	0.06	0.8^{a}	0.23	1.32^{a}	0.008
TOC	1	*3388.44^{b}	3.54	2238.72(ns)	1.51	**7943.28^{a}	3.54	18197(ns)	0.49
	2	4168.69^{c}	3.31	2511.88	2.18	9332.54^{b}	1.25	18620.87	0.40
	3	1202.26^{a}	2.81	3630.78	2.45	21379.62^{c}	1.90	19054.6	0.99
TON	1	**137.75^{a}	2.44	338.84(ns)	1.47	****912.01^{b}	1.69	***933.1^{b}	1.81
	2	337.75^{b}	2.19	263.02	1.81	812.83^{a}	1.34	496.8^{a}	1.22
	3	537.75^{c}	1.94	407.38	2.23	2089.29^{c}	1.51	1954.3^{c}	1.47
Prtoteins	1	**346.73^{c}	2.33	***6.3^{a}	1.28	26.91(ns)	1.62	22.38	1.58
	2	537.03^{b}	1.69	8.95^{b}	1.47	14.79	1.34	17.78	1.29

	3	199.52[a]	1.94	10.96[c]	1.44	17.37	1.47	16.59	1.56
Carbohydrates	1	*301.99[b]	1.81	****199.52[a]	1.23	****389.04[a]	1.90	758.57(ns)	1.81
	2	457.08[c]	2.88	363.07[b]	1.47	512.86b	1.31	954.99	1.40
	3	204.17[a]	1.77	588.84[c]	1.73	1122.01[c]	1.86	977.23	1.90
Lipids (ns)	1	138.03(ns)	1.17	134.89(ns)	1.02	77.62(ns)	1.86	58.88(ns)	1.90
	2	144.54	1.17	104.71	1.23	125.89	1.07	97.72	1.11
	3	131.82	1.12	112.2	1.81	69.18	2.45	66.06	2.33
C-BPF	1	**223.87[b]	1.47	****169.82[a]	1.14	***218.77[a]	1.51	380.18(ns)	1.66
	2	323.59[c]	1.84	234.42[b]	1.25	288.4[b]	1.23	446.68	1.40
	3	169.82[a]	1.31	316.22[c]	1.41	436.51[c]	1.90	467.73	1.89

DO – Dissolved oxygen

Mn. Gr. Sz. – Mean grain size

Sed. Sort. – Sediment sorting

TOC – Total organic carbon

TON – Total organic nitrogen

C-BPF – Carbon of the Biopolymeric fraction

Table 3 (a6): Annual mean and SD of environmental parameters at different sites.
The * after variable name refers to the significance level from ANOVA.
The superscripts refer to Tukey HSD tests, where values with the same letter in each row are not different at the 0.05 significance level.

ns –not significant; **** - P< 0.0001

	SITES							
	M 1		M2		Z2		Z3	
VARIABLES	Mean ($\bar{x}$)	SD($\pm$)	Mean($\bar{x}$)	SD($\pm$)	Mean ($\bar{x}$)	SD ($\pm$)	Mean($\bar{x}$)	SD($\pm$)
Temperature****	27.2^{a}	1.07	29.04^{b}	1.11	29.83^{b}	1.12	30.45^{b}	1.12
Salinity ****	21.97^{b}	1.64	12.77^{a}	3.11	28.82^{c}	1.16	20.1^{b}	1.97
Dissolved Oxygen ****	4.3^{b}	1.17	5.06^{c}	1.5	3.96^{a}	1.14	4.42^{b}	1.17
pH (ns)	7.02	1.12	7.3	1.11	8.2^{a}	1.1	7	1.1
Chlorophyll-*a* (ns)	1.02	2.88	0.92	7.09	1.73	1.83	1.63	2.57
Mean grain size ****	2.44^{c}	0.73	2.07^{d}	0.36	3.43^{b}	0.65	5.25^{a}	0.12
Sediment sorting ****	0.18^{b}	0.23	0.24^{a}	0.12	0.09^{b}	0.48	0.03^{c}	0.14
Total organic Carbon ****	2587.02^{a}	3.57	2759.30^{a}	2.21	11697.77^{b}	2.5	17198.08^{c}	1.71
Total organic Nitrogen ****	337.75^{a}	2.19	334.11^{a}	1.88	1174.08^{b}	1.8	2015.57^{c}	2.29
Proteins ****	8.42^{a}	2.37	8.57^{a}	1.51	15.38^{c}	1.51	18.38^{c}	1.32
Carbohydrates****	309.45^{a}	2.29	355.95^{a}	1.82	615.03^{b}	2.01	867.13^{c}	1.54
Lipids****	140.08^{c}	1.16	117.27^{b}	1.46	88.49^{a}	1.95	75.04^{a}	2.15
C-BPF****	232.48^{a}	1.68	236.1^{a}	1.43	305.28^{b}	1.71	422.47^{c}	1.36

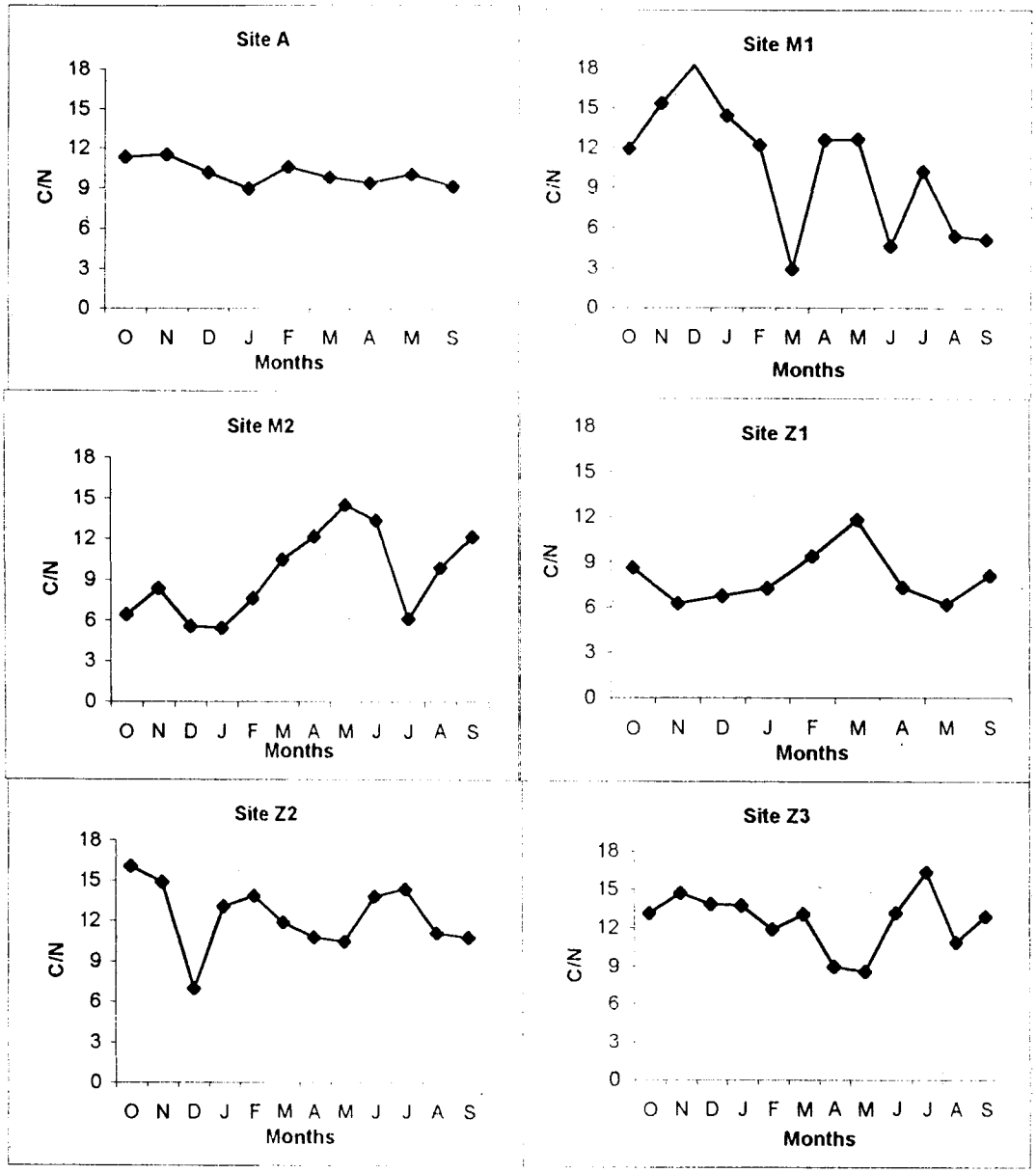


Fig 3 (a): Variations in the C/N ratio observed at different sites over a period of one year.

Fig 3 (b): Variations in the protein concentrations at different sites over a period of one year.

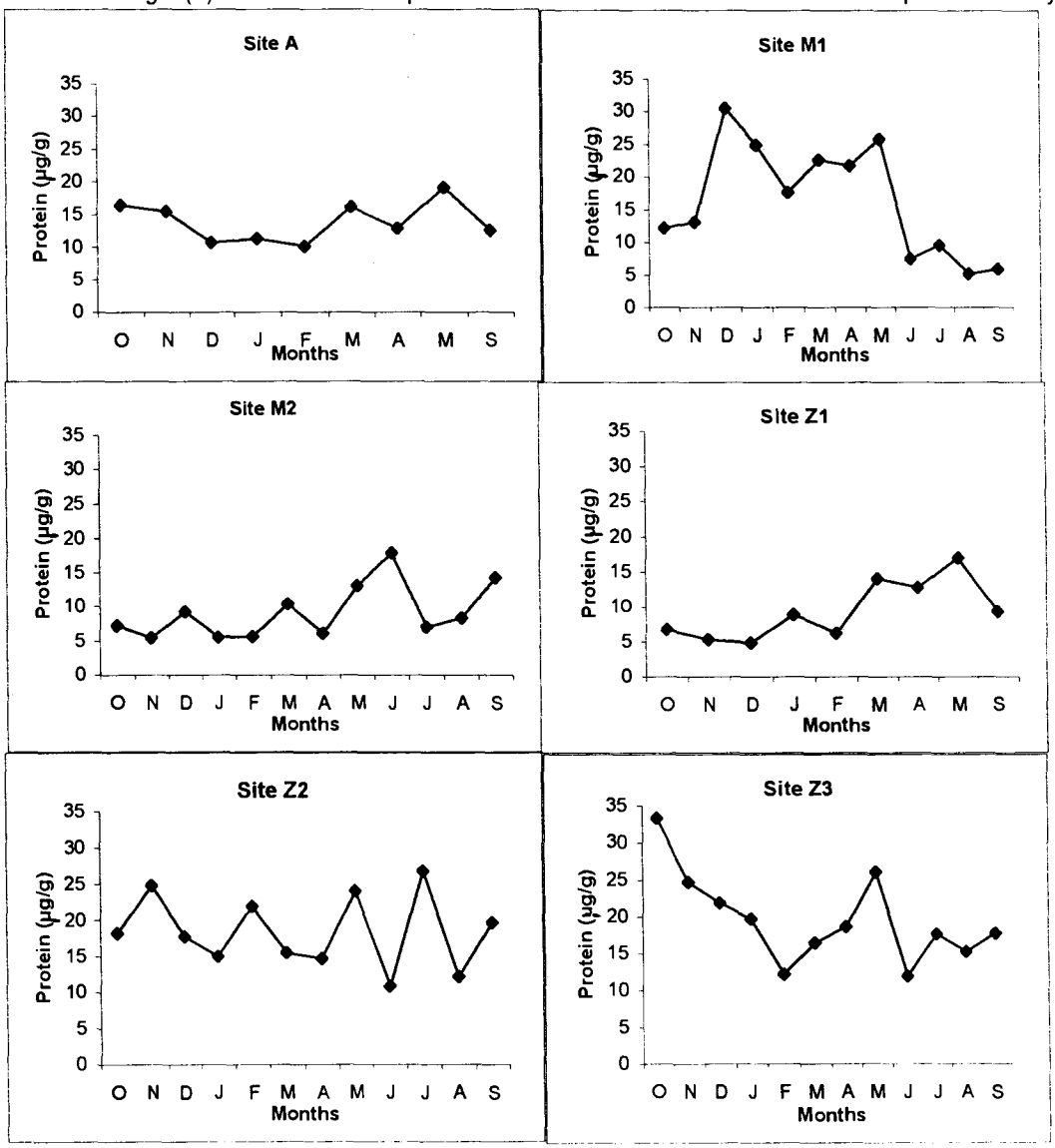
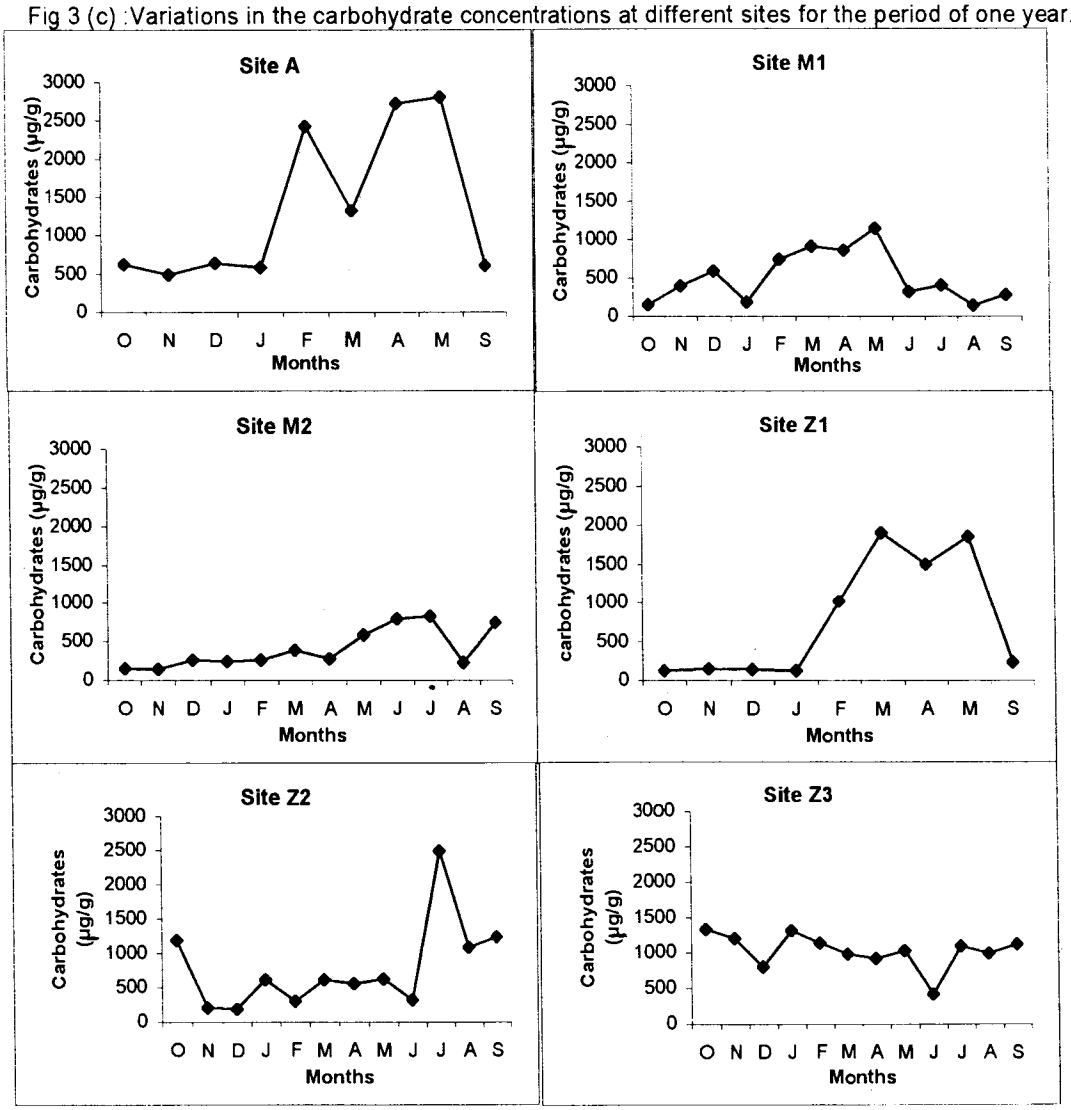


Fig 3 (c) :Variations in the carbohydrate concentrations at different sites for the period of one year.



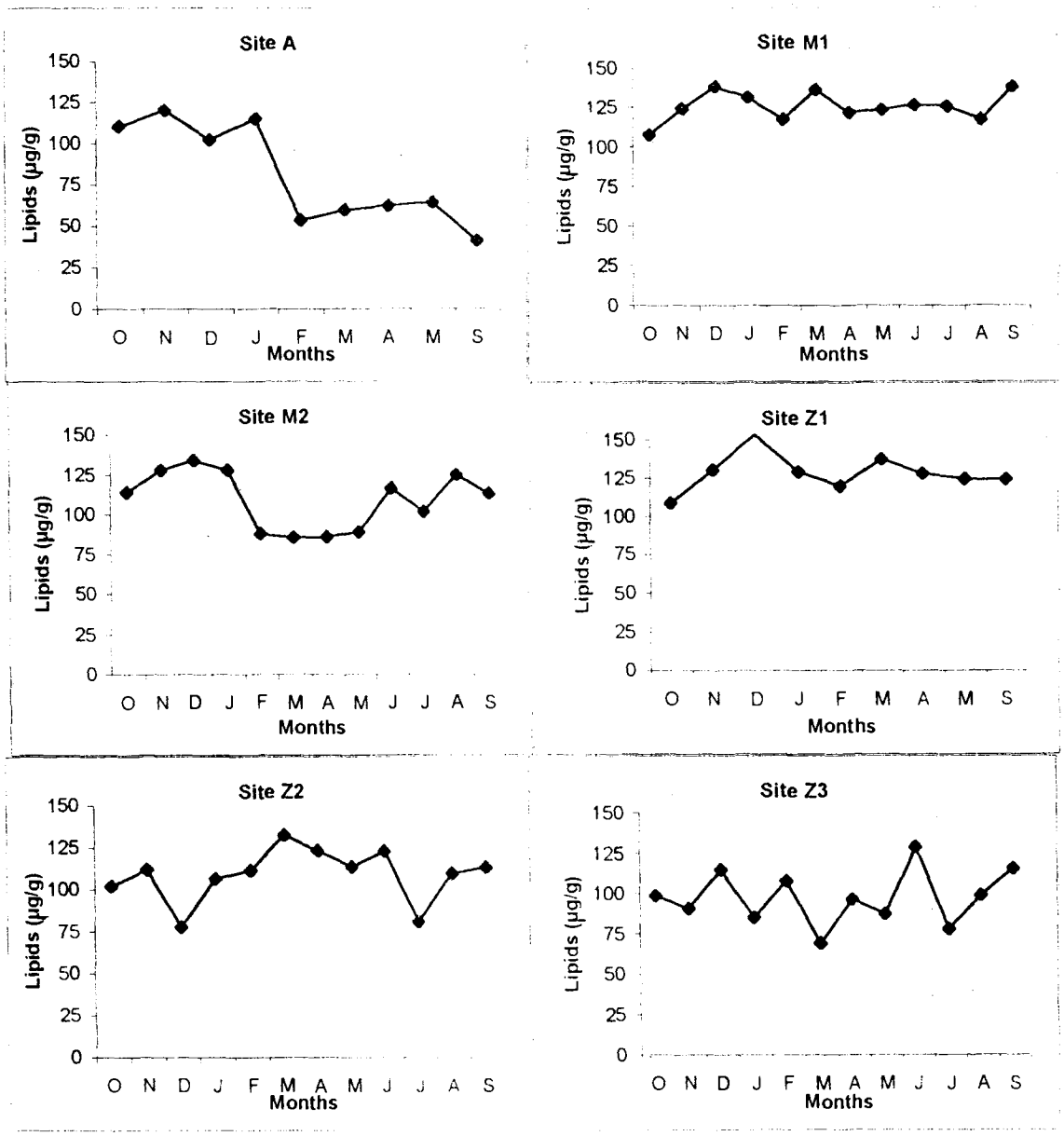


Fig 3 (d): Variations in the lipid concentrations at the study sites for a period of one year.

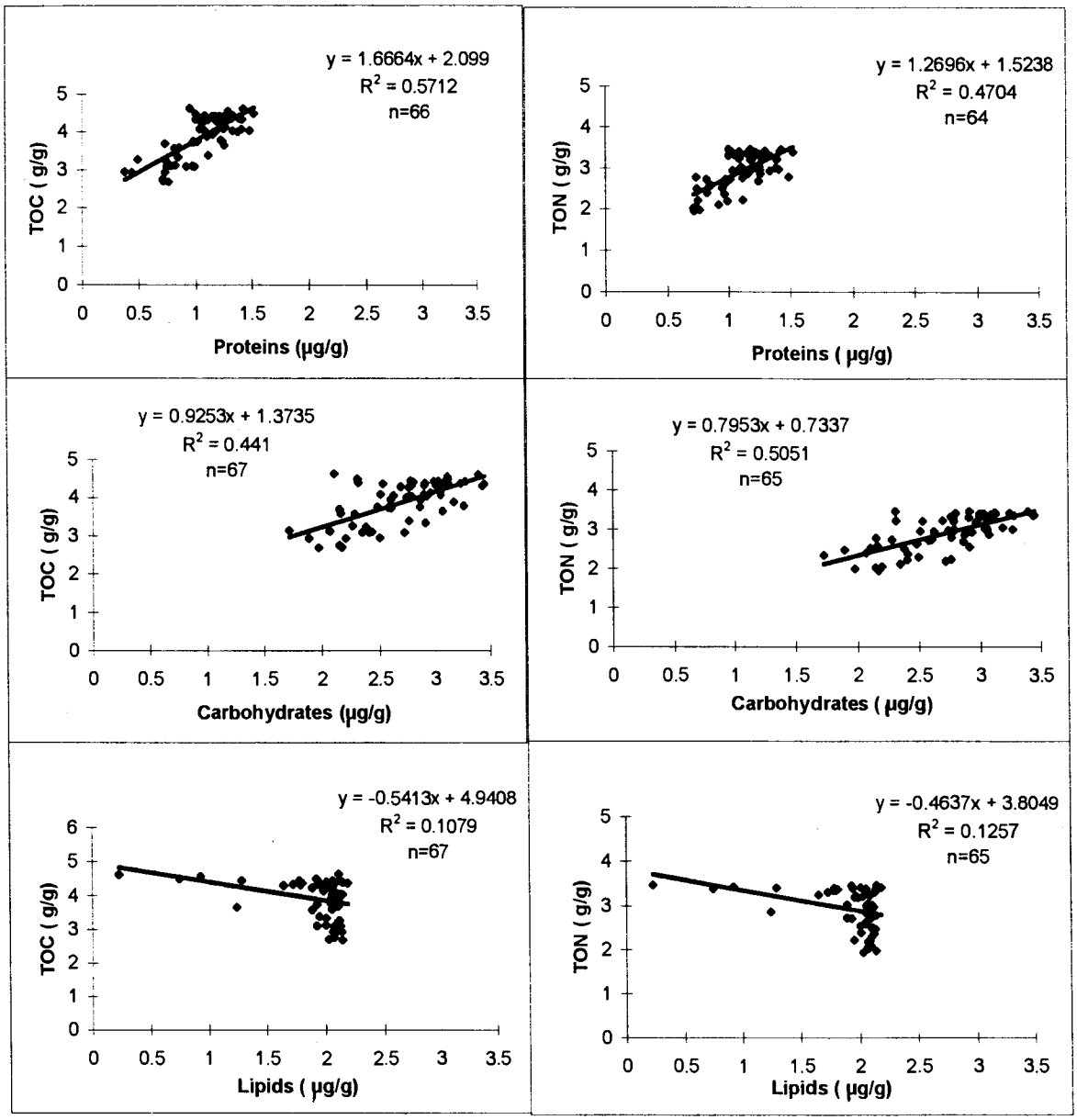


Fig 3(e): Relationship between TOC, TON and the biochemical components at different sit

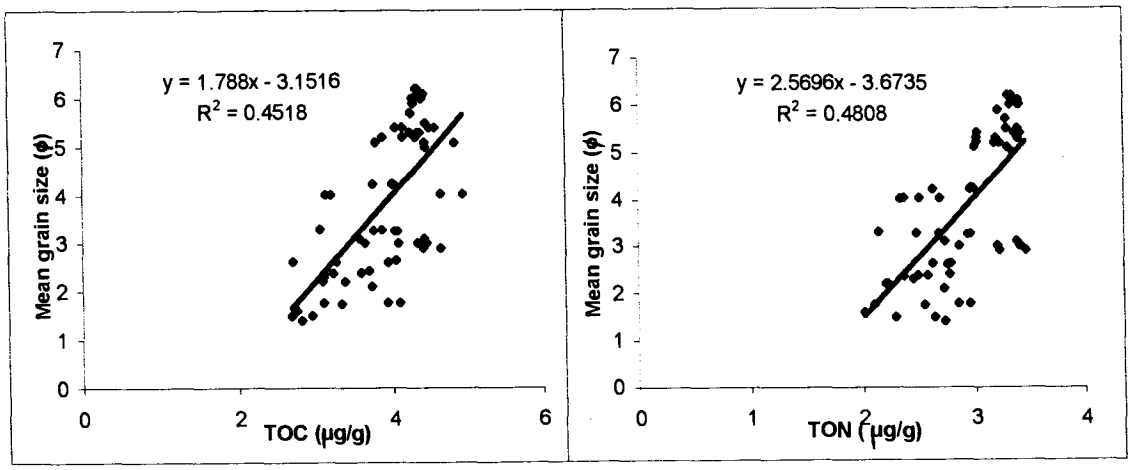


Fig. 3(f): Relationship between TOC, TON and mean grain size.

CHAPTER 4

MACROBENTHIC COMMUNITY STRUCTURE

4.1. INTRODUCTION:

The concept of '*animal community*' can be credited to Mobius. From this stems a modern definition of community which means 'a group of organisms occurring in a particular environment and separable by means of ecological surveys from other groups' (Mills, 1969). Marine benthic communities were first described by Petersen (1913) and have since been classified according to biotopes (Jones, 1950). In short a community is any assemblage of populations of living organisms in a decribed habitat.

The community is not a stable unit. The community structure changes in response to changes in natural environmental parameters (Odum, 1967; Alongi, 1990). The change in communities may be a temporal one which is called succession and which lead to a stable *climax community* or the change may be spatial along environmental gradients. Also benthic faunal community is very vulnerable to pollution of various kinds. The macrofauna community structure alters with respect to the changes in the various environmental parameters which may be due to natural causes as well as anthropogenic.

In marine biology two approaches have been followed to simplify and extract information from very complex patterns and collections of multispecies populations. The first is classification in which collections are classified on the basis of their biotic content, or species are classified on the basis of their distribution within a series of collections according to some mathematical criteria. Some examples are Field (1971) and Stephenson et al. (1970). The second approach is the analysis of 'community structure' in which the distribution of

importance (as measured by one of the number of criteria, usually abundance) among the species is of primary interest. This includes such aspects as species diversity and it's components, dominance, constancy and periodicity. Some marine examples include, McCloskey (1970). Analysis of community structure is important not only for an understanding of the magnitude of production and energy pathways, but also in evaluating environmental changes on biota. Increased human activity in coastal areas has produced deleterious effects on the marine biota (McIntyre, 1977). This has generated interest among scientists to study the marine environment in relation to human interventions and changes, including pollution. Benthic organisms largely sessile in habitat, are known to be reliable indicators of marine pollution. Knowledge about the scale and magnitude of seasonal and annual variations in benthic community structure is needed for valid estimates of population shifts, which are presumably due to human activity. Such studies of community structure further helps in the management and conservation of the environment.

Ecological succession is the orderly process of community changes which are directional and therefore predictable. It is the sequence of communities which replace one another in a given area. Species succession consists of the sequence of changes in community structure that occur after a site has been disturbed (McCook, 1994). It can be considered as a local progression of species invasion and occupancy (Paine and Levin, 1981). Rhoads and Boyer (1982) defined soft-bottom benthic succession as a significant directional change in pattern of animal-sediment interaction rather than change in species

composition. Clements' (1916) view was that succession was driven by changes in external environment. Typically, in an ecosystem, community development begins with pioneer stages which are replaced by a series of more mature communities until a relatively stable community is evolved which is in equilibrium with the local conditions.

If succession begins on an area which has not been previously occupied by a community, the process is known as *primary succession*. If community development is proceeding in an area from which a community was removed, the process is called *secondary succession*. Secondary succession is usually more rapid because some organisms, at least, are present already. Furthermore, previously occupied territory is more receptive to community development than are sterile areas.

Species succession (also called as *colonisation*) largely depends on the life history strategies and recruitment process. The pattern seems to be that if one ignores the initial microbial aspects, then the first microscopic species to colonise the sediment are the so-called *r*-selected opportunist species. Such species obtain their name from the logistic equation for population growth:

$$\frac{dN}{dt} = rN\left(\frac{K-N}{K}\right),$$

where r is the intrinsic rate of natural increase,

N is the population size,

K is the asymptotic density or carrying capacity of the environment, and

t is time.

From this MacArthur and Wilson (1967) suggested that there were basically two extreme types of life cycles. When the population *N* is very small compared with *K*, then *r* is the main determinant of population size and so species with attributes ensuring a high value of r will be selected for – hence *r*-selected species. As colonisation proceeds, competitive ability becomes increasingly important as *K* is approached, and so species at later successional stages – so-called *K*-selected species – have as their main attribute, competitive ability. Thus, species which have *r*-selected and opportunistic traits will be found during early stages, while species which have less opportunistic and *K*-selected traits will be found at later stages (Grassle and Grassle, 1974; Gray, 1981).

Based on many views Connell and Slayter (1977) have formulated three models of succession – facilitation, tolerance and inhibition. *Facilitation* is based on biotic habitat modification by each group of species that enhances the settlement of subsequent groups. *Tolerance* mechanism centers around difference in species resource utilisation pattern and life histories. *Inhibition* involves suppression of settlement and/or growth of other species by those already established in the disturbed area. This fundamental ecological process has been studied in a number of soft bottom environments in temperate waters (McCall, 1977; Santos and Simon, 1980; Whitlach, 1980; Rhoads and Boyer, 1982; Zajac and Whitlach, 1982; Trueblood et al., 1984). Though there are some studies on soft bottom macrofauna in Indian estuaries (Harkantra, 1975; Parulekar et al., 1980; Harkantra and Parulekar, 1985) no such approach was made. The multivariate techniques – Chord Normalised Expected Species

Shared (CNESS) and Principal Component Analyses of Hypergeometric Probability of species matrices (PCA-H) were applied to soft-bottom macrofauna data to assess the pattern of species succession.

Earlier investigations on the benthos along the Indian coast relate to faunal distribution in relation to salinity incursion and sediment distribution. Also these studies are basically qualitative and quantitative. These studies carried out covered the annual cycle of environmental and biotic factors in relation to distribution, production, trophic relations and other relevant aspects of the benthic macrofauna (Parulekar, 1973; Parulekar and Dwivedi, 1974; Parulekar et al., 1975; Parulekar et al., 1980; Harkantra et al., 1980; Harkantra and Parulekar, 1984; Parulekar et al., 1986; Ansari et al., 1986; Harkantra and Parulekar, 1994; Mathew and Govindan, 1995; Varshney et al., 1999). But there is no much information on community structure analysis and their interaction with the environmental parameters. This work presents the environmental factors (described in Chapter 3) along with the studies on community structure. In addition, species succession of macrobenthos was also studied, the results of which are presented in this chapter. The influence of the abiotic factors on the faunal community was studied by using various multivariate techniques and this is described in Chapter 5.

4.2. RESULTS

4.2.1. Community structure:

67 macrofaunal species belonging to diverse taxonomic groups were obtained from the study area. An attempt was made to identify the organisms upto the species level. This exercise did not prove to be a complete success and hence some organisms are identified upto the genus level. Polychaetes, bivalves and amphipods were the main inhabitants found at the different study sites. The mean species density of the various species is given in **Tables 4(a) – 4(f)**.

Site A: 34 species were recorded at site A. Altogether 6 groups were observed. Of the total groups polychaetes were the maximum (55.83%), followed by bivalves (17.64%), then gastropods (14.70%), coelenterates (5.88%), echinoderms (2.94%) and echiurids (2.94%). Amongst the polychaetes, the spionid *Prionospio pinnata* was present throughout the sampling period. *Cossura coasta* appeared in most of the months except for September. The gastropod *Architectonica laevigata* was seen to be present in all the months sampled. Besides these species, the polychaetes *Sternaspis scutata*, *Clymene annandalei*, echiurid *Thalassema* sp. and the coelenterate *Dendrostomum* sp. were present in most of the months. Over the year the maximum density of 94/0.04m^2 of *Architectonica laevigata* was observed in February. Species diversity index varied from 2.29 in February to 3.32 in December. Species evenness ranged from 0.53 in February to 0.88 in November. Species richness values varied from 2.2 in April to 4.27 in January. Total biomass values ranged from 0.16 g/m^2 in

September to 49.6183 g/m^2 in March. While the total density varied from 450/m^2 in July to 4413/m^2 in March. Species number fluctuated between 5 in August and 19 in February.

Site M1: A total number of 44 species were recorded at this site. Altogether 7 groups were identified at this site. Polychaetes were the maximum (38.63%), followed by bivalves (25.0%), then by amphipods (20.45%), coelenterates (6.81%), gastropods (4.54%), echinoderms (2.27% and echiurids (2.27%). The polychaete *Nereis capensis* was found on all the occassions except in the month of January. Polychaetes such as *Glycera alba*, *Nereis* sp., bivalve *Paphia malabarica*, amphipod *Urothoe platydactyla* and the echiurid *Thalassema* sp. were found in most of the months. *Thalassema* species was the dominant species with a density of 467/0.04m^2 seen in the month of September. Species diversity index varied from 1.37 in July to 3.61 in April. Species evenness ranged from 0.37 in February to 0.92 in November. Species richness values varied from 0.93 in June to 5.5 in April. Total biomass values ranged from 0.1358 g/m^2 in January to 104.472g/m^2 in December. While the total density varied from 225/m^2 in January to 3775/m^2 in February. Species number fluctuated between 3 in July and 25 in April.

Site M2: 29 different species were recorded from this site, which belonged to 6 groups. Polychaetes were the maximum with 41.37%, followed by bivalves with 24.13% and amphipods also with 24.13%, then by gastropods

(3.44%), echiurids (3.44%) and nematodes (3.44%). Among the polychaetes *Prionospio pinnata* and *Glycera alba* was found in most of the collections. Similarly *Meretrix casta* and *Thalassema* sp. also appeared in most of the samples. The clam *Meretrix casta* was found in maximum numbers, the highest density being 238/0.04m^2 in May. Species diversity index varied from 0.26 in May to 2.56 in November. Species evenness ranged from 0.1 in July to 0.91 in November. Species richness values varied from 0.93 in August to 2.93 in November. Total biomass values ranged from 0.1355 g/m^2 in April to 7.5538 g/m^2 in November. While the total density varied from 200 /m^2 in June, November and February to 6125/m^2 in May. Species number fluctuated between 4 in August and 12 in September.

Site Z1: 30 species were recorded from this site. Totally 7 different groups were identified. The maximum number of species belonged to the polychaete worms and they comprised 46.66% of the total number of species, followed by bivalves that constituted 20.0%, then the amphipods with 16.66%, coelenterates with 6.66% and finally gastropods, echinoderms and echiurids each with 3.33%. *Prionospio pinnata* appeared in most of the collections except during October and May. *Glycera alba* also appeared on most of the occasions. The maximum density seen was that of *Thalassema* species that was 48/0.04m^2 in the month of January. Species diversity index varied from 0.99 in May to 3.34 in December. Species evenness ranged from 0.66 in January to 0.99 in May. Species richness values varied from 1.44 in May to 3.91 in December. Total

biomass values ranged from 0.675 g/m^2 in May to 1.5603 g/m^2 in November. While the total density varied from 50/m^2 in May to 2550/m^2 in January. Species number fluctuated between 2 in May and 18 in December and January.

Site Z2: Totally 36 species were recorded from this site belonging to 9 different groups. Polychaetes were the maximum comprising 52.77%, followed by amphipods that made up 16.66%, then the bivalves that made up 11.11%, then the coelenterates that comprised 5.55% and finally the gastropods, echinoderms, echiurids, nermertine worms and fish each constituting 2.77%. *Prionospio pinnata* was the most dominant appearing throughout the year except in May and July. Other polychaetes such as *Nephthys inermis*, *Sternaspis scutata*, *Glycera alba*, *Clymene annandalei* and the amphipod *Urothoe platydactyla* were also seen during most of the time in a year. The maximum density seen was that of *Prionospio pinnata* (46.5/0.04m^2) in September. Species diversity index varied from 0.99 in July to 3.65 in November. Species evenness ranged from 0.44 in October to 0.99 in July. Species richness values varied from 0.99 in July to 3.64 in February. Total biomass values ranged from 0.025 g/m^2 in July to 5.5341 g/m^2 in January. While the total density varied from 25/m^2 in July to 1675/m^2 in January. Species number fluctuated between 1 in July and 17 in November.

Site Z3: A total of 25 species were recorded from this site belonging to 4 groups. Polychaetes comprised 64.00%, followed by amphipods constituting 20.00%, then the bivalves 12.00% and finally the echiurids that made up to 4%. Here too *Prionospio pinnata* was found in abundance throughout the year except in April. Also *Clymene annandalei* was present during all the months except for February. *Glycera alba*, *Cossura coasta* and the echiurid *Thalassema* sp. were also present most of the times. *Prionospio pinnata* was the dominant species with the highest individual density of 54/0.04m^2 in March. Species diversity index varied from 1.27 in October to 2.51 in November. Species evenness ranged from 0.43 in August to 0.89 in November. Species richness values varied from 0.68 in March to 2.76 in August. Total biomass values ranged from 0.6775 g/m^2 in December to 12.7675 g/m^2 in January. While the total density varied from 208/m^2 in December to 1950/m^2 in March. Species number fluctuated between 4 in October & March and 11 in September.

4.2.2 Description of families:

Totally 67 species were recorded belonging to various groups. Polychaetes constituted the major group (38.23%), followed by bivalves (22.05%), then amphipods (19.11%) and finally the gastropods (5.88%). The miscellaneous group constituted 14.70%.

Polychaeta:

26 species of polychaetes belonging to 15 families were recorded (see Faunal List).

Spionidae:

The spionids were the most abundantly found. They are bipalpate, usually tubicolous worms, both frequent and abundant on all substrata. This family was represented by 2 species – *Prionospio pinnata* Ehlers and *Prionospio cirrifera* Wiren. Both these species inhabited all the six sites. The maximum population density of *Prionospio pinnata* was found to be 54 /0.04m^2 at site Z3 in March while that of *Prionospio cirrifera* was 4/0.04m^2 at Z^2 in September.

Eunicidae:

The family Eunicidae was represented by 5 species – *Lumbriconereis heteropoda* Marenzeller; *Diopatra neapolitana* Delle Chiaje; *Eunice tentaculata* Quatrefages; *Arabella iricolor* Montagu and *Onuphis eremita* (Audouin and Milne-Edwards). Eunicids are tubicolous worms which have paired mandibles and complex sets of maxillae in a strongly muscular and eversible pharynx. *L. heteropoda* was present at all the sites and maximum density was found to be 3/0.04m^2. *D. neapolitana* was found only at M1 and Z1 and was maximum in December with 17.3/0.04m^2. *E. tentaculata* was found only at M2 the highest density being 0.5/0.04m^2. It was recorded only on one occasion (June). The fourth eunicid, *A. iricolor* was present at A and Z2 in the months of December and April respectively with density being highest at site A (3.6/0.04m^2). *Onuphis*

eremita (Audouin and Milne-Edwards), was present at site M1 only and it showed a maximum density of 1/0.04m^2 in April.

Nephthydidae:

This family was represented by 3 species – *Nephthys inermis* Ehlers; *Nephthys dibranchis* Grube and *Nephthys oligobranchia* Southern. Nephthyids are free living burrowers commonly found in soft substrata, from the intertidal to the abyssal (Sanders, 1968). *N. inermis* was present at all the study sites. While all the three species together co-existed only at sites M1, Z2 and Z3. The maximum density of *N. inermis* was 8/0.04m^2, recorded from site A in November. *N. dibranchis* also showed a maximum density of 8/0.04m^2 but at site Z1 in the month of January. While *N. oligibr*anchia was maximum at site Z2 in September with a highest density of 2.5/0.04m^2.

Nereidae:

Nereids or clam worms are elongated, rounded or flattened worms, having a prostomium with 4 eyes, 2 subulate tentacles, 2 massive two-joint palps, 4 pairs of tentacular cirri, proboscis with a pair of horny jaws and a series of horny teeth. They are either carnivores or herbivores. 3 species of nereids were identified – *Nereis capensis* Willey; *Nereis mirabilis* Kinberg and *Perinereis nuntia* Savigny. *Nereis capensis* was found at all the sites, but was abundantly found at site M1. Here it was found throughout the year except for in January.

Highest density recorded for this species was 35/0.04m^2 in September. Whereas *N. mirabilis* and *Perinereis nuntia* both were found in less numbers.

Glyceridae:

Glycerids are slender, long bodied polychaetes with enormous eversible pharynges. The jaws are penetrated by a canal connected basaly to a gland. They are also called as blood worms. This family was represented by 2 species – *Glycera alba* Rathke and *Goniada emerita* Audouin and Milne-Edwards. *Glycera alba* was found at all the study sites and almost in all the collections. The maximum population density recorded was 11.5/0.04m^2 in September at site A. *Goniada emerita* was also found at all the sites except Z1 and Z3. It's density was very low compared to that of *Glycera alba* and it was collected only in the months of December, January and February. The maximum density was 1/0.04m^2 at M1 in January.

Maldanidae:

They are cylindrical worms, having few and long segments and a small prostomium destitute of appendages. Maldanids or bamboo worms as they are usually called are deposit feeders and some conveyor-belt species are present in this family. This family was represented by *Clymene annandalei* Southern and *Maldane sarsi* Malmgren. *Clymene annandalei* was present at all the six sites but site A and Z3 showed populations of this species throughout the year. The maximum density recorded was 37/0.04m^2 in March at A. While the other

maldanid, *Maldane sarsi*, was present at A and Z3 only in November and December respectively, the highest density being 2.3/0.04m^2 in Dec.

Magelonidae:

This family was represented by only one species *Magelona rosea* Moore. These magelonids are long, slender or filiform with a flattened, oval, spade-like prostomium devoid of tentacles. They have 2 very long ventrally attached papillated palps and a big proboscis. They are good burrowers living in sands and muds. This species was present at sites A, Z1, Z2 and Z3 the maximum density being 6.6/0.04m^2 at Z1 in November.

Capitellidae:

Capitellids are elongated worms, reddish and without obvious parapodia so as to appear like oligochaetes. They possess a large prostomium. They are mainly deposit-feeders. It was represented by *Heteromastus similis* Southern, only which was found to inhabit sites A, M1, Z2 and Z3. Maximum density recorded was 1/0.04m^2 at Z3 in November.

Orbiniidae:

They have a vermiform body with a conical prostomium devoid of sensory appendages or palps. They are commonly found in mud and have sac-like or dendritic eversible pharynges. This family was represented by a single species, *Scoloplos marsupialis* Southern. It was present only at A, M2 and Z2 and showed the maximum density of 1/0.04m^2 at M2 in October.

Cossuridae:

They are small thread-like worms with numerous segments. They have a conical prostomium without appendages. They possess a single, very long, cylindrical, dorsal tentacle. They inhabit sandy-mud in fairly deep water and are deposit feeders. So far only one genus has been recorded belonging to this family. This species *Cossura coasta* Kitamori, was found at sites A, M2, Z2 and Z3. Maximum density (18.5/0.04m^2) was seen at Z3 in September and it was found in abundance at A and Z3 throughout the year.

Sternaspidae:

These polychaetes have a short, swollen body, which is often ovoid or dumb-bell shaped, having a few segments. Anterior end has a small prostomium. It also possesses a terminal tuft of branchial filaments. It has a single genus. The organism, *Sternaspis scutata* Renier, has a sausage-shaped body often constricted in the middle. It feeds on buried organic matter and burrows head downwards in stiff mud with the help of stout spines. The hard anal plates cover the entrance of the burrow. It was found at A, Z2 and Z3 in abundance on many ocassions with maximum density of 9/0.04m^2 at Z2 in March.

Cirratulidae:

Body is cylindrical and tapered at both the ends. They possess a small prostomium. Cirratulids are deposit feeders and gather food particles from the sea bottom by numerous grooved tentacular filaments. They are sluggish worms

and commonly bury their bodies just below the surface of the sea bottom. The species representing this family, *Cirratulus filiformis* Keferstein was present at sites A, Z1, Z2 and Z3 and it had highest density of 1/0.04m^2 during February, March, April and September respectively.

Sabellidae:

They are tubicolous, filter feeding worms, living in tough tubes reinforced with mud or sand. They possess two grooved palps and often a pair of membranous lips. The peristome often develops a collar which ensheaths the base of the branchial lobes. They rely entirely on suspended particles. They make tough tubes lined with mucous and covered with mud, sand or general debris. It's representative *Sabella melanostigma* Schmarda was found at M1 and Z1 with maximum density of 4.5/0.04m^2 at Z1 in January.

Terebellidae:

Terebellids are tubicolous worms with soft , tapered bodies, encased inmucous tubes, encrusted with sand or mud. They are highly adapted deposit feeders. They usually live in quiet areas where organic particles and these are picked up by the sticky tentacles or by ciliary action. The representative, *Terebella ehrenbergi* Grube was present at M1 and Z2 with maximum density of 0.5/0.04m^2 in February, April and February respectively.

Sabellaridae:

They too are tubicolous worms and live in dense sandy tubes. Head is crowned with a golden paleae. The prostomium is hidden. They are suspension feeders. The representative *Sabellaria cementarium* Moore inhabited only Z1 with a density of 0.3/0.04m^2. in December.

Bivalvia:

15 species of bivalves belonging to 9 different families were recorded (see Faunal List). Bivalves are generally filter feeders, which burrow into the substrata for protection.

Veneridae:

5 species were recorded from this family – *Meretrix casta* (Chemnitz); *Paphia malabarica* (Chemnitz); *Paphia textile* (Gmelin); *Gafrarium tumidum*, Röding and *Villorita cyprinoides* (Grey). This family is characterised by a regular shell, three cardinal teeth (with an additional tooth in front of the left valve and a hollow on the right) and a sinuate pallial line. *Meretrix casta* (Chemnitz) was found at all the sites except A. It was found abundantly at site M2 and it showed highest density of 238/0.04m^2 at this site in May. *Paphia malabarica* (Chemnitz) was present only at M1 and was in high numbers in September (6/0.04m^2). Whereas *Paphia textile* (Gmelin) was seen only at two sites A and M1, the highest density of 7.3/0.04m^2 seen at M1 in December. *Gafrarium tumidum* Röding, was found at sites A, M1 and Z1. Highest density was recorded at Z1 in

November (15/0.04m^2). *Villorita cyprinoides* (Grey) was seen only at M2, on one ocassion only (0.3/0.04m^2).

Mytilidae:

In this family the shell is extremely inequilateral and the anterior adductor is feebly developed and in some cases altogether lacking. They are also referred to as mussels or date shells. This family is represented by 2 species – *Perna viridis*, Linné and *Perna indica* (Henley). *Perna viridis* Linné, was found only at site M1, coexisting with *P. indica* (Henley). It was collected only on one ocassion in December (0.3/0.04m^2). *P. indica* was seen at M2 besides M1. At both the sites, their numbers did not exceed 0.5/0.04m^2 and was collected during March, June and August at M1 and March, July and August at M2.

Mactridae:

They are also called as false clams. Their shell is mostly light and triangularly ovate (except *Lutraria* sp.). There is a prominent hinge-pit, thin and elongated lateral teeth and in the left valve only one cardinal tooth. This family was represented by 2 species – *Lutraria arcuata* Deshayes and *Mactra cuneata* (Chemnitz). *Lutraria arcuata* was present at sites M1, M2, Z2 and Z3. But it was highest (8.5/0.04m^2) at M1 in February. *Mactra cuneata* was seen at A and M1. It was found abundantly at A and it reached it's highest density (72.5/0.04m^2) at A in March.

Cardiidae:

In this family the shell is nearly rounded with strong radial ribs, external ligament and similar hinge teeth on both the valves. They have two cardinal teeth and two lateral teeth. The shells in this family are also called cockles. A single species , *Cardium flavum* Linné was recorded at all the sites except Z3. It's highest density was at M2 in April (25/0.04m^2).

Arcidae:

Members of this family are characterised by the possession of straight hinge beset with numerous teeth. They are sometimes called as ark shells. The single species that represented this family, *Arca granosa* Lamarck, was seen only at M2 and only in the month of December (1/0.04m^2).

Donacidae:

These shells are triangular and have the anterior sides longer than the posterior. Hence they are also referred to as wedge shells. The pallial sinuses are large and rounded. *Donax faba* Gmelin was the species that represented this family and it was recorded from Z1 only, on one ocassion in December (1/0.04m^2).

Tellinidae:

These thin shells, also called as paper shells, have a large pallial sinus and usually a beaked hind margin. The ligament is situated externally. Furthermore, in addition to the cardinals, the right valve bears lateral teeth.

Tellinidae was represented by *Tellina bruguieri*, Hanley, which was collected from sites M2 and Z3 with maximum density of 1/0.04m^2 at Z3 in April.

Solenidae:

Razor shells as they are usually called are tubular with the umbo usually placed at it's anterior end. It was represented by *Solen truncatus* Wood, and was found to inhabit sites M1, Z1 and Z2. It showed highest density of 1/0.04m^2 at M1 in October.

Pholadidae:

These are also called piddocks and are usually wood borers. They have white, equivalved, ribbed shells (often toothed). The ligament and hind margin are absent. The valves are held together by muscles only. *Pholas orientalis* (Gmelin) was the representative of this family, found only at A in October, February, April and May. They burrow in muddy sand substratum in the littoral zone or compact bluish-gray muddy sand in the sub-littoral zone. They burrow to a depth of 0.3 m and once extracted can never return. It's highest density was 4.5/0.04m^2 seen in May.

Gastropoda:

4 species of gastropods were identified belonging to 4 families. *Cerithedia fluviatilis* (Potiéz and Michaud) belonging to family Potamididae was found at sites M1, M2, Z1 and Z2 with highest density of 8.5/0.04m^2 at Z2 in August. *Turritella attenuata* Reeve of family Turritellidae (turret or screw shells) was seen

at site M1 only in February and April the highest density being 1.5/0.04m^2 in April. *Architectonica laevigata* Lamarck, that belongs to family Architectonicidae was found to inhabit only site A. This species was found abundantly throughout the year and maximum density was recorded to be 94/0.04m^2. *Dentalium octangulatum* Donovan, inhabited sites A and Z1 with highest density of 6/0.04m^2 at site A in March.

Crustacea:

13 species were recorded from this group belonging to different families. Of the 13 species, *Portunus sanguinolentus* (Herbst); *Urothoe platydactyla* Rabindranath; *Metapenaeus dobsoni* (Miers) and *Ampelisca_brevicornis* (Costa) were found in quite high densities.

Portunus sanguinolentus (Herbst) was found at site A, M1 and Z1 with highest density of 7/0.04m^2 recorded at site A in April.

Urothoe platydactyla Rabindranath, was recorded from all the sites except A. maximum numbers of 115.5/0.04m^2 was found at site M1 in February.

Metapenaeus dobsoni (Miers) was present at all sites except Z1 with maximum density of 3.5/0.04m^2 at Z3 in May.

Ampelisca brevicornis (Costa), was seen at M1, M2 and Z2. Highest density of 0.5/0.04m^2 was found at all 3 sites M1; M2; Z2 in April; February and March; September respectively.

The other amphipods recorded are *Sphaeroma annandalei*, Stebbings; *Sphaeroma walkeri*, Stebbings; *Gastrosaccus simulans*, W.T.Tattersall; *Diogene*

affinis, Henderson, *Perioculodes megapleon*, (Giles); *Paradiastylis* species; *Eurydice* species; *Cyathura* species and *Scotollana* species.

Other groups:

Several other species were recorded besides the ones described. They are *Edwardsia tinctrix* Annandale; *Cavernularia* species; *Sertularia* species and *Dendrostomum* species belonging to Sipunculida. Also *Ophiothrix* species of Echinodermata, *Thalassema* species of Echiurida, *Boleopthalmus dussumieri* Cuv. & Val. belonging to Pisces were collected. Nematode and Nemertine worms were also seen.

4.2.3 Macrobenthic species succession:

A total of 67 species were recorded (see faunal list) of which 18 were new to the local benthic fauna. Species density varied from sites to months with highest density being of Echiurida - *Thalassema* sp. 467/0.04 m^2. Polychaetes formed the dominant taxa followed by molluscs and crustacea. **Fig. 4(a)** shows cluster of species based on the cos Ø between the species vectors in the Gabriel covariance plot. Only 6 -10 species contributed to more than 2% of the CNESS variation among the samples of the 59 species (for sites M1, M2, Z2 and Z3 only) recorded. The stages of succession of species formed three distinct clusters of the species vectors shown as 1, 2 and 3. Stage1, 2 and 3 represent post, pre and southwest monsoon seasons species samples. The orientation of the species vectors in a 12 dimensional sample space are seen in three groups each oriented at different angles between 55° to 138° to others **[Fig. 4(b)]**. These three

groups indicate three stages of succession, which produced the triangular pattern of seasonal samples **[Fig. 4(b)]**. Cluster analyses also describe the composition of the three successional stages and show the percentage of proportional contribution of each species to CNESS distance among the samples. Stages 1, 2 and 3 were composed of different species at different sites **[Fig. 4(a)]**. The most important species that controlled the orientation of the samples were the grazer amphipod - *Urothoe platydactyla* (18%) at site M1, filter feeding bivalve - *Meretrix casta* (79%) at site M2 and head-down burrowing sub-surface deposit feeder- *Clymene annandalei* at sites Z2 (14%) and Z3 (33%) during succession stage 1 of the post-monsoon season. Onset of succession was largely due to 1st stage of recruitment, which occurred after the southwest monsoon disturbance, and stability of the environment. The first shift in the successional topology was from stage 1 to stage 2. Stage 1 species do not facilitate or inhabit stage 2 in this sequence because their population has declined before stage 2 species recruit. The cause for this shift in succession to topology was the premonsoon 2nd stage of recruitment state. The important species that controlled the orientation of stage 2- premonsoon period were echiurid- *Thalassema* sp. (58%) at site M1, the filter feeding bivalve- *Cardium flavum* (7%) at site M2 and *Prionospio pinnata* at site Z2 (43%) and Z3 (34%). Defaunation of macrofauna occurred largely due to a sudden decline in salinity and sediment disturbance during stages 2 - stage 3, which were brought about by southwest monsoon. Stage 3 - southwest monsoon succession was distinguished from stage 2 primarily by a presence of low salinity tolerance species. The important species that controlled the orientation of stage

3 were the polychaete - *Nereis capensis* at site M1 (13%) and M2 (4%) and Nematoda at sites Z2 (8%) and Z3 (3%). These three important species each formed different successional stages 1, 2 and 3, that account for, 89% at site M1, 90% at site M2, 65% at site Z1 and 70% at site Z2 of the total variation in CNESS distance among the samples. The species association was better analysed with a co-variance bi-plot **[Fig. 4(b)]** and shows three groups of species vectors, indicated by 1,2 and 3.The species vectors do not form a continuum but fall into three discrete group of vectors. The species vector gives a picture of the association among the succession of species. In the PCA-H analyses [Fig. 4(b)] the variation in CNESS was explained by the first two axes (as percentage). The first axis depicts the difference between post- pre-monsoon sampling months with dominant species primarily contributing to the orientation of the axis. Similarly, the second axis was formed by the difference between the pre and southwest monsoon season sampling months. The estuarine soft bottom species succession varied both temporally and spatially and showed three distinct seasonalities over a period of 12 months. No two stages were similar, each site exhibiting different species succession and composition.

4.3. DISCUSSION

Macrobentic communities in the two estuaries studied are characterised by temporal and spatial changes in their component populations. These patterns of estuarine distribution can be explained in terms of distribution and abundance of euryhaline and opportunistic species of marine and estuarine origin (Boesch,

1977). During the present study, the noteworthy trend was the changes in species abundance accompanied by changes in diversity indices. The fauna was unstable at different sites in the two estuaries. The fauna in the present study comprised a number of marine forms such as *Turitella attenuata*, Nemertinea sp. and *Thalassema* sp. which were concentrated in the region of the river mouth. The estuarine endemic species which were consistently observed in the estuarine region were *Meretrix casta* and *Cerithedia fluviatilis*. These species tend to be dominant in the middle and upper regions of the estuary. The occurrence of juveniles of Crustacea in the sample and their seasonal variability in the present study confirm the earlier findings of Parulekar et al., 1980. Seasonality in both reproduction and larval settling is known to occur in many marine benthic species (Thorson, 1957). It is quite likely then, that the population may decline to very low densities between recruitments, thus resulting in great fluctuation in population sizes. While the temporal variations are due to seasonal distribution of various species and their reproduction and larval settlement, the spatial differences are governed mainly by the regional effects.

The macrobenthic population as assessed from numerical counts shows wide fluctuations **[Tables 4(a) – 4(f)]** at different sites. The population density is highest (6125/m^2) at M2 which lies in the mesohaline zone. This high count was due to the high density of the clam *Meretrix casta*. High numbers of macrofauna were also seen at site A (4413/m^2) lying in the euhaline zone, and the lowest density (1675/m^2) was seen in the mesohaline zone, corroborating the findings of Parulekar and Dwivedi, 1974.

The value of H' (index of diversity) showed temporal and spatial variations. A decrease in faunal diversity was observed from the mouth as we go upstream. Also there was a decrease in diversity at most of the sites, from that observed during 1971-73 (Parulekar et al., 1980).

The estuarine fauna is generally formed of marine, brackish water, freshwater and migratory component (Day, 1951) and the faunal composition is determined by several mutually independent parameters, having a limited influence on the number of species. In the present study it was seen that the euhaline and the polyhaline zones have the maximum number of faunal group representation. Another interesting feature is the observed numerical superiority of the molluscan faunal elements. In predominantly sandy bottom, the molluscs, especially bivalves, outnumber other faunal groups, by more than 10 times. In the Mandovi estuary, the commercially important clam, *Meretrix* casta, mainly due to it's euryhaline and euroecious abilities (Parulekar et al., 1973) forms an extensive animal community as is seen at site M2, in the present study. The other important faunal group, viz. annelids, are mainly represented by polychaetes and in the distribution exhibit limitations in relation to the abiotic factors. They are present in varying abundance in all the salinity zones. The crustaceans also are represented in all the zones but they exhibit a preference for regions of higher salinities. Being epifaunal and therefore *"detriophages"* in trophic structure (Neymann et al., 1971) they do not have much substratum specificity.

A comparison of the earlier data with those reported earlier (Parulekar et al., 1980; Ansari et al., 1986) indicates that the general trend in the abundance, biomass and number of species has changed considerably **[Table 4(o)]**. Maximum faunal density (nos/m^2) showed a decrease from an average of 4382/m^2 during 1971-73 to an average of 2425/m^2 during 1982-83 (Ansari et al., 1986) and further to 956/m^2 on an average during 1997-98 (present study). While the average biomass (g/m^2) showed a decline over the years, from 233.79 g/m^2 in 1971-73 to 113.45 g/m^2 in 1982-83, to 30.24 g/m^2 in the present study. However, total number of species that decreased from 111 (1971-73) to 69 (1982-83) remained at 67 in this study. A total of 18 new species were also recorded. The polychaetes and bivalves accounted for more than 70% and dominated the fauna during 1971-73. In the other study conducted 10 years later polychaetes remained the dominant group but the bivalves were replaced by crustaceans as the second most dominant group. In the present study, polychaetes continued to be the dominant group, while the bivalves again replaced back the crustaceans, which were very close to the bivalves in order of dominance. Fluctuation in population density is a common feature in shallow epifaunal community (Davis and Blaricon, 1978). Out of 67 species, 18 species were not recorded in 1971-73 indicating the changes that have taken place.

The estuarine system of Goa, subject to the monsoonal gyre and receiving about 3000 mm of annual rainfall undergoes wide temporal and spatial variations in the salinity values, thus resulting in considerable decrease in the qualitative and quantitative distribution of the macrobenthic fauna. Changes in benthic

community structure can also be caused by turbulent events such as sediment scouring and colonisation of adults and juveniles of various species. These processes could be responsible for spatial differences in the distribution of benthic invertebrates at different sites in the present study.

The patterns of benthic faunal succession found in this study exhibit it elements of each of the models mentioned in the introduction (Harkantra and Rodrigues, 2003). A variety of abiotic and biotic factors like hydrodynamic, salinity, sediment properties, competetion for food and space, spawning period, recruitment process, prey-predator relationship, might have affected this pattern including human perturbation (Rhoads and Boyer, 1982; Trueblood et al., 1994). For example, the initial establishment of population by early colonizing species or opportunistic species with *r*-selected traits, *Clymene annandalei* (Polychaeta - Maladanidae, head-down burrowing subsurface deposit feeder) was followed by increase in dominance of less opportunistic species or *K*-selected traits, *Prionospio pinnata* (Polychaete – Spionidae surface deposit feeder) at sites Z2 and Z3. This was a component of the tolerance model. This was mainly due to the use of different level of food resources and different life history strategies (Jumars and Fauchald, 1977; Santos and Simon, 1980; Zajac et al., 1982). If the decline of the initial colonizers (*C. annandalei)* was due to resource depletion and intra-and interspecific competition, then the subsequent domination by a different species (*P. pinnata)* was mainly due to more efficient exploitation of food and/or space resources (Kinne, 1977; Thistle, 1981). Biotic habitat modification by earlier species may also enhance the settlement of subsequent species, which

suggest that facilitative mechanisms of succession can occur in soft bottom communities (Thistle, 1981). However, the extent to which these interactions shape successional patterns has to be tested by manipulative experiments. Similarly, early succession of grazer amphipod - *Urothoe platydactyla* and later by deposit feeding Echiuirid- *Thalessema* sp. at sites M1 can be explained by tolerance and facilitative models. The model of inhibition holds good at site M2, where we observed a succession by the filter feeding bivalves- *Meretrix casta* and *Cardium flavum* in post- and premonsoon. These species can occupy all niches and keep off all the later arriving species. Species succession of *N. capensis* at M1 and M2 sites and Nematoda at sites Z2 and Z3 during southwest monsoon was largely due to presence of earlier stage tolerant species and defaunation of other non-tolerant species. This succession was not a fresh recruitment. Defaunation was mostly due to adult/larval mortality, migration to nearby areas, physical disturbance etc. Some of the other explanation could be sudden changes in the environmental parameters such as lowering of salinity which may trigger the gonadal release from benthic invertebrates (Kinne,1977) in the water column thereby increasing the larval abundance. Larval forms may also undergo adaptive strategies like cyst formation, postponement of larval settlement etc. during these severe conditions. Later on these larvae will settle once the condition was favourable (Kinne, 1977; Osman, 1977). Though seasonality was clear at all the sites, their species compostion differed among sites and seasons **[Figs. 4(a), 4(b)]**. This was mainly due to significant differences among the sites and seasons. It is clear from the foregoing account

that the species succession was mainly brought about by southwest monsoon and local abiotic and biotic factors which largely agree with concept of Clement (1916), Connel and Slayter (1977) and Rhoads and Boyer (1982).

The pattern of species succession differed from season to site in the Mandovi and Zuari estuarine complex. The study was limited to 12 months, with three seasons. Whether seasonality of species succession repeats in a similar pattern has to be ascertained from the long-term monitoring of the macrobenthos. Manipulative experiments are needed to understand the species interactions and influence of biotic factors. Based on this study, we designated *C. annandalei*, *M. casta*, *U. platydactyla* as *opportunistic* or *r*-selected species and *P. pinnata*, *C. flavum*, *Thalassema* sp. as *equilibrium* or *K*-selected species. *N. capensis* and Nematoda were considered as *stress-tolerance* species and taxon, respectively.

Faunal List

Polychaeta

Prionospio pinnata, Ehlers

Prionospio cirrifera, Wiren

Lumbriconereis heteropoda, Marenzeller

Diopatra neapolitana, Delle Chiaje

Eunice tentaculata, Quatrefages

Arabella iricolor, Montagu

Onuphis eremita, Audouin and Milne-Edwards

Nephthys inermis, Ehlers

Nephthys dibranchis, Grube

Nephthys oligobranchia, Southern

Nereis capensis, Willey

Nereis mirabilis, Kinberg

Perinereis nuntia, Savigny

Glycera alba, Rathke

Goniada emerita, Audouin and Milne-Edwards

Clymene annandalei, Southern

Maldane sarsi, Malmgren

Magelona rosea, Moore

Heteromastus similis, Southern

Scoloplos marsupialis, Southern

Cossura coasta, Kitamori

Cirratulus filiformis, Keferstein

Sternaspis scutata, Renier

Sabella melanostigma, Schmarda

Terebella ehrenbergi, Grube

Sabellaria cementarium, Moore

Bivalvia

Meretrix casta, (Chemnitz)

Paphia malabarica, (Chemnitz)

Paphia textile, (Gmelin)

Gafrarium tumidum, Röding

Villorita cyprinoides, (Grey)

Perna viridis, Linné

Perna indica, (Henley)

Lutraria arcuata, Deshayes

Mactra cuneata, Chemnitz

Cardium flavum, Linné

Arca granosa, Lamarck

Donax faba, Gmelin

Tellina bruguieri, Hanley

Solen truncatus, Wood

Pholas orientalis, (Gmelin)

Gastropoda

Cerithedia fluviatilis, (Potiéz and Michaud)

Turritella attenuata, Reeve

Architectonica laevigata, Lamarck

Dentalium octangulatum, Donovan

Crustacea

Portunus sanguinolentus, (Herbst)

Urothoe platydactyla, Rabindranath

Metapenaeus dobsoni, (Miers)

Ampelisca brevicornis, (Costa)

Sphaeroma annandalei, Stebbings

Sphaeroma walkeri, Stebbings

Gastrosaccus simulans, W.T.Tattersall

Diogene affinis, Henderson

Perioculodes megapleon, (Giles)

Paradiastylis sp.

Eurydice sp.

Cyathura sp.

Scotollana sp.

Other groups

Edwardsia tinctrix, Annandale

Cavernularia sp.

Sertularia sp.

Dendrostomum sp.

Ophiothrix sp.

Thalassema sp.

Boleopthalmus dussumieri, Cuv. & Val.

Nematode worms

Nemertine worms

Table 4 (a): Mean species density ($0.04m^2$) for duplicate grab samples at station A.

SPECIES	MONTHS								
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Sept
Prionospio pinnata	2.6	5	0.3	1.6	2	1.5	8.5	2.5	5.5
P. cirrifera								1	
Nephthys inermis		8	1.6	0.3		1.5			1
N. dibranchis			2.3	1.6	2.5				
Sternaspis scutata		1	1.3	2	1	1	3		
Magelona rosea		3			1		0.5	0.5	
Glycera alba				0.3	0.5	0.5			11.5
Goniada eremita				0.3					
Lumbriconereis heteropoda	0.6	3			0.5	0.5			1
Cossura coasta	0.3	17	8.6	3	2.5	0.5	9.5	5.5	
Maldane sarsi		2							
Clymene annandalei		4		3.3	8.5	37	14	13.5	4
Heteromastus similis									0.5
Cirratulus filiformis					1				
Nereis capensis	0.6								
Pisionidense indica				0.3					
Pisione sp.			0.3					4	3.5
Scoloplos marsupialis	0.6								
Arabella iricolor			3.6						

Mactra cuneata	4.0			0.3	8.5	72.5			
Paphia textile			1.6						
Cardium edule				1.6	2.5			0.5	
Gafrarium tumidum		2	0.3						
Pholas orientalis	4.0				0.5		3	4.5	
Dentalium octangulatum	0.3				1.5	6	5	0.5	
Architectonica laevigata	4.6	10	2.3	11.6	94	28	27	6	0.5
Metapeneaus dobsoni			1					0.5	
Portunus sanguinolentus			0.3	0.3	4	4	7		
Gastrosaccus simulans									1
Perioculodes megapleon	1		2	1	1.5			2	
Ophiothrix sp.		1			1	1			
Thalassema sp.		10	3.3	3.3	5.5	3.5	14	9	
Dendrostomum sp.		10	1.3	2.6	15.5	18	2	5	
Paracondylactis indicus						1			

Table 4(b): Mean species density ($0.04m^2$) for duplicate grab samples at station M1.

SPECIES	MONTHS											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**
Prionospio pinnata	4		0.6		0.5		6		1			
P. cirrifera							1					
Nephthys inermis	1	4	2				6	1				
N. dibranchis			0.6	0.3								
N. oligobranchia				0.3								
Glycera alba	2		1.6	2	0.5	0.5	1		1			
Goniada emerita				1								
Lumbriconereis heteropoda					0.5							
Clymene annandalei							8					
Heteromastus similis			0.3									
Nereis capensis	3	7	15		6	2.5	16.5	2	2	3	12	35
Pisionidense indica				1.6		0.5	1					

Pisione sp.		2	0.3			12	0.5	2	1			8
Diopatra neapolitana	4		17.3		6.5							
Onuphis eremita							1					
Sabella melanostigma			0.3									
Terebella ehrenbergi					0.5		0.5					
Mactra cuneata			1									
Paphia textile			7.3		0.5		0.5					
Cardium flavum			0.3				0.5				0.5	
Gafrarium tumidum			4.6									
Paphia malabarica		3			3		4.5	3	6			6
Meretrix casta		5	0.3			3				4.5	6	
Perna viridis			0.3									
Perna indica						0.5			0.5		0.5	

Solen truncatus	1											
Tellina bruguieri			0.3				2.5					
Lutraria arcuata					8.5							
Cerithedia fluviatilis					1.5			2				
Turritella attenuata					0.5		1.5					
Metapenaeus dobsoni			1.6		0.5		1					
Portunus sanguinolentus			0.3		1							
Sphaeroma walkeri					2.5		1					
Scotollana sp.		1										
Cyathura sp.							1					
Paradiastylis sp.											0.5	1
Diogene affinis							0.5					
Ampelisca brevicornis							0.5					

Urothoe platydactyla	1		1.6	0.3	115.5		16.5	14		1	1	
Ophiothrix sp.					1		1.5					
Thalassema sp.		2	0.3	0.3		0.5	3.5		0.5		2	467
Edwardsia tinctrix							1					
Cavernularia sp.					2							
Sertularia sp.			0.3				1					

Table 4(c): Mean species density ($0.04m^2$) for duplicate grab samples at station M2.

SPECIES	MONTHS											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**
Prionospio pinnata	4.5		0.3					1.5	2.5	0.5		16.5
Nephthys inermis										1		0.5
Glycera alba	0.5		0.6	1	1	5	1	0.5		0.5		
Goniada emerita			1									
Lumbriconereis heteropoda												1.5
Cossura coasta						0.5						
Clymene annandalei		1.6				1			3			0.5
Nereis capensis			1	2				2			6.5	4.5
Pisionidense indica				5	0.5			1				
Pisione sp.	1		0.3				0.5					
Scoloplos marsupialis	1											
Eunice tentaculata									0.5			

Villorita cyprinoides			0.3									
Cardium flavum	0.5	1					25		1			
Arca granosa			1									
Lutraria arcuata						1						
Meretrix casta	3.5	1.3	21		4	30.5		238		18	16.5	4
Perna indica						0.5				0.5	0.5	
Tellina bruguieri						0.5						0.5
Cerithedia fluviatilis							1.5		1			
Metapenaeus dobsoni		0.6		1		0.5						0.5
Sphaeroma annandalei		2.3						0.5		1		
Gastrosaccus simulans				1								
Ampelisca brevicornis					0.5	0.5						
Urothoe platydactyla		0.6		1	1.5					0.5		6.5

Paradiastylis sp.	1					1.5						0.5
Eurydice sp.												1
Thalassema sp.	0.5	0.3		1	0.5		0.5	2		1	1	1.5
Nemertinea sp.										0.5		

Table 4 (d): Mean species density ($0.04m^2$) for duplicate grab samples at station Z1.

SPECIES	MONTHS								
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Sept
Prionospio pinnata		3.3	11.3	9.5	11.5	5	1.5		43
P. cirrifera				0.5					
Nephthys inermis		4.6		3		1			
N. dibranchis				8	3.5				
Magelona rosea		6.6	5.3	0.5					1
Glycera alba	2.5	2.6	2.6	9	2.5		1		
Lumbriconereis heteropoda					0.5				
Clymene annandalei			5.6	1		3	8.5		7
Cirratulus filiformis						1			
Nereis capensis		1	0.6	3.5	2.5			1	
Pisione sp.			2		0.5		2		2.3
Diopatra neapolitana			5						
Sabella melanostigma			0.3	4.5	1				
Sabellaria cementarium			0.3						
Cardium flavum		1	18.3		0.5				
Meretrix casta				0.5					
Donax faba			1						
Gafrarium tumidum	1.5	15	0.6	2					
Solen truncatus		0.3							

Dentalium octangulatum	0.5						1.5		
Cerithedia fluviatilis	1								
Portunus sanguinolentus				0.5					
Sphaeroma annandalei		3	2.3						
Paradiastylis sp.			1.3	0.5		1		1	
Cyathura sp.		0.3	5	2					
Urothoe platydactyla	0.5	14	13.3	7	3				
Ophiothrix sp.			0.3						
Thalassema sp.		0.6		48	1.5				
Dendrostomum sp.		0.6	0.3	0.5	3				
Sertularia sp.				1					

Table 4(e): Mean species density ($0.04m^2$) for duplicate grab samples at station Z2.

	MONTHS											
SPECIES	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Prionospio pinnata	20	3	5.3	20	6.5	12	9		0.5		13.5	46.5
P. cirrifera		0.3									2.5	4
Nephthys inermis	1.5	1.6	0.3						1		1	5.5
N. dibranchis				2	2.5							
N. oligobranchia											0.5	2.5
Sternaspis scutata	0.5		4.3	5	7	9	8					
Magelona rosea		0.3		1								
Glycera alba	2	0.6	0.6	10	0.5	4	3	0.5	2.5			
Goniada emerita					0.5							
Lumbriconereis heteropoda						1	1	0.5				
Cossura coasta				2							4.5	1
Clymene annandalei	0.5	0.6	3.6	9	8			6	13			2

Heteromastus similis		0.3										
Nereis capensis		0.3	1									
Pisione sp.		1									24.5	
Scoloplos marsupialis												0.5
Cirratulus filiformis							1					0.5
Terebella ehrenbergi					0.5							
Arabella iricolor							2					
Cardium flavum					0.5							
Lutraria arcuata						3						
Meretrix casta		0.6					1				0.5	0.5
Solen truncatus		0.3										0.5
Cerithedia fluviatilis					1.5						8.5	
Metapenaeus dobsoni		0.6			1							

Diogene affinis					1							
Cyathura sp.		0.6										
Urothoe platydactyla	0.5	1			4	4	1	0.5		0.5	0.5	0.3
Ampelisca brevicornis												0.5
Paradiastylis sp.		0.3				3	3					0.5
Ophiothrix sp.					0.5			0.5				
Cavernularia sp.				0.2							2.5	
Dendrostomum sp.		0.3	0.3						2			
Thalassema sp.					1.5		4	1	1			1
Nemertinea sp.		0.6										
Boleopthalmus dussumieri						1	1					

Table 4(f): Mean species density ($0.04m^2$) for duplicate grab samples at station Z3.

	MONTHS											
SPECIES	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Prionospio pinnata	1	7	4.3	28	8.5	54		5	0.5	1	2	2.5
P. cirrifera											1.5	2
Nephthys inermis				2				2		6		2
N. dibranchis			0.3		0.5						5.5	
N. oligobranchia											1.5	
Sternaspis scutata			0.6		1.5							
Magelona rosea									0.5			
Glycera alba		2		13	2.5	9	1		1.5			
Lumbriconereis heteropoda	0.5											
Cossura coasta	1	3			0.5	13	1	4			3	18.5
Maldane sarsi			2.3									
Clymene annandalei	6.5	7	1	24		2	8	22.5	10	12	9.5	4

Heterromastus similis		1										
Cirratulus filiformis												0.5
Nereis capensis							1					
Pisione sp.		9										
Lutraria arcuata							1.					
Tellina bruguieri							1					
Meretrix casta										1	1.5	2
Metpenaeus dobsoni					1.5		1	3.5	0.5			0.5
Diogene affinis				1					1			
Paradiastylis sp.										0.5	0.5	3
Cyathura sp.										0.5	0.5	0.5
Urothoe platydactyla								0.5			0.5	
Thalassema sp.		3		3	1.5			0.5	0.5			2

Table 4 (g) : Community structure indices of macrofauna at site A.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	2.66	0.8	3.11	0.19	10	458	3.5908
November	3.26	0.88	2.77	0.11	13	1975	0.6925
December	3.32	0.85	4.11	0.14	15	992	1.0508
January 1998	3.17	0.79	4.27	0.2	16	850	3.0566
February	2.29	0.53	3.57	0.46	19	3850	40.9831
March	2.46	0.63	2.7	0.36	15	4413	49.6183
April	2.96	0.85	2.2	0.14	11	2400	3.6208
May	3.21	0.84	3.24	0.15	14	1875	29.305
June	2.44	0.77	2.38	0.22	7	521	0.2154
July	2.46	0.75	2.29	0.16	6	450	0.2569
August	2.45	0.76	2.35	0.14	5	625	0.321
September	2.44	0.75	2.26	0.19	9	713	0.16

Table 4 (h) : Community structure indices of macrofauna at site M1.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	2.57	0.91	2.16	0.08	7	400	29.1036
November	2.58	0.92	1.88	0.07	7	600	40.5283
December	2.95	0.67	4.96	0.32	21	1425	104.472
January 1998	2.36	0.84	2.27	0.15	7	225	0.1358
February	1.55	0.37	3.18	0.62	17	3775	49.7131
March	1.76	0.62	2.01	0.37	7	488	0.4233
April	3.61	0.77	5.5	0.22	25	1950	6.6616
May	2.08	0.74	1.86	0.25	7	625	0.97
June	2.2	0.78	0.93	0.21	7	300	0.3175
July	1.37	0.87	1.92	0.13	3	213	1.0673
August	1.86	0.66	1.95	0.33	7	563	0.3545
September	1.79	0.52	1.94	0.24	5	450	3.1891

Table 4 (i) : Community structure indices of macrofauna at site M2.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	2.47	0.82	2.77	0.17	8	313	2.4906
November	2.56	0.91	2.93	0.08	7	200	7.5538
December	1.12	0.37	2.15	0.62	8	650	0.9858
January 1998	2.44	0.87	2.41	0.12	7	300	0.5416
February	2.07	0.8	2.4	0.19	6	200	0.3845
March	1.5	0.45	2.41	0.54	10	1038	0.4358
April	0.76	0.32	1.19	0.67	5	725	0.1355
May	0.26	0.09	1.09	0.9	7	6125	0.3803
June	2.05	0.88	1.92	0.11	5	200	0.6833
July	0.34	0.1	2.55	0.89	9	575	4.555
August	1.19	0.59	0.93	0.4	4	613	3.4496
September	1.25	0.51	0.95	0.5	12	1875	2.2451

Table 4 (j) : Community structure indices of macrofauna at site Z1.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	1.78	0.89	1.75	0.1	4	138	0.9375
November	2.84	0.76	3.02	0.23	13	1350	1.5603
December	3.34	0.8	3.91	0.19	18	2000	1.0723
January 1998	2.78	0.66	3.67	0.33	18	2550	1.4941
February	2.82	0.81	2.94	0.18	11	775	0.8525
March	1.97	0.84	1.66	0.15	5	275	0.5533
April	1.78	0.77	1.49	0.22	5	363	0.8291
May	0.99	0.99	1.44	0.1	2	50	0.675
June	1.44	0.63	0.92	0.3	4	100	0.8763
July	1.46	0.62	0.91	0.35	3	152	0.7544
August	1.48	0.6	0.89	0.36	4	140	0.7219
September	1.44	0.63	0.96	0.36	5	140	0.9783

Table 4 (k) : Community structure indices of macrofauna at site Z2.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	1.24	0.44	1.85	0.55	7	638	1.6816
November	3.65	0.89	6.37	0.89	17	342	2.699
December	2.19	0.78	2.19	0.21	7	392	1.2683
January 1998	2.42	0.8	1.78	0.19	8	1675	5.5341
February	3.12	0.82	3.64	0.17	14	888	2.1991
March	2.58	0.86	1.93	0.13	8	1125	1.7833
April	2.96	0.85	2.83	0.14	11	875	2.3891
May	1.66	0.64	2.27	0.35	6	450	1.1991
June	1.67	0.64	1.66	0.35	6	500	1.0916
July	0.99	0.99	0.99	0.99	1	25	0.025
August	2.36	0.71	2.21	0.28	10	1463	0.7625
September	2.12	0.75	2.12	0.24	14	575	4.5156

Table 4 (I) : Community structure indices of macrofauna at site Z3.

MONTHS	H'	J	SR	D	Species Number	Density (individuals/m^2)	Biomass (g/m^2)
October 1997	1.27	0.63	1.36	0.36	4	225	1.43
November	2.51	0.89	1.73	0.1	7	800	1.2133
December	1.8	0.77	1.86	0.22	5	208	0.6775
January 1998	1.73	0.67	1.13	0.32	6	1825	12.7675
February	2.15	0.76	2.14	0.23	7	738	3.5963
March	1.29	0.64	0.68	0.35	4	1950	3.5598
April	2.09	0.74	2.27	0.25	7	350	8.7299
May	1.87	0.66	1.64	0.33	7	950	5.4883
June	1.64	0.58	2.24	0.41	7	363	1.2266
July	1.65	0.63	1.64	0.36	6	525	3.0833
August	1.42	0.43	2.76	0.56	10	663	0.9775
September	2.43	0.86	2.37	0.13	11	313	1.0283

H' – Species diversity J – Species evenness SR – Species Richness D – Dominance

Table 4 (m): Seasonal mean and SD for the different biotic parameters at different sites. The superscripts refer to Tukey HSD tests where values with the same letter are not different at the 0.05 significance level.

	SITES							
VARIABLES	SEASON	M 1		M 2		Z2		Z3
		MEAN ($\bar{x}$)	**SD (±)**	**MEAN ($\bar{x}$)**	**SD (±)**	**MEAN ($\bar{x}$)**	**SD (±)**	**MEAN ($\bar{x}$)**
Species diversity	1	$^{**}2.5^{b}$	0.46	$^{***}2.12^{b}$	0.57	$^{***}2.77^{c}$	0.72	2.07(ns)
	2	2.4^{b}	0.74	1.25^{a}	0.74	2.42^{b}	0.64	1.87
	3	1.82^{a}	0.42	1.16^{a}	0.5	1.79^{a}	0.6	1.96
Total biomass	1	$^{****}30.96^{c}$	0.37	$^{***}1.93^{b}$	0.08	$^{***}1.33^{c}$	0.16	$^{*}1.26^{b}$
	2	3.73^{b}	0.16	0.77^{a}	0.01	1.16^{b}	0.15	1.47^{c}
	3	1.31^{a}	0.01	2.85^{c}	0.02	1.04^{a}	0.28	1.13^{a}
Population Density	1	$^{**}725.55$	1.74	$^{**}354.61^{a}$	0.05	456.3(ns)	382.3	764.5^{b}
	2	1085.49	2.76	1219.33^{c}	13.27	206.3	107.2	997^{c}
	3	388.62	0.02	742.24^{b}	0.59	425	486.5	466^{a}
Species number	1	7.25	5.65	7.77^{a}	8.86	5.08(ns)	0.84	5.05(ns)
	2	7.25	6.15	69.37^{b}	102.9	5.3	0.46	5.33
	3	14	13.9	10.75^{a}	7.71	4.55	1.38	4.57

ns – not significant

* - P < 0.05
** - P < 0.01
*** - P < 0.001
**** - P < 0.0001
For SD of site Z3, see last page/appendix

Table 4 (n): Annual mean and SD of biotic parameters at different sites.
The * after variable name refers to the significance level from ANOVA.The superscripts refer to Tukey HSD tests, where values with the same letter in each row are not different at the 0.05 significance level.
ns – not significant; **** - P < 0.0001

	SITES							
	M1		M2		Z2		Z3	
VARIABLES	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)
Species Diversity****	2.25^{c}	0.63	1.51^{a}	0.74	2.33^{c}	0.75	1.97^{b}	0.41
Total Biomass ****	6.71^{b}	0.42	1.741^{a}	0.29	1.86^{a}	0.01	2.76^{a}	0.01
Population Density (ns)	687.19	1.63	703.37	3.5	610.11	0.96	615.04	0.01
Species Number	9.66	8.5	29.29	39.82	12.73	10.8	10.56	11.56

Table 4 (o): Comparison of quantitative data on macrofauna during different study periods.

Parameters	**1971-73**	**1982-83**	**1997-98**
Maximum faunal density (nos/m^2)	4382	2425	956
Maximum average biomass (g/m^2)	233.79	113.45	30.24
Total number of species	111	69	67
Dominant taxa	Polychaetes, bivalves	Polychaetes, crustaceans	Polychaetes, bivalves

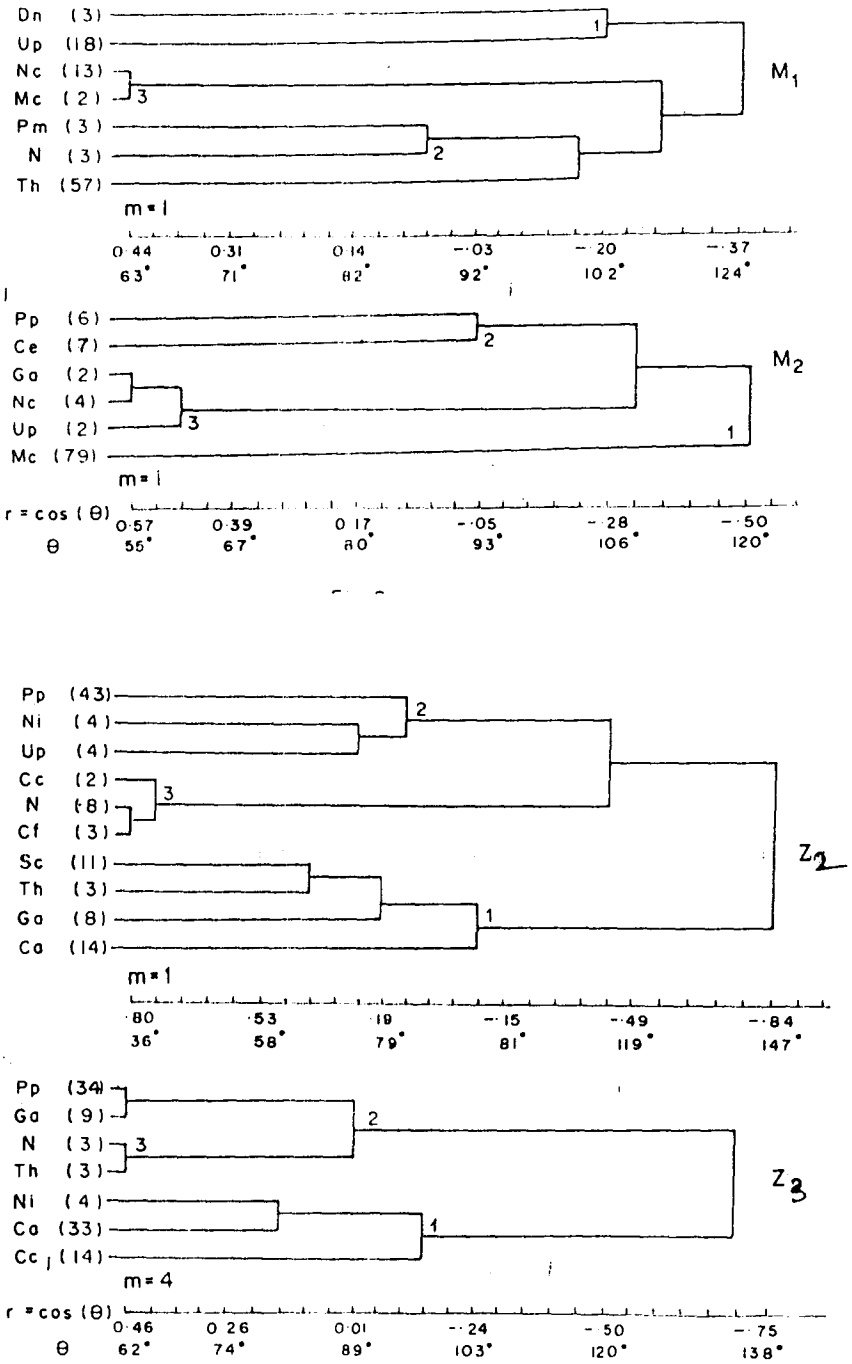


Fig 4 (a): Single linkage clustering of the columns of the hypergeometric probability (H) matrix at different sites indicating species with frequencies at m =1,4 using Pearson's r. Clustering with Pearson's r is mathematically equivalent to clustering the species vectors displayed in Fig 4 (b) using cos ϕ similarity, where ϕ is the angle between species vectors in 12 dimensional ordination space. The three successional stages 1, 2 and 3 and cos ϕ (=Pearson's r) and ϕ value at which these clusters fuse are indicated. Numbers in parenthesis are the percentage of contribution of species to the CNESS analysis. Species code: Ca- *Clymene annandalei*; Cc- *Cossura coasta*; Ce- *Cardium edule*; Cf- *Cerothidea fluviatilis*; Dd- *Dendrostomum species*; Dn- *Diopatra neapolitana*; E- *Thalassema*; Ga- *Glycera alba*; Mc- *Meretrix casta*; N- Nematoda; Nc- *Nereis capensis*; Ni- *Nephthys inermis*; Pp- *Prionospio pinnata*; Sp-*Sternaspis scutata*; Up- *Urothoe platydactyla*

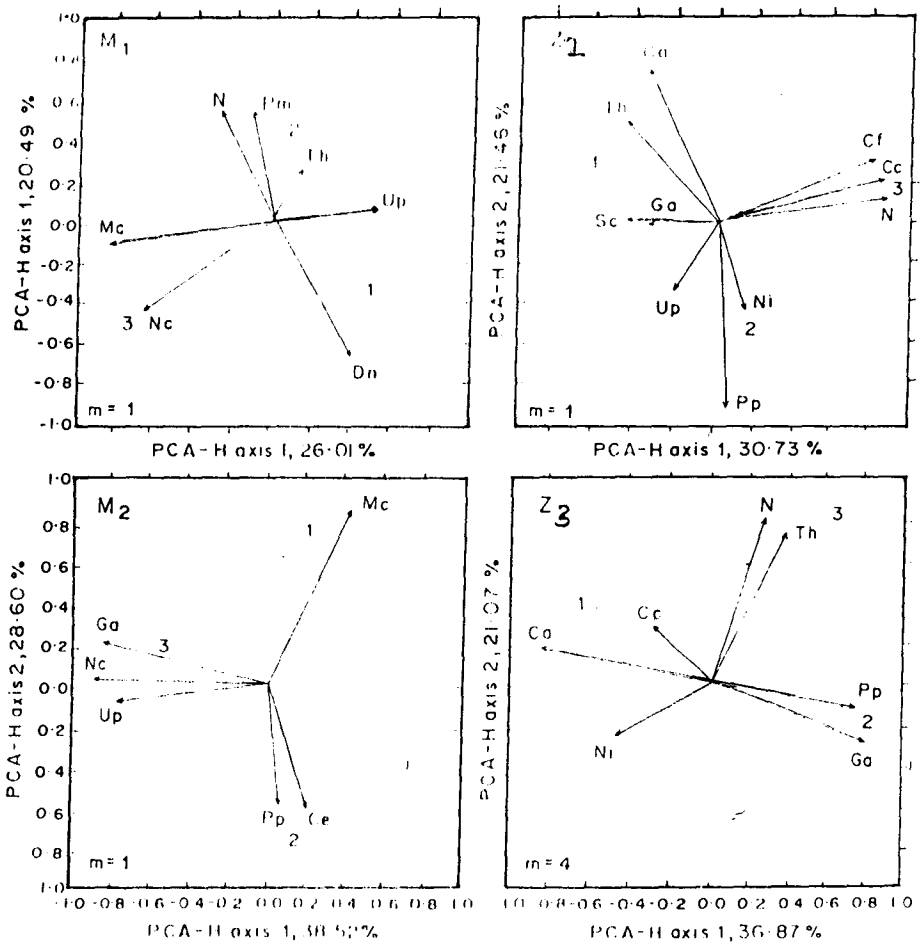


Fig. 4 (b) Three dimensional covariance plot of species vectors The angles between vectors indicate the temporal association among species, with acute angle indicating species with frequencies at m = 1, 4 that are highly correlated in time Three group of species comprising successional stages 1, 2 and 3 are albelled.

143

CHAPTER 5

INFLUENCE OF EVIRONMENTAL PARAMETERS ON THE BENTHIC COMMUNITY STRUCTURE

5.1. INTRODUCTION

Numerous studies have indicated the influences of environmental parameters on species diversity, biomass and population of soft bottom macrofauna in temperate estuaries (Boesch, 1977; Longhurst, 1978; Holland et al., 1987; Frouin, 2000) than the tropical estuarine systems Kinne, 1964; Brown et al., 2000; Frouin 2000; Edgar and Barrett, 2002). However magnitude of variation will change on a spatio-temporal scale at a particular geographical area (Harkantra and Parulekar, 1985, 1991). Estuaries form an ideal ecosystem in which to observe such interactions due to their wide range of environmental parameters (Boesch, 1977; Holland et al., 1987). Though there were some studies on macrobenthos in these estuaries (as mentioned in the earlier chapters) no attempt was made to apply the multivariate technique such as best multiple regression model to predict the benthic community indices based on abiotic factors. Hence, this study was conducted at sites M1, M2, Z2 and Z3 in the Mandovi-Zuari twin tropical estuarine system, central west coast of India, to test the hypothesis that environmental parameters significantly affect the soft bottom benthic community structure such as Shannon-Wiener species diversity, total wet biomass and total population at different sites. Best linear multiple regression models were used to assess the relative significant influencing environmental parameters on the benthic community structure and for the prediction of benthic indices based on the abiotic factors. One year (1997-98) monthly spatio-temporal data was used for this purpose. ANOVA tests were applied to the data to examine any significant differences.

5.2. RESULTS

5.2.1.Environmental parameters

Table 5(a) reveals annual mean and standard deviation of 13 environmental parameters studied at all the sites. All the environmental parameters significantly varied among the sites, except pH and chlorophyll *a* (ANOVA, $P<0.0001$, **[Table 5(a)]**. Temperature, dissolved oxygen, pH, chlorophyll *a* were within the range of 27.2 ± 1.07 - 30.45 ± 1.12 ^{0} C, 3.96 ± 1.14 - 4.42 ± 1.17 ml/l, 7.3 ± 1.12 - 8.2 ± 1.1 and 0.92 ± 1.09 - 1.73 ± 1.83 µg/g respectively. Salinity varied between 12.77 ± 3.11 to 28.82 ± 1.16 psu, and was significantly higher at sites near the mouth of the rivers **[Table 5(a), Tukey]**. Grain size varied from 0.03 to 0.24 mm and was significantly finer at sites in Zuari river than Mandovi river **[Table 5(a), Tukey]**. The muddy regions varied from clayey silt to sand – silt – clay whereas grain size in the sandy region varied from medium to very fine sand. Sediment sorting varied from 0.56 to 1.64 showing well sorted to poorly sorted sediments. Biochemical composition such as total organic carbon, total organic nitrogen, protein, carbohydrates, lipids and biopolymeric fraction showed wide ranges of variations from 8.42 ± 2.37 to 17198.08 ± 1.71 µg/g and significantly higher values were observed at sites in Zuari river than in Mandovi river **[Table 5(a), Tukey]**.

5.2.2. Benthic community structure

A total of 144 grab samples (0.04 m^2) were sorted equivalent to 5.76 m^2. This yielded 2344 individuals and 67 species. Polychaetes formed the dominant taxa followed by molluscs and crustacea. These included 26 species of polychaetes, 15 species of bivalves, 4 species of gastropod, 13 species of crustacea, 1 species of fish and 8 other species that included Sipuncula, Nemertinea, sea anemone, Echiurida, Nematoda and Coelenterata. The benthic community largely composed of deposit feeding polychaete *Prionospio pinnata* and *Clymene annandalei* in Zuari sites and filter feeding bivalve *Meretrix casta* and carnivorous polychaete *Neries capensis* in Mandovi sites. The species succession has been described in Chapter 4.

Table 5(b) also reveals the annual mean with SD of benthic community structure values such as species diversity (Shannon-Wiener), total wet biomass and total population at different sites and these values varied between 1.51 ± 0.74 - 2.25 ± 0.63, 1.74 ± 0.29 - 6.71± 0.42 g/m^2 and 610.11 ± 0.96 - 687.19 ± 1.63 nos/m^2 respectively. Significant high species diversity was noticed at high salinity, fine sand and high sediment biochemical composition sites. Medium grain size sites supported significant high biomass whereas population showed no significant relationship **[Table 5(b), Tukey]**.

Table 5 (d) reveals the significant best multiple regression model and their significant influencing parameters based on maximum R^2 and minimum Cp values. All the 13 environmental variables significantly influenced the benthic

community structure (except temperature) that explained 32-72% of the total variations. No significant best regression fit could be obtained at site Z2 for species diversity. The combination of significant influencing parameters and % of variation varied form site to community indices. Water properties like salinity and dissolved oxygen were the significant influencing parameters in terms of ability to explain the variation of community structure. Similarly, sediment properties like mean grain size, sediment sorting and sediment biochemical composition were the significant influencing parameters. Though we observed significant regression fit ($P<0.001$) for all the community indices their % of variation varied between 37-39% for species diversity, 41-70% for biomass and 32-72% for population at all the sites. Similarly Cp values varied between – 3.2 - 4.0, 2.0 - 29.8 and 5.1 - 71.9 for species diversity, biomass and population respectively. Similarly predictive best multiple linear equation also changed from sites to community indices **[Table 5(d)]**. Total organic nitrogen and salinity become the dominant abiotic parameters in view of its higher frequency of occurrence in combination of two or three variables.

5.3. DISCUSSION

13 environmental parameters and their relative influence on the species diversity, biomass and population density were examined. Salinity formed a significant parameter (Mannino and Montagna, 1997) to explain the variations in community structure especially species diversity and biomass. Wide fluctuation in salinity was mainly brought about by southwest monsoon land runoff, riverine

and tidal flow (Qasim and Sen Gupta, 1981; Shetye et al., 1995). These large variations in salinity in an estuary increases the physiological stress, which can result in the reduction in the number of species and restrict the species distribution depending on the species salinity tolerance thresholds. For example, some euryhaline species like *Thalassema* sp. (echiurid worms) were only found in high salinity sites M1, whereas oligohaline species like *Meretrix casta* (bivalve) was only observed in low salinity site M2 in Mandovi estuary. Such a distribution and the species succession has been described elsewhere (Pielou,1975). This indicates that salinity acts as a physiological barrier for oligo and euryhaline species due to the functional physiology of the species (Kinne, 1964; Parulekar et al., 1980; Harkantra and Parulekar, 1985; Holland et al., 1987; Alongi, 1990; Harkantra and Parulekar, 1991; Mannino and Montagna, 1997; Brown et al., 2000; Edgar and Barrett, 2002). This parameter is more critical in the early stages of larval stages of benthos (Holland et al., 1987). Hence, species diversity reduces in low salinity sites.

Dissolved oxygen variations which are dependent on the mixing process (Qasim and Sen Gupta, 1981) was a significant parameter in explaining community structure especially species diversity and population **[Table 5(b)]** and suggests a oxygen threshold. Typically macrofauna exhibit reduced diversity and extreme dominance in oxygen minimum zone (Diaz and Rosenberg, 1995). However, we did not observe such a situation.

Biochemical composition which mainly comprises proteins, carbohydrates and lipids besides other components, forms the food for benthic organisms

(Marsh and Tenore, 1990). It is stongly influenced by particle size due to adsorption (Keil et al., 1994) coupled with detritus particle input from the mangroves (Wafar et al., 1997), sedimentation process from the overlying waters, that is often a function of hydrodynamic regime (Christensen and Kanneworff, 1985). In this study, proteins, carbohydrates and lipids formed significant parameters to explain the variation in community structure **[Table 5(a)]**. This is mainly attributed to the food and feeding relationship (Marsh and Tenore, 1990) as supported by higher species diversity at high biochemical composition sites **[Table 5(a)]**.

Bottom water chlorophyll *a* largely depends on overlying water column productivity (Mountford et al., 1997) which forms food for the benthic organisms (Marsh and Tenore, 1990). It also formed a significant parameter in explaining the species diversity only at site Z1. Similarly pH which is dependent on water quality (Qasim and Sen Gupta, 1981) also showed significance for same site and indices.

Mean grain size and sediment sorting distribution is a function of hydrodynamic regime (Mountford et al., 1997). These played a significant role in explanation of benthic community structure especially biomass and diversity **[Table 5(a)]**. Relatively finer sediments supported high species diversity [**Table 5 (a)]** corroborating with earlier findings and indicating wider niches (Nichols, 1970; Mannino and Montagna, 1997; Coleman et al.,1997). Well sorted sediments occur in high energy areas while poorly sorted sediments are associated with low energy areas (Grebmeir et al., 1989). Well sorted

sediments, because they offer a smaller range of grain sizes and of interstitial spaces, may provide fewer niches than the poorly sorted sediments, and so contain a less diverse fauna (Nichols, 1970; Gray, 1974; Etter and Grassle, 1992). Sediment sorting increases at shallower depths, indicating the increasing influence of wave action and an increasing homogenity of the sedimentary environment. Species richness decreases as sorting increases, which is in agreement with the hypothesis that well sorted sediments provide a relatively narrow range of niches for species to exploit. Because the well sorted sediments are in shallower water, reduced species richness could also be due to increased physical disturbance, through increased wave action in these areas (Coleman et al., 1997). In the present study, such a condition was noticed at site M2, which has a shallow depth and low species richness on an average, supporting earlier findings (Nichols, 1970; Field et al., 1987; Grebmeir et al., 1989). Absence of significant regression fit at some sites for certain community structure partly reflects the influence of unmeasured environmental parameters, such as hydrodynamic and sediment transport process that affects the distribution of both sediments and fauna (Snelgrove and Butman, 1994). The other possible reason is that it may be tied up with other unmeasured environmental parameters and biotic factors in absence of significant relationship.

Multivariate statistical methods can extract information from data sets containing larger amounts of variance, simultaneously considering the interrelationships of several influential variables. Further, these methods also allow to analyze patterns in biotic patterns to spatio-temporal environmental

variable (Clarke et al., 1996). It is known that environmental parameters can modify, support or augment each other by acting independently or in combination (Boesch, 1977). Clarke et al., 1996 demonstrated the importance of simultaneously studying the influence of a whole suite of environmental variables on benthic organisms in order to assess their relative contributions. In the present study, strong multicollinearity between measured environmental variables suggested such a combined effect on benthic community structure. Amount of total variation in benthic community structure explained by the regression model using the 12 environmental variables was 72%. The major ecological assumption for the development of this model was that the benthic community structure fluctuates greatly in relation to the environmental conditions *in situ* rather than mortality, inter-specific competition or predation.

It is clear from an examination of the R^2 values that the predictor variable subsets selected did not account for all the variance in the dependant variable. Several reasons may be attributed to this. At first, the important variables with a strong influence were omitted due to multicollinearity and the procedure used to fit the linear regression model assume that predictive variables are measured without errors (Wiesberg, 1985). Secondly, the sampling procedure adopted and thirdly, the variance may be due to an error in estimating community structure itself. Therefore, any error in community structure would certainly introduce variance in the model, which cannot be accounted for any independent variable.

The best model selected had a minimum Cp value of – 4.2 indicating that the models are relatively precise in estimating the true regression coefficient and predicting future responses. The precision did not improve by incorporating additional variables. Fitting hypothetical models to such a data-set is a compromise unless the variables and relationships are correctly chosen. The validity of such models depends on the accuracy of the measured variables. Emphasis should be placed on achieving maximum accuracy in all sampling events, when designing and performing such benthic studies.

All the 13 environmental parameters except temperature showed significant influence on the benthic community structure that explained 32-72% of the total variation. TON and salinity formed the main significant factors. Unexplained variations and absence of significant regression fit suggests the influence of unmeasured environmental parameters and biotic factors. Hence, *in situ* manipulative experiments are needed to understand the biotic factors in this area. The model shown here is a pure representation of the available data set and interpretation is limited to study sites and period. We believe that many of the relationships revealed by these analyses make good ecological sense and can be used in benthic resource management in estuarine ecosystem elsewhere.

Table 5 (a): Annual mean and SD of environmental parameters at different sites.
The * after variable name refers to the significance level from ANOVA.
The superscripts refer to Tukey HSD tests, where values with the same letter in each row are not different at the 0.05 significance level.

ns –not significant; **** - P< 0.0001

	SITES							
	M 1		M2		Z2		Z3	
VARIABLES	Mean ($\bar{x}$)	SD ($\pm$)	Mean($\bar{x}$)	SD($\pm$)	Mean ($\bar{x}$)	SD ($\pm$)	Mean($\bar{x}$)	SD ($\pm$)
Temperature****	27.2^{a}	1.07	29.04^{b}	1.11	29.83^{b}	1.12	30.45^{b}	1.12
Salinity ****	21.97^{b}	1.64	12.77^{a}	3.11	28.82^{c}	1.16	20.1^{b}	1.97
Dissolved Oxygen ****	4.3^{b}	1.17	5.06^{c}	1.5	3.96^{a}	1.14	4.42^{b}	1.17
pH (ns)	7.02	1.12	7.3	1.11	8.2^{a}	1.1	7	1.1
Chlorophyll-*a* (ns)	1.02	2.88	0.92	7.09	1.73	1.83	1.63	2.57
Mean grain size ****	2.44^{c}	0.73	2.07^{d}	0.36	3.43^{b}	0.65	5.25^{a}	0.12
Sediment sorting ****	0.18^{b}	0.23	0.24^{a}	0.12	0.09^{b}	0.48	0.03^{c}	0.14
Total organic Carbon ****	2587.02^{a}	3.57	2759.30^{a}	2.21	11697.77^{b}	2.5	17198.08^{c}	1.71
Total organic Nitrogen ****	337.75^{a}	2.19	334.11^{a}	1.88	1174.08^{b}	1.8	2015.57^{c}	2.29
Proteins ****	8.42^{a}	2.37	8.57^{a}	1.51	15.38^{c}	1.51	18.38^{c}	1.32
Carbohydrates****	309.45^{a}	2.29	355.95^{a}	1.82	615.03^{b}	2.01	867.13^{c}	1.54
Lipids****	140.08^{b}	1.16	117.27^{b}	1.46	88.49^{a}	1.95	75.04^{a}	2.15
C-BPF****	232.48^{a}	1.68	236.1^{a}	1.43	305.28^{b}	1.71	422.47^{c}	1.36

Table 5 (b): Annual mean and SD of biotic parameters at different sites.
The * after variable name refers to the significance level from ANOVA.The superscripts refer to Tukey HSD tests, where values with the same letter in each row are not different at the 0.05 significance level.
ns – not significant; **** - P < 0.0001

	SITES							
	M1		M2		Z2		Z3	
VARIABLES	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)	MEAN ($\bar{x}$)	SD ($\pm$)
Species Diversity****	2.25^{c}	0.63	1.51^{a}	0.74	2.33^{c}	0.75	1.97^{b}	0.41
Total Biomass ****	6.71^{b}	0.42	1.741^{a}	0.29	1.86^{a}	0.01	2.76^{a}	0.01
Population Density (ns)	687.19	1.63	703.37	3.5	610.11	0.96	615.04	0.01
Species Number	9.66	8.5	29.29	39.82	12.73	10.8	10.56	11.56

Table 5(c): Best multiple regression (BMR) for species diversity (H'), wet biomass (B), and total population (P) on 13 variables (Best model selection based on adjusted R^2 and minimum Cp value).

	SITES											
	M1			M2			Z2			Z3		
VARIABLES	**H'**	**B**	**P**	**H'**	**B**	**P**	**H'**	**B**	**P**	**H'**	**B**	**P**
Temperature												
Salinity		****			****			****			***	
DO	***						***		****			**
pH	***						**					
Chlorophyll-*a*												**
Mean grain size			***	****								
Sediment sorting								***	****		****	
TOC		****		*		***						
TON		****	***		**	****			****			***
Proteins	*								****			
Carbohydrates						***	***					
Lipids				***								
C-BPF			****		****						****	
BMR	****	****	****	****	****	****	****	****	****	ns	****	***
R^2	0.45	0.73	0.62	0.42	0.46	0.46	0.44	0.63	0.75		0.54	0.38
Adjusted R^2	0.39	0.7	0.59	0.37	0.41	0.41	0.39	0.61	0.72		0.51	0.32
Cp	-3.2	3.2	13.9	-3.2	2	11.8	0.4	5.7	5.1		29.8	71.9

ns – not significant

* - $P < 0.05$

** - $P < 0.01$

*** - $P < 0.001$

**** - $P < 0.0001$

Table 5 (d): Best linear multiple regression equations for predicting the community indices from the environmental parameters.

M1 H' = 0.27 - 4.46 DO + 5.14 pH + 0.49 Prt.

B = 0.28 + 2.06 Sal. + 2.65 TOC - 4.14 TON

P = - 1.94 + 0.78 Mn.Gr.Sz. - 1.80 TON + 4.11 C-BPF

M2 H' = - 8.27 + 1.30 Mn.Gr.Sz. + 0.57 TOC + 2.47 Lip.

B = 3.54 - 0.40 Sal. + 0.34 TON - 1.18 C-BPF

P = 1.44 + 3.58 TOC - 5.98 TON + 2.54 Carb.

Z2 H' = 13.5 - 5.69 DO - 5.93 pH - 0.95 Carb.

B = -2.95 + 2.95 Sal. - 0.17 Sed. Srt

P = 9.98 - 12.3 DO + 1.31 Sed. Srt. + 2.64 TON - 6.07 Prt.

Z3 H' = ns

B = 1.06 + 0.41 Sal. - 0.69 TOC + 0.99 C-BPF

P = 13.0 - 0.75 Chl-*a*. -7.14 pH - 0.35 Mn.Gr.Sz.

H" – Species diversity
B – Biomass
P – Population density
TOC – Total organic carbon
TON – Total organic nitrogen
C-BPF – Carbon of biopolymeric fraction
Sed. Srt - Sediment sorting

DO – Dissolved oxygen
Sal. – Salinity
Mn. Gr. Sz. – Mean grain size
Prt. – Proteins
Carb. – Carbohydrates
Lip. – Lipids
Chl-*a* – Chlorophyll *a*

ns – not significant

CHAPTER 6

EFFECT OF ORGANIC ENRICHMENT ON MACROBENTHIC COMMUNITY STRUCTURE

6.1. INTRODUCTION

The most universal of environmental disturbances which may be loosely termed *"marine pollution"* and perhaps the best documented is that of the organic enrichment of marine waters. The world's highly productive estuaries are receiving a great quantity and variety of effluents as a result of man's activities. One category of effluents includes waste materials and solutions that have high concentrations of various nutrients that may stimulate primary production and thus increase the availability of organic material in the ecosystem. Assemblages of benthic macroinvertebrates form a characteristic response gradient with distance from sources of organic input or enrichment. Generally, three zones are recognised (Reish, 1973; Nichols, 1977). The first zone closest to the effluent source is abiotic (grossly polluted). This zone lacks any macrofauna due to hypoxic or anoxic conditions. At a greater distance there exists a polluted zone, generally categorised by a few, very tolerant species. In this polluted zone the total number of individuals may be high (Reish, 1973) due to exploitation of enhanced organic material by a few eurytopic species inhabiting this zone. Beyond the polluted zone is a normal unaffected zone with many more species and generally with a more even distribution of individuals among the species. The primary factor influencing this pattern is believed to be the oxygen gradient and the presence of any toxic substances (Pearson and Rosenberg, 1976). In some studies a fourth zone is found between the polluted and normal zones. This zone has been termed the enriched, hypertrophic or transitory zone (Reish, 1973; Pearson and Rosenberg, 1976).

In this zone the number of individuals, biomass and species may be increased above the levels in the normal zone.

Variation in the organic input to any area, whether from natural or artificial causes, results in changes in a complex of other chemical, physical and biological factors which in turn have direct and indirect effects on the fauna present. Hence, fluctuations in organic input may be considered to be one of the principal causes of faunal change in nearshore benthic environments. A number of recent studies have given details of macrobenthic community changes in relation to both organic gradients and other environmental variables. Such changes may be discerned through variations in space or, more relevantly, in time. Analysis of temporal variations resulting in successional change have ranged from seasonal studies to variations followed over periods of years.

Analyses of changes in benthic communities in response to environmental variations usually include estimates of the changes in the biomass of the total fauna, the faunal groups within the fauna, and of individual species. Such estimates may include the enumeration of individual species, and an assessment of changes in relation to other species and to the physical environment. Various mathematical techniques have been used to summarise the complex data so obtained, most commonly diversity indices, similarity indices and multivariate analysis (Pearson and Rosenberg, 1978).

A basic tenet of invertebrate ecology is that macrobenthos are good indicators of pollution (Rhoads and Young, 1970; Boesch, 1973, 1977; Reice and Wohlenberg, 1993), and thus benthic community structure is being

widely used in programmes on monitoring pollution effects (Warwick, 1986). These soft bottom macro-invertebrates are widely used in monitoring the effects of marine pollution, as they are mostly sessile, relatively larger in size, have a longer life span, and also due to availability of information about their general biology and taxonomy as compared to meio- and microfauna.

Soft bottom benthic organisms especially polychaetes are known to adapt as *r*- or *K*-selected strategies to different gradients of pollution. This will result in changes of benthic community structure from that of normal structure. The pattern of benthic community structure variation reflects the effects of pollutant over a period of time. Organisms adapt to high chemical stress by increasing their tolerance. Under high disturbance the best adaptive strategy is to have a high *r* value, by having a rapid reproductive rate and turn-over time, reaching maturity rapidly, and being relatively short-lived. Under normal conditions without pollution stress *r*-selected species are gradually outcompeted and replaced by *K*-selected species, which reproduce more slowly, are slow to reach maturity and are long-lived (Gray, 1981).

Generally, the richness and biomass of macrobenthic species are highest in stable, undisturbed communities and grade to depauperate populations in unstable regions of constant disturbance (Pearson and Rosenberg, 1978; Boesch and Rosenberg, 1981). Most confounding, however, is the response of populations to modest or irregular disturbance. Sewage pollution is primarily fine, particulate matter falling onto the sediment. The particles are rich in organic matter and bacterial activity is consequently high. If the sewage loading is high, many species are simply smothered by

the falling particles and cannot survive. Opportunistic species seem to gain advantage during times of disorder. They may rapidly colonise polluted sediments, may occur in high densities for relatively long periods of time, and may respond differently to each suite of environmental conditions (Andreeva and Andreeva, 1990; Diaz and Schaffner, 1990; Elias, 1992; Diaz and Rosenberg, 1995). For example, *Capitella* survives because it is a classical *r*-selected species: it can reproduce throughout the year, both by planktonic larvae and by benthic larvae, has a short life-cycle, and reaches maturity from the egg in about three weeks. It can, therefore, continuously repopulate sediments subjected to pollution from organic matter. *Capitella* does not use tolerance as an adaptive strategy, but adapts to continuous disturbance by continuous reproduction (Gray, 1981).

With pollution perturbation of a community, the *conservative species* are less favoured and are the first casualties while the *opportunistic species* are more favoured and often become the biomass dominant as well as the numerically dominant (Gray, 1979).

Benthos appears to respond in a characteristic manner with distance from the source of organic inputs or enrichment (Ansari et al, 1984). Generally three zones are recognised: *grossly polluted*, *polluted* and *unpolluted*. Pearson and Rosenberg (1976) reported a fourth zone called *enriched zone* where individual number, biomass and species may increase above the levels encountered in the normal zone (Dauer and Connor, 1980).

Earlier, the method of identifying pollution effects on benthos were relatively crude and generally based on the information about number of species, dominance of species and reduction in species diversity (Gray et al., 1988). Over the years a number of methods and techniques have been developed to distinguish the natural and pollution effects on the benthic community (Burd et al., 1990). Among these Pearson and Rosenberg Model (PRM-SAB curve) (Pearson and Rosenberg, 1978) is widely cited which states that high organic carbon enrichment will result in a decrease in species richness and increase in abundance by few opportunistic species, reduction of biomass except for a small increase at the peak of opportunistic species and decrease in body size of the average species or individual [Fig. 6(b)]. Based on these hypotheses a number of other methods have been evolved such as Abundance Biomass Comparison (ABC) curve technique (Warwick, 1986) where disturbance is evaluated based on trend of ABC curve [Fig. 6(d)] at the particular site without any reference site. Gray and Mirza (1979) also described geometrical class distribution of species plot to assess the site disturbance depending on the slope of the graph and number of geometrical classes. This method also allows the objective selection of group of indicator species (Gray and Pearson, 1982; Pearson et al., 1983). Feeding types of benthic organisms also help in evaluating the disturbance at particular site (Gaston and Nasci, 1988). Dominance of deposit feeders usually indicates organic pollution (Pearson and Rosenberg, 1978). Disturbance can also be assessed based on the slope of dominance-diversity curve (Southwood, 1978). Multivariate techniques such as cluster, MDS and principal component analysis are being used to discriminate sites based on the species attributes

(Field et al., 1982; Gray et al., 1988). Such univariate and multivariate techniques are used and evaluated for benthic data by numerous authors elsewhere (Gray et al., 1988; Hall, 1994; Warwick and Clarke, 1994; Reizopoulou et al., 1996; Lardicci and Rossi, 1998; Roth and Wilson, 1998; Frouin, 2000). However, validity of such techniques for use on marine global scale and different habitats needs to be tested along a known gradient since some of the methods may at times be unsuccessful as a measure of benthic community distribution (Weston, 1990; Reizopoulou et al., 1996; Lardicci and Rossi, 1998). There is no such approach from Indian seas, although there are a number of publications on benthos (Parulekar et al., 1980; Ansari et al., 1984; Harkantra and Parulekar, 1985, 1994). Some deal with pollution aspects based on diversity index or dominance of polychaete species (Raman and Ganapati, 1983; Parulekar et al., 1986; Devi et al., 1991). In view of this, an approach was made in this study to test the applicability and effectiveness of some of the univariate and multivariate techniques mentioned above by applying them to the numeric and biomass data of soft bottom macroinvertebrates obtained from a sewage discharge site near site M1. One of the aims of this study is to test some of the above hypotheses and to select a suitable objective analytical protocol that is simple to apply, and which preferably does not require reference control sites and gives comparative measure of pollution induced disturbance on the benthic community (Warwick, and Clarke, 1993; Agard et al., 1993). The present study deals with the impact of organic enrichment (sewage) on benthic life in the Mandovi estaury of Goa. This is the first time such approach is made for benthic data from tropical Indian coastal waters. This functional approach is

essential in understanding complex ecosystems, such as those in estuaries, as it provides a mechanism to view community response to disturbance and may be useful for assessing differences in ecosystem structure and function over space and time.

Mandovi estuary, which opens into the Arabian Sea near Panjim (site M1) on the west coast of India [(Fig. 6(a)] receives about 1300 million litres of urban runoff annually (Anonymous, 1978). During the present study, a section of the beach of the estuary, receiving domestic sewage through a "nullah", was sampled, at 3 different points, with I at high tide mark (sewage disposal point), II at mid tide mark and III at the low tide mark (described in detail in chapter 2). A reference point , i.e. IV was also sampled.

6.2. RESULTS

6.2.1 Data analyses

ABC curves (Warwick, 1986) and dominance-diversity curves (Southwood, 1978) were drawn to assess the disturbance at particular sites. Weighted pair group average squared Euclidean distance cluster analyses were carried out. The population and biomass data were transformed into double square root before any statistical analyses (Clarke and Green, 1988). These analyses were carried out using PRIMER – v5 software (Clarke and Gorley, 2001).

6.2.2 Environmental parameters

The salinity of water varied from 31.0 at site IV to 35.0 psu at site I ($\bar{X}$= 32.5 ± 1.37). The sediment temperature ranged from 26.9 at site IV to 32.0 °C at site I ($\bar{X}$ = 29.66 ±1.82). The dissolved oxygen of the surrounding water ranged between 0.75 at site I and 3.88 ml/l at site IV ($\bar{X}$ = 2.24 ± 0.96). BOD value of the same water varied from 0.045 at site II to 1.92 at site III ($\bar{X}$ = 0.80 ± 0.58). pH of water ranged from 7.11 at site I to 8.05 at site IV ($\bar{X}$= 7.46 ± 0.33). Sediment chlorophyll *a* ranged from 0.2055 at site IV to 1.403 µg/g at site II ($\bar{X}$= 0.94 ± 0.46). Organic carbon was the highest at site I with a value of 3.97 % and lowest at site IV with 0.10 % ($\bar{X}$ = 2.03 ± 1.40). Sediment texture was mainly sandy, with higher percentage of sand being recorded from I and IV (95.33 – 97.33%), while the other two sites II and III showed lesser percentage of sand (86.66 – 92.0%) **[Table 6(a)]**.

6.2.3 Biological characteristics

The total abundance of benthos ranged between 950.3 to 14641.5 n/m^2 ($\bar{X}$ = 4086.15 ± 4104.5), total biomass varied between 11.875 to 158.78 g/m^2 ($\bar{X}$ = 62.99 ± 49.66) **[Table 6(b)]**. Species number ranged between 7 to 19 ($\bar{X}$ = 13.41 ± 3.44), species diversity varied between 0.756 to 2.059 ($\bar{X}$= 1.70 ± 0.42), species richness ranged between 0.522 to 2.22 ($\bar{X}$= 1.57 ± 0.48) **[Table 6(c)]**.

The highest density was found at site I (sewage discharge point) with the faunal numbers reaching 10,210.76 nos/m^2, on an average. The lowest average was 1,360 nos/m^2 recorded at site IV (considered as reference site based on the low percentage of organic carbon i.e 0.10%). Highest average

biomass was also recorded from site I (139.81 g/m^2) while lowest value of 22.41g/m^2 was recorded from site IV. Species number was highest at site III which showed 17 species, on an average compared to lowest of 11 species at site I **[Table 6(b)]**.

Site I: A total of 11 species on an average were recorded from this site, their numbers ranging from 7-16. Total faunal density ranged from 7,174.4 – 14,641.5 ind/m^2 with an average of 10,210.76 ind/m^2. Similarly biomass ranged from 107.04 – 158.78g/m^2 with an average of 139.81 g/m^2. The capitellid , *Capitella capitata* was numerically the most dominant organism contributing nearly 31-77% of the fauna. The worm attained densities as high as 11,340.7 ind/m^2 at the point of sewage disposal. The nereid , *Perinereis nuntia* is next to *C. capitata* and accounted for nearly 8-26% of the total faunal density. Other more important species from this site are *Prionospio pinnata*, which accounted for nearly 0.77-14%, *Glycera alba*, *Diopatra neapolitana*, molluscs such as *Tellina ala* and the crab *Dotilla myctiroides*. Also the echiurid *Thalassema* sp. was recorded.

Site II: Species number increased to an average of 14 ranging from 11-18. Total faunal density ranged from 2,010.3 – 2851.8 ind/m^2 with an average of 2388.93 ind/m^2. Similarly biomass values varied from 32.92 – 54.87 g/m^2 with an average of 45.26 g/m^2. At this site the most dominant of all the polychaetes was *Prionospio pinnata* showing density range of 26-38%. This polychaete attained densities as high as 902.8 ind/m^2. The other polychaetes found at this site are *Capitella capitata, Nephthys polybranchia, Perinereis*

nuntia, Glycera alba, Goniada emerita. The bivalves comprised *Tellina ala* in higher numbers than other bivalves.

Site III: At this site the abundance of fauna ranged between 1,668.3 – 3316.8 ind/m^2 with an average of 2384.23 ind/m^2. While biomass varied from 34.12 – 50.90 g/m^2 having an average of 44.49 g/m^2. Species number varied between 14-19, showing an average of 17. The most dominant polychaete was *Prionospio pinnata* along with the bivalve *Tellina ala*. Both occurred in nearly the same densities. The other organisms comprised of *Capitella capitata* (in very few numbers, 136.8 – 314.6 ind/m^2), *Nephthys polybranchia, Perinereis nuntia, Glycera alba* and *Goniada emerita*.

Site IV: This site considered as the reference site (based on the comparatively low organic carbon values) showed an average of 12 species, ranging from 10-14. Faunal densities ranged from 950.3 – 1969.4 ind/m^2, with an average of 1360.66 ind/m^2. Biomass ranged from 11.87 – 40.06 g/m^2 with an average of 22.41 g/m^2. The polychaetes of this site comprised of *Prionospio pinnata*, *Nephthys polybranchia, Perinereis nuntia, Glycera alba* and *Goniada emerita*. Also *Capitella capitata* was present but in very less numbers (minimum 95.7 ind/m^2). Among bivalves *Tellina ala* was found in maximum numbers.

6.2.4 Determination of disturbance and comparison between the sites

SAB Curves **[Figs. 6 (b), 6(c)]**:

The basic quantitative parameters in almost all benthic ecological investigations are the number of species, their abundance and biomass. As the inputs increase species numbers and biomass initially increase, then decrease to the ecotone point, followed by secondary maxima of biomass and abundance associated with a few small opportunistic species which, if enrichment proceeds further, then fall off rapidly to an afaunal state. The *Species Abundance Biomass (SAB) curves* summarise the changes in the basic faunal parameters occurring along transects originating at the effluent discharge points and culminating in areas beyond the effects of the discharged material. Sediments in the vicinity of the discharge point are devoid of benthic macrofauna. The species first encountered are small and few. Further away from the most organically enriched area, the number of species rise, at first slowly, but after having passed the ecotone point the number increases more rapidly towards an asymptotic value. The *ecotone point* on this environmental gradient is a transition zone within which is a community poor in species, abundance, and biomass. On the heavily polluted side of this point, the community is composed of a few pollution-tolerant opportunistic species. On the less polluted side of the ecotone point the different transitory assemblages gradually approach the composition of the community in the unpolluted environment. The community at the ecotone point consists of species from both adjacent communities. There is an initial small peak in biomass corresponding to the maximum abundances of small opportunistic species, followed by a decline to the ecotone point. Beyond this,

the biomass increases to a second higher maximum as a greater variety of larger species are encountered, and finally stabilises at a somewhat lower level as the normal non-polluted communities develop. The secondary biomass maximum probably occurs in that area of the gradient where organic enrichment of the sediments is sufficient to provide a rich food source but not yet high enough to cause serious oxygen depletion. Thus, in short, it can be concluded that, as inputs increase species numbers and biomass initially increase, then decrease to the ecotone point, followed by secondary maxima of biomass and abundance associated with a few small opportunistic species which, if enrichment proceeds further,then fall off rapidly to an afaunal state (Pearson and Rosenberg, 1978) **[Fig. 6(b)]**.

In the present study also, where the organic inputs were highest, the biomass showed an increase along with an increase in abundance. But the species number remained to be low. As the biomass and abundance fell, species number began to rise **[Fig. 6(c)]**.

ABC Curves **[Figs. 6(d), 6(e)]**:

According to the scenario of pollution effects, the distribution of numbers (abundance) of individuals among species in macrobenthic communities behave differently from the distribution of biomass. The expected curves for unpolluted communities, have the biomass curve above the numbers curve throughout its entire length, indicating higher *"numbers diversity"* than *"biomass diversity"*. Under moderate pollution, the large competitive dominants are eliminated and the inequality in size between the numerical and biomass dominants is reduced so that there is no difference

between the biomass and numbers curves, which should be close together and may cross each other one or more times. As pollution becomes more severe, benthic communities become increasingly dominated numerically by one or a few very small species. In such a case, the numbers curve is above the biomass curve throughout its length showing higher *"biomass diversity"* than *"numbers diversity"* (Warwick, 1986) **[Fig. 6(d)]**.

In the present study, ABC curves showed that biomass curves lie above the abundance curves at sites II, III and IV during March and April and at II during May, indicating unpolluted sites. Biomass and abundance curves closely coincided and crossed each other at site I during March, April and May and at III and IV during May, indicating moderate pollution **[Fig. 6(e)]**.

Cluster classification **[Fig. 6(f)]**:

Clusters showed similarity of the fauna at different tide levels. The fauna at high tide (site I or sewage disposal site) formed one cluster and those at mid tide (site II), low tide (site III) and the reference site (site IV) formed another cluster based on faunal similarity **[Fig. 6(f)]**.

6.3 DISCUSSION

Salinity showed fluctuations predominantly due to the influence of tides and freshwater influx. Earlier investigations showed that this area is in the euhaline zone of the estuary and is also rich in organic carbon. So any heterogeneity in benthic populations at different sites may be due to variations in the substratum, depth, hydrological differences in the

environment and may also be due to the effect of sewage. Data on dissolved oxygen indicated very low values at the sewage outfall site. Here, nearly anoxic conditions existed evidently due to heavy loads of organic matter. In the area and close to it, only pollution – tolerant worms such as *Capitella capitata* lived, often in large numbers. At the sites away from this point oxygen availability was relatively more owing to the proximity of the open sea. Here the characteristic bottom inhabitants were *Prionospio pinnata, Perinereis nuntia*. Sites still further away, represented more oxidised environment and the faunal community shifted towards still higher numbers of *Prionospio pinnata* with some individuals of *Tellina ala*. Owing to several mixing processes characteristic of the sea, dissolved oxygen remains stable in this area.

It is well known that substrate organic matter represents a food source for deposit feeders (Mare, 1942) apart from it's value as an indicator of pollution (Parrish and Mackenthun, 1968; Wade, 1976). At site I or sewage outfall site where the organic carbon was the highest (3.97%) there was a depletion in the number of species. Such areas located near the outfall are characterised by high faunal densities (mean density 10,210.76 ind/m^2) with low species diversity (species number =11). Here only one or two pollution-tolerant species (*Capitella capitata*) inhabited the bottom. In the adjacent area (site II) where organic content ranged from 2.6 % to 2.82% (average 2.74%) as many as 14 species of fauna were encountered with an average faunal abundance of 2388.93 ind/m^2. At site III where the organic content was still low (0.19 %), the species number was still higher (average = 17) and average density was 2384.23 ind/m^2. At site IV where organic carbon was lowest (0.10

%), the species number remained 12 and densities remained at a low of 1360.66 ind/m^2.

The influence of sediment nature on the distribution of benthic organisms has often been the subject of study. During the present study, an attempt has been made to find out the substrate nature of the selected sites. At the outfall area the sediment was predominantly sand (medium to fine). These sediments were tainted and frequently possessed a sulphide odour. Individuals of *Capitella capitata* and *Prionospio pinnata* were the conspicuous inhabitants of such bottoms.

The major effect of sewage is that it reduces the oxygen content and stimulates the formation of H_2S which is harmful to the benthic fauna (Bozzini, 1975). This effect was clear at site I where oxygen of the interstitial water was very low compared to the values at other sites. It was further supported by the presence of black sulphide layer on the sediment surface. However, at the other sites there was a totally different effect on the macrofauna. Thus it appears that the enriched sediment attracts benthic population and encourages settlement of the favoured species.

It may be concluded that moderate input of organic enrichment like domestic sewage while encouraging the settlement of benthos may result in progressive build up of anoxic conditions on long term basis. Such stress conditions, if developed, will eliminate all but those few species with the capacity to survive the stress.

The numerical analytical techniques used showed evidence of effects of anthropogenic input on the benthic community at some of the sites studied. Some of the uni and multivariate techniques such as Abundance Biomass

Comparison (ABC) Curve and Species Abundance Biomass (SAB) Curve were found to be simple and effective techniques to diagnose the disturbance among the sites in the present study. The area under study could be categorised as "moderately polluted". However, it needs long term spatio-temporal data along the known pollution gradient to arrive to any definite conclusion and to apply the above techniques effectively.

Measurement of the biological impact of pollutant, as in the present study has a significant role in the management and conservation of productive estuarine environment. Unless preventive measures are taken to minimise the human interference with these sensitive environments, it may result in heavy loss of the estuarine life on a long-term basis.

Faunal List

Polychaeta

Prionospio cirrifera, Wiren

Prionospio pinnata, Ehlers

Diopatra neapolitana, Delle Chiaje

Nephthys polybranchia, Southern

Nereis burmensis, Monro

Dendronereis aestuarina, Southern

Perinereis cultrifera, Grube

Perinereis nuntia, Savigny

Glycera alba, Rathke

Goniada emerita, Audouin and Milne-Edwards

Cirratulus filiformis, Keferstein

Terebella ehrenbergi, Grube

Capitella capitata, Fabricius

Bivalvia

Meretrix casta, (Chemnitz)

Paphia malabarica, (Chemnitz)

Perna indica, (Henley)

Lutraria arcuata, Deshayes

Cardium flavum, Linné

Tellina ala, Hanley

Solen truncatus, Wood

Dosinia puella, Angas

Gastropoda

Cerithedia fluviatilis, (Potiéz and Michaud)

Turritella attenuata, Reeve

Natica tigrina, (Röding)

Oliva gibbosa, (Born)

Littorina sp.

Crustacea

Metapenaeus dobsoni, (Miers)

Diogene affinis, Henderson

Dotilla myctiroides, Milne-Edwards

Sesarme oceanica,

Cumacea

Scotollana sp.

Gammarus sp.

Other groups

Edwardsia tinctrix, Annandale

Lingula anatina, Lamarck

Thalassema sp.

Poecilochaetous johnsoni

Table 6 (a): Summary of the environmental parameters at the different sites.

March	Salinity (psu)	pH	DO (ml/l)	BOD	Temperature (^{0}C)	Organic carbon (%)	% of sand	Chl-*a* (µg/g)
I	35.0	7.11	0.79	0.81	27.7	3.74	97.33	1.00
II	32.0	7.27	2.01	0.10	27.0	2.60	92.0	1.2691
III	33.0	7.14	2.84	1.64	27.8	1.45	90.66	0.7406
IV	31.0	7.68	2.9	0.94	26.9	0.13	97.33	0.2055
April								
I	31.1	7.11	0.75	0.75	32.0	3.60	96.0	1.108
II	33.0	7.23	2.84	0.045	30.7	2.81	90.4	1.331
III	33.5	7.13	2.18	0.581	30.3	1.19	91.8	1.1109
IV	31.5	7.72	1.89	0.497	30.0	0.10	97.0	0.2323
May								
I	32.0	7.72	1.59	0.84	31.5	3.97	95.33	1.295
II	31.5	7.75	1.82	0.32	31.0	2.82	86.66	1.403
III	32.5	7.72	3.42	1.92	31.1	1.56	92.0	1.388
IV	32.5	8.05	3.88	1.24	30.0	0.49	96.0	0.250

Table 6 (b): Summary of the biological characteristics at different sites.

March	Abundance (nos/m^2)	Biomass (g/m^2)
I	14641.5	107.04
II	2851.8	54.87
III	1668.3	34.13
IV	1969.4	40.06
April		
I	8816.4	153.62
II	2304.7	48.01
III	2167.6	50.90
IV	950.3	11.87
May		
I	7174.4	158.78
II	2010.3	32.92
III	3316.8	48.44
IV	1162.3	15.30

Table 6 (c): Summary of the community indices at different sites.

	Sp. no.	H'	J	SR
March				
I	7	0.756	0.4223	0.522
II	13	2.004	0.7815	1.508
III	17	1.995	0.7043	2.156
IV	14	1.904	0.7214	1.714
April				
I	11	0.918	0.3828	1.101
II	11	1.848	0.7705	1.292
III	14	1.91	0.7238	1.692
IV	10	1.876	0.8147	1.313
May				
I	16	1.622	0.5851	1.69
II	17	1.844	0.6509	2.105
III	19	2.059	0.6992	2.22
IV	12	1.683	0.6771	1.558

Sp. no. – Species number H'–Species diversity

J–Species evenness SR–Species richness

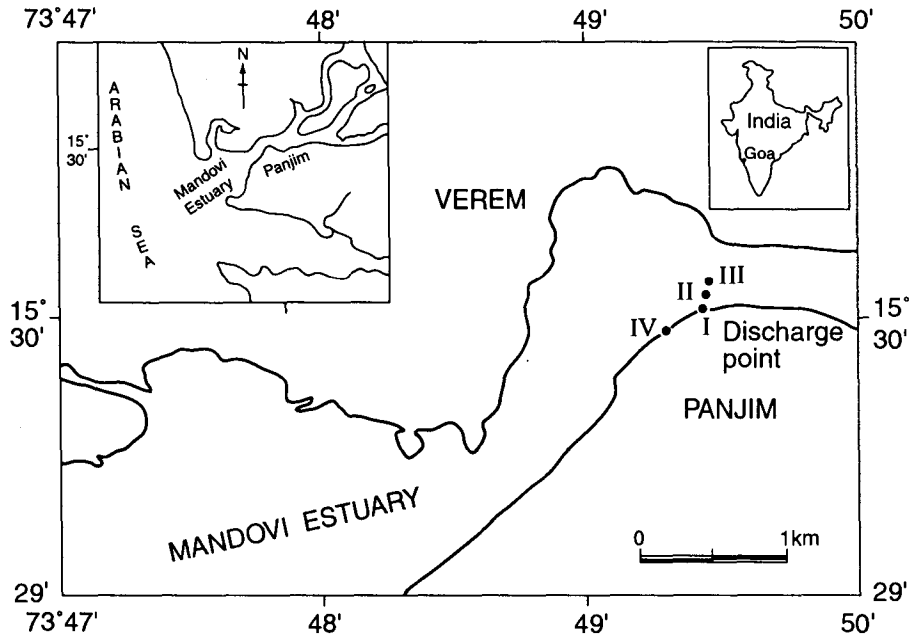


Fig. 6(a) Map showing sites of sewage derived organic enrichment gradient in the Mandovi estuary.

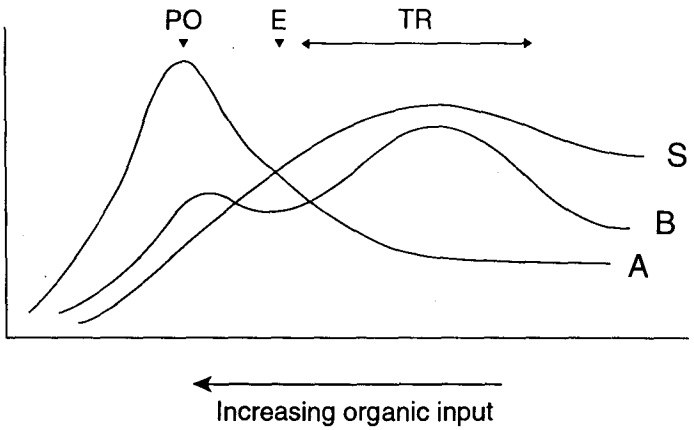


Fig. 6 (b) Generalised SAB curve, of changes along a gradient of organic enrichment; S - species number, A - total abundance. B - total biomass, PO - peak opportunists, E - ecotone point, TR - transition zone.

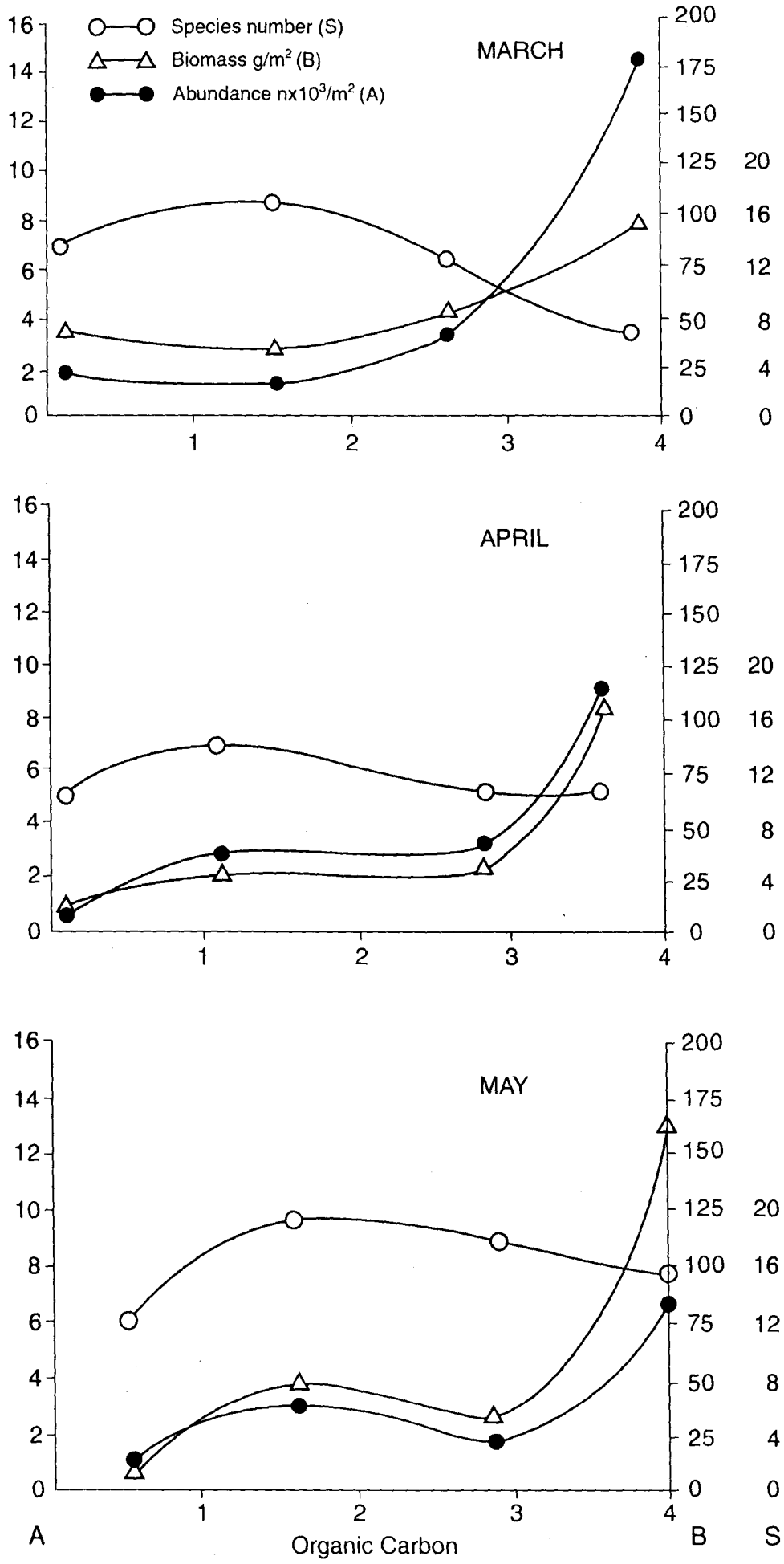


Fig. 6(c) Species, abundance and biomass curve

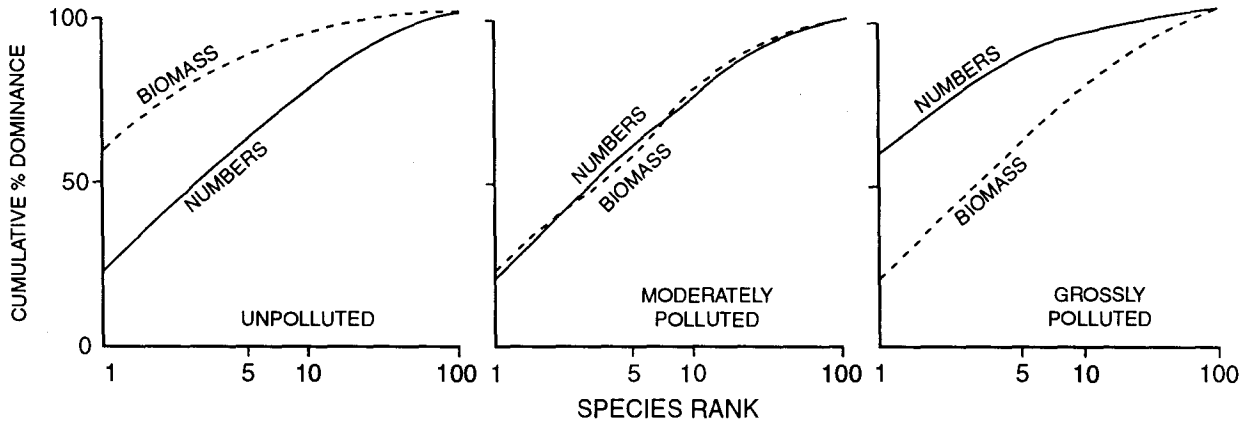
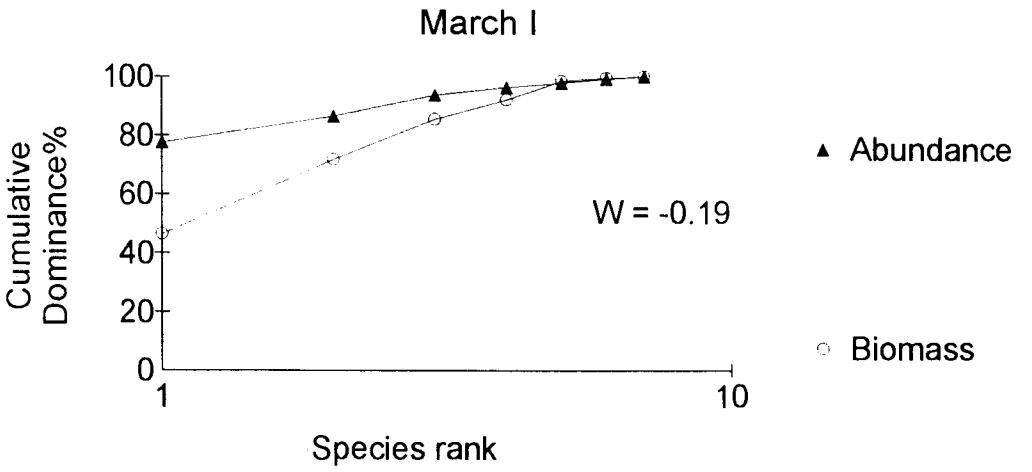
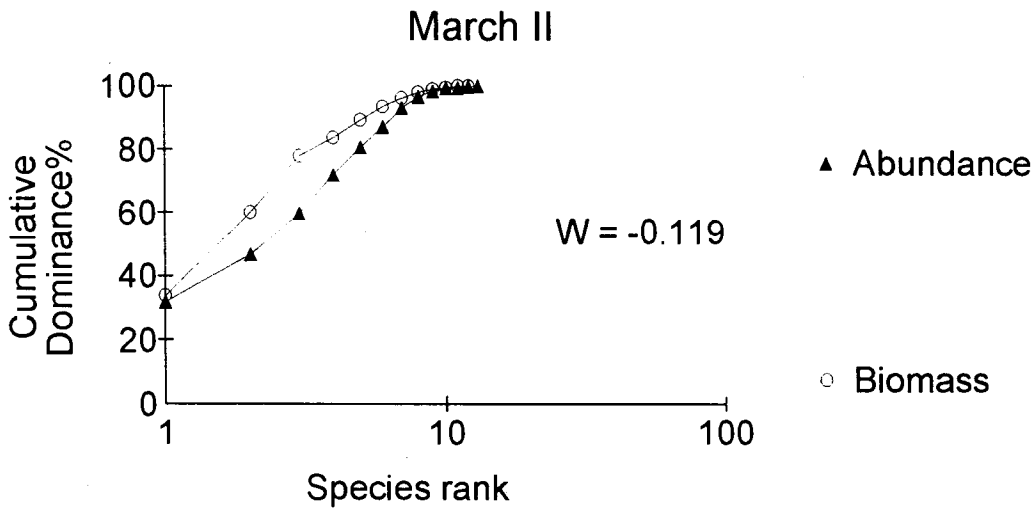
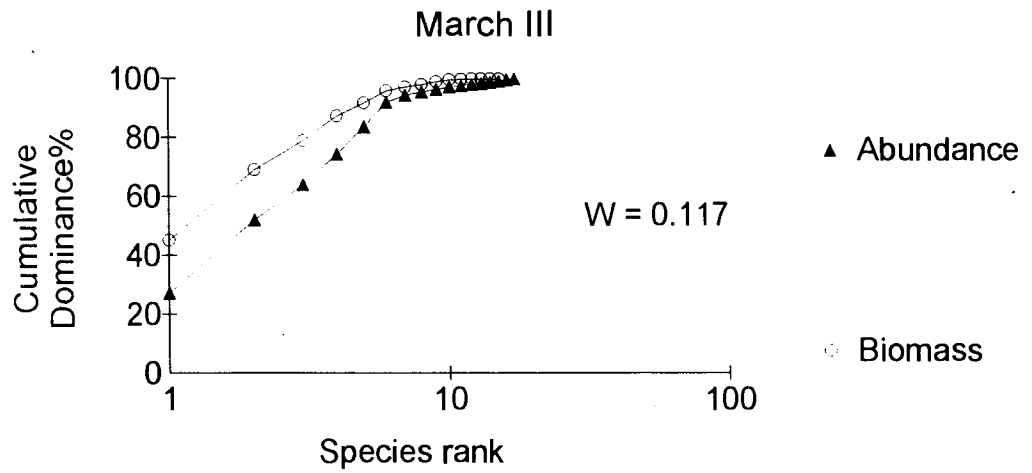
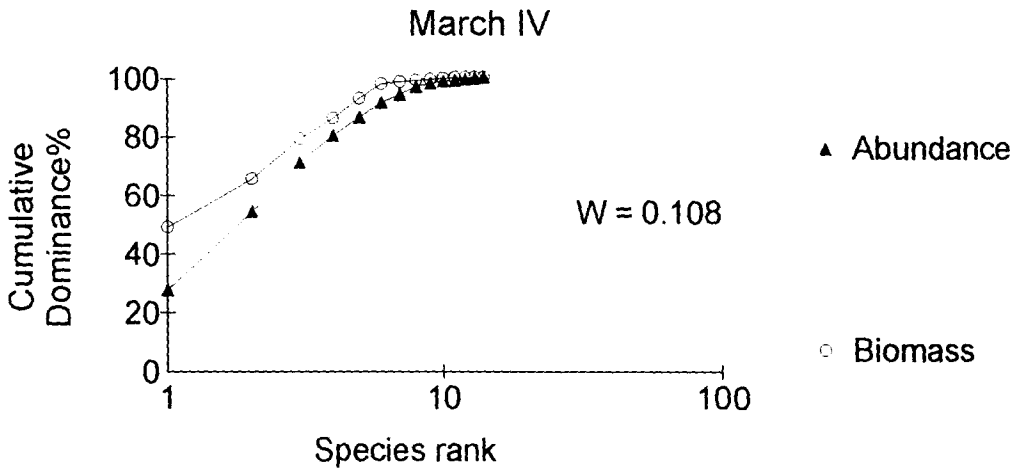


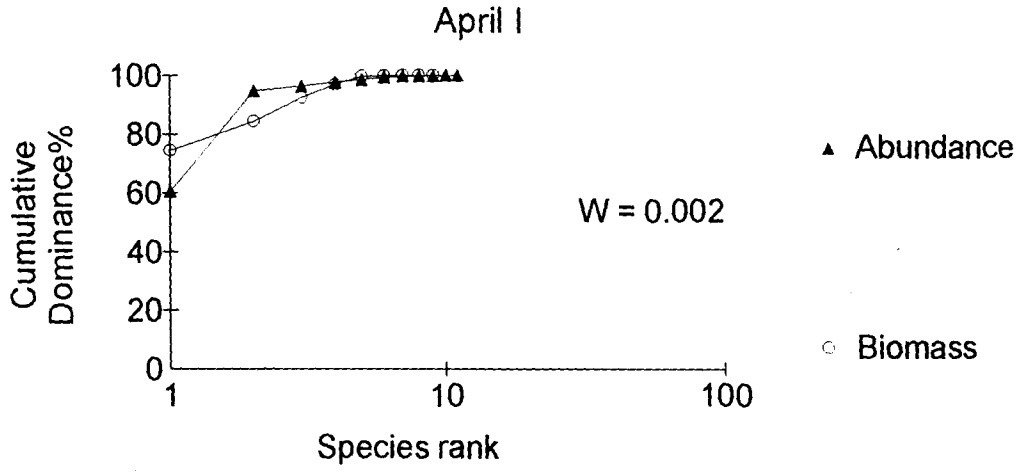
Fig. 6 (d) Hypothetical abundance - biomass curves

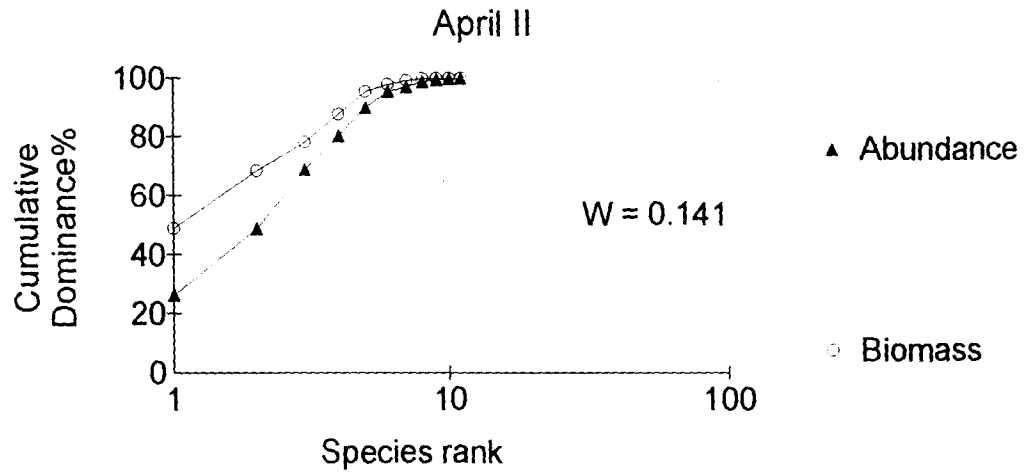

March I
Cumulative Dominance%
100
80
60
40
20
0
1
10
W = -0.19
Abundance
Biomass
Species rank

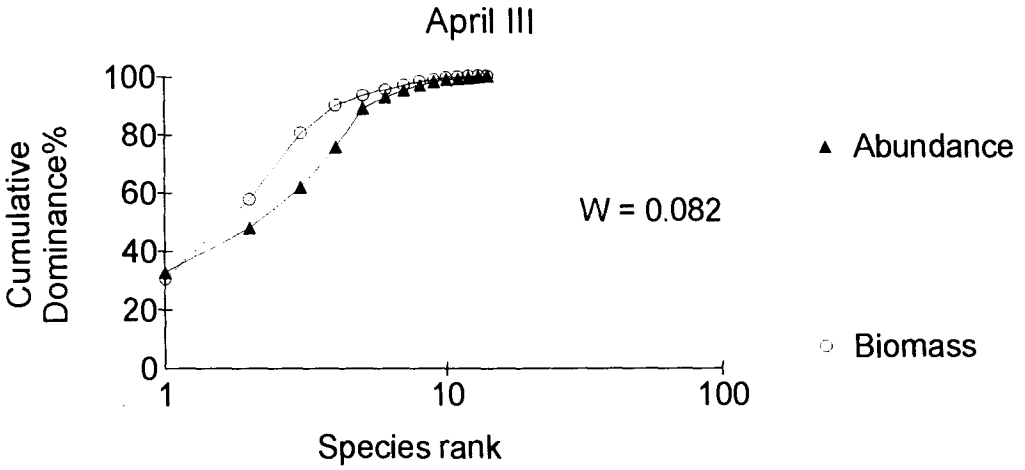

March II
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
W = -0.119
Abundance
Biomass
Species rank

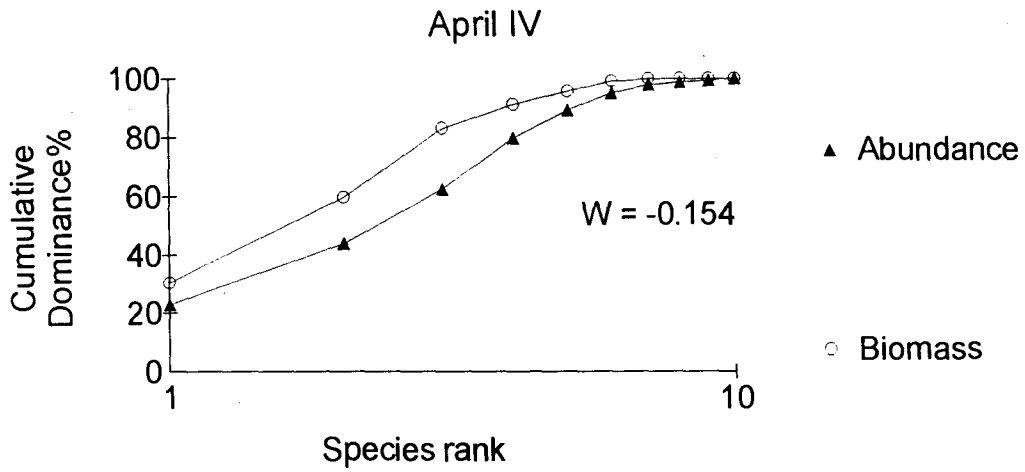

March III
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
W = 0.117
Abundance
Biomass
Species rank

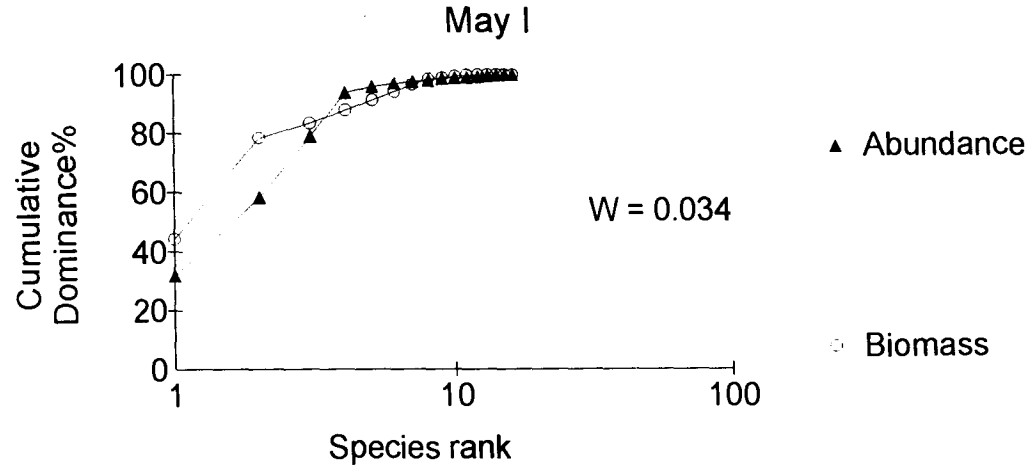

March IV
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
Species rank
W = 0.108
Abundance
Biomass


April I
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
Species rank
W = 0.002
Abundance
Biomass


April II
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
Species rank
W = 0.141
Abundance
Biomass


April III
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
Species rank
W = 0.082
Abundance
Biomass


April IV
Cumulative Dominance%
100
80
60
40
20
0
1
10
Species rank
W = -0.154
Abundance
Biomass


May I
Cumulative Dominance%
100
80
60
40
20
0
1
10
100
Species rank
W = 0.034
Abundance
Biomass

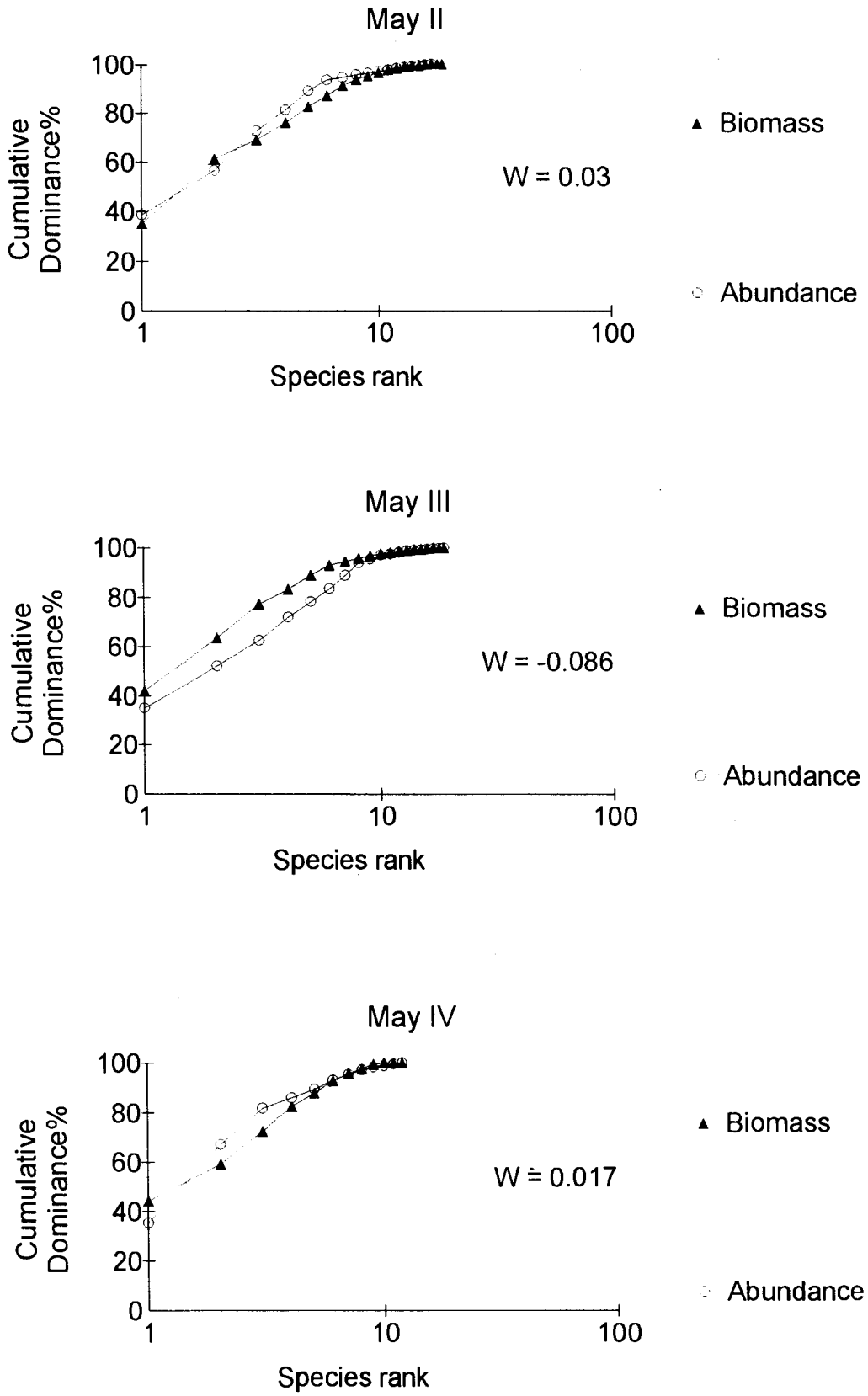


Fig. 6(e): ABC curves for macrofauna at different sites during different months.

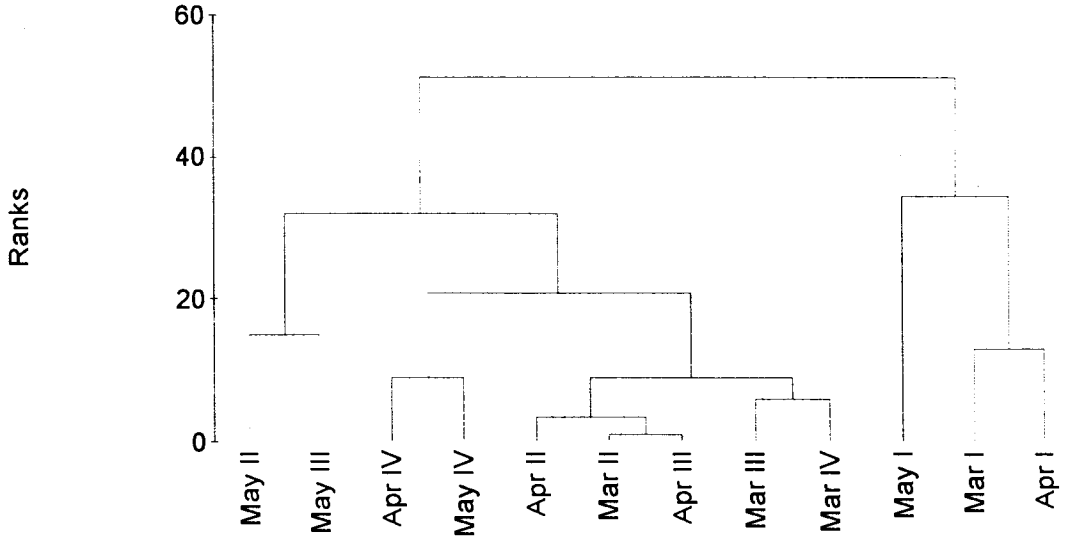


Fig. 6 (f): Site clustering for different months.

CHAPTER 7

ASSESSMENT OF BIOTURBATION ACTIVITIES

7.1 INTRODUCTION

Bioturbation is a phenomenon of particle reworking by benthic organisms during the process of feeding, defecation, locomotion and respiration. A variety of biological, chemical, geological and physical changes occur around sediment-water interface due to these macrofaunal activities. Vertical stratification and redox potential discontinuity (RPD) layers are altered due to the burrowing fauna. New structures such as burrows and tubes are formed. These affect rates of diffusion of dissolved nutrients, gases and synthesis of refractory or inhabitory structural products (tube lining, halophenols and body structural products). The chemical environment is locally altered by the metabolic activities of sediment-inhabiting macroinvertebrates. The burrowing macrofauna are able to form new potential niches for the enrichment of a variety of physiologically diverse micro-organisms due to irrigation, aeration of subsurface sediment layers, particle transport as a feature of different feeding habits, excretion of nutrients, metabolites and defecation. Bioturbated structures such as burrow walls and fecal casts have been recognised as potential enrichment sites for the sediment bacteria. Inspite of it's importance, there is no much information from Indian waters, although a lot of work has been done in USA and Europe. Hence, studies were carried out to understand the role of bioturbation brought about by benthic organisms. Although these studies are preliminary the data generated here helps in better understanding of benthic dynamics in trophic ecosystem .

Numerous studies have indicated the importance of bioturbation in the sediment in the marine environment. Inspite of significant influence no such

studies are being carried out in India, though it has been studied extensively elsewhere.

There are numerous methods to assess the bioturbation process. Among these chlorophyll *a* is widely used as a tracer to assess the bioturbation process. Other methods include studies on nutrient flux from the sediment to the water column due to bioturbation activities of the benthic organisms and estimation of sediment turnover or sediment reworking rate by bioturbating organisms.

7.2 Chlorophyll-*a* as a marker for bioturbation activities

7.2.1 INTRODUCTION:

About 30% of phytoplankton carbon produced by photosynthesis is delivered to the seafloor based on Riley's (1956) estimate of primary production.

Chlorophyll *a* is widely used to estimate water column phytoplankton biomass because it is the most abundant pigment component in almost all species of phytoplankton. Bioturbation is a phenomenon of particle reworking by benthic organisms during the process of feeding, defecation, locomotion and respiration. A variety of biological, chemical, geological and physical changes occur around sediment-water interface due to these benthic faunal activities (Aller and Aller, 1998).

This aspect has been extensively studied in temperate waters (Aller and Aller, 1998; Boon and Duniveld, 1998; Stoeck and Kroncke, 2001) and numerous techniques had been used to assess this process (Gerino et al., 1998). Among these estimation of chlorophyll *a* is one of the techniques which is largely used since it is the most abundant pigment in the water column (Sun et al., 1991; 1994). Primary production by phytoplankton in surface waters is a major source of labile organic carbon to coastal sediments. Nearly 40% of the particles from the euphotic zone sink to the sediment-water interface (Bhaskar et al., 2000), where the benthic organisms such as macro and meiofauna, bacteria, virus etc. rapidly degrade it and related chemical processes take place in the labile organic compounds present in the settled materials (Aller and Aller, 1998).Thus chlorophyll *a* can be used as an indicator of metabolisable organic

matter delivered to the sea-floor as a food source for benthic organisms (Kanneworff and Christensen, 1986). In water column, cholrophyll *a* can be converted into phaeopigments (derivatives of Chl-*a* with similar ring structures) as well as colourless residues during bacterial, viral, or autolytic cell lysis, photo-oxidation, and grazing activities by zooplankton (Welschmeyer and Lorenzen, 1985). Also, particles from the euphotic zone sink to the sediment-water interface, where benthic organisms rapidly degrade the labile organic compounds present in the settled materials by various chemical processes (Andersen and Christensen, 1992; Sun et al., 1994). Phaeopigments can be used as diagnostic indicators of physiological status, detrital content and grazing processes in natural populations of phytoplankton (Mantoura and Llewellyn, 1983). With sinking of intact cells, fecal pellets, carcassess, and clumps of detrital particles, chl-*a* and its major degradation products are delivered to the seafloor. After deposition, these labile chloropigments are rapidly degraded by benthic organisms. The rate and extent of organic matter degradation significantly affect the chemistry of marine sediments (Berner, 1980). Sediment mixing by macrofauna has been proposed as a dominant mechanism for redistributing organic material in subsurface sediments (Wheatcroft et al., 1990; Blair et al., 1996). Sedimentary chlorophyll distributions reflect supply from primary production in overlying waters, transport during sedimentation/bioturbation and alteration due to decomposition/transformation reactions. Thus, the resulting sedimentary chloropigment profile has potential

use for estimating the rates of certain biogeochemical processes occuring at and just below sediment water interface.

Inspite of its importance there is no information on this aspect from the coastal shelf of India. Hence to examine the bioturbation processes this study was carried out to examine chlorophyll *a* and phyaeophytin profile in the sediment column at site A during October 1997 to May 1998.

7.2.2 RESULTS

[Figs. 7(a) & (b)] reveal the temporal variation of Chl-*a* and phaeophytin on a vertical scale. Surface chlorophyll *a* varied between 0.45-.80 ug/g, with mean value of $\bar{X}$=0.65 ± 0.12, and phaeophytin varied between 3.5-7.0 ug/g, with mean value of 5.93 ± 1.47. These values increased from post to premonsoon months. The vertical profile of chlorophyll *a* concentration at each month decreased exponentially below sediment–water interface and approached lower during post monsoon months, essentially constant, background level at depth. Chl-*a* concentration gradients with depth were large and sub-surface maxima were observed in premonsoon months. Phaeophytin increased concentration with depth and from post to premonsoon **[Table 7(c)]**. Similarly phaeophytin /chlorophyll *a* ratio increased with depth and from post to premonsoon **[Table 7(c)]**.

Integrated inventories of chloropigment *a* varied between between 2.37-5.5 ug/g, with a mean value of $\bar{X}$=4.08 ± 1.12 and phaeophytin varied between

23.8-38.0, with a mean value of $\bar{X}$=32.90 ± 7.03. Similarly, reactive inventories of chloropigment varied between 1.75-4.2 ug/g with mean value of $\bar{X}$=3.16 ± 0.88 and phaeophytin 15.8-28.0, $\bar{X}$=24.13 ± 5.42. Pattern of temporal variation of integrated inventories of chloropigment and phaeophytin followed similar pattern of variation as that of surface chlorophyll *a*. Seasonally, chlorophyll *a* surface and reactive inventories were greater premonsoon months bloom period and smaller during postmonsoon months. Peak values of pigments between the sediment and water did not coincide with each other. However, there was a time lag of I-2 months between the maximum values in the sedimentary and water column pigments. This offset in maximum concentration reflects reaction occurring both in water column and sediments (Sun et al 1991;1994). Chlorophyll *a* in intact cell can be converted into phaeopigment during grazing zooplankton (Downs, 1989). The lag between the appearances of Chl-*a* and the paeopigment in the sediment may reflect the difference in time dependent growth pattern of water column phytoplankton and later delivery of zooplankton faeces to bottom. Off Cabo, the offset between maximum primary production in late early summer and maximum zooplankton abundance is similar to the lag between the maximum sedimentary chlorophyll *a* and phaeopigment invetories.

7.2.3 DISCUSSION

Monthly and seasonal variations of sedimentary chlorophyll *a* reflect seasonal variation of phytoplankton in the water column. High surface concentrations in upper 2 cm and inventories in the upper 10 cm occur during

premonsoon, immediately after the major annual bloom, while lower value occur in postmonsoon. However, there seems to be a time lag between maximum values for chlorophyll *a* in early post-monsoon and those for total identified phaeophytin in late premonsoon. This offset in maximum concentration may reflect reactions occurring both in the water column and at the seafloor.

Chlorophyll *a* in intact cell can be converted into phaeopigment during grazing zooplankton (Downs, 1989). The lag between the appearances of chlorophyll *a* and the paeopigment in the sediment may reflect the difference in time dependent growth pattern of water column phytoplankton and later delivery of zooplankton faeces to the bottom. Off Cabo, the offset between maximum primary production in late early summer and maximum zooplankton abundance is similar to the lag between the maximum sedimentary chlorophyll *a* and phaeopigment inventories. The differential rate of pigment conversion in the bottom sediments should produce the observed relative inventories successions (Sun et al., 1994), but as shown subsequently, vertical profile implies more substantial role for water column or surface most sediment reactions.

Surface concentration of chloropigments exhibit relatively stronger seasonal changes than the inventories because inventories reflect input and degradation process integrated over longer time scales. Mixing processes due to bioturbation can also transport labile organic matter from the interface to deeper sediments, decreasing surface concentrations. With increase of temperature in summer, mineralization of organic carbon and mixing speeds up due to increased benthic organism activity.

Depth penetration pattern

Depth distributions of chloropigments are mainly controlled by mixing and degradation processes. The nearly exponential decrease of chlorophyll *a* with depth in many cases demonstrates that degradation is faster than particle transport. Characteristic penetration to background level is ~4-5 cm. The profile of phaeophytin often exhibits a slight increase with depth presumably due to zooplankton grazing and delivery from the water column.

The increase in phaeophytin concentration with depth implies significant *in situ* production due to chlorophyll *a* degradation within the sediments. Experiments reveal that paheophytin is one of the major products of Chl-*a* degradation in the sediments. The ratios of phaeophytin / chlorophyll *a* always increase with depth, suggesting that either the phaeophytin accumulates due to production during chlorophyll *a* degradation or decay at lower rate than chlorophyll *a*.

In general, relatively larger concentration gradients occur with depth and reactive chloropigments penetrate only 2-4 cm during summer when the deposition of chloropigments from the overlying water is high. Reactive chloropigments penetrate deeper 4-8 cm at late summer although supply is presumably lower. Several processes may cause subsurface maxima in the pigment profiles: variable input, vertical and lateral transport, variable decay rates and mechanisms with depth. Vertical transport within deposits involves both diffusive mixing (dependent on concentration gradient) and non-diffusive

(advective) mixing. Diffusive mixing together with depth-independent decay cannot result in subsurface maxima, even with variable input. When the surface input is low and activities of the organisms become more intense during warmer periods, nondiffusive mixing may dominate vertical transport of pigment through *'conveyer-belt'* feeding (Rice, 1980).

Bioturbation also leads to oscillation of particles between oxic and anoxic conditions during mixing and resuspension (Aller, 1982).

7.3 Microcosm experiments for nutrient flux studies

7.3.1 INTRODUCTION

Sediment plays a crucial role in determining the load and chemical form of nutrients in marine ecosystems. It acts as a substrate and provides continuous supply of food source for benthic organisms. The surface sediment particularly in shallow water may exert a strong influence on nutrient recycling between the sediment and the water column (Fisher et al., 1982). However, the bottom sediment in deeper depths can act both as a source and sink for nutrient dynamics of the system (Skyring et al., 1992). The integrity of the sediment is affected by various behavioural activities of benthic organisms which have penetrating influence on the physical, chemical, biological and geological properties of the sediment (Bordovsky, 1965; Aller and Aller, 1998). Bioturbation or sediment reworking by benthic burrowing organisms is one such activity and refers to the spatial rearrangement of the sediments by diverse benthic organisms resulting in the mixing of the sediment layers. This implies that all sedimentary particles in the upper layers, inhabited by benthic fauna are subjected to a continual transfer and this activity can reach to a considerable sediment depth (Schulz, 2000). Sediment reworking rates and the subsequent agitation of the surface sediment to greater depths by burrowing animals plays an important role in mixing up of nutrients (Marinelli, 1994).

7.3.2 RESULTS

NO_3 value in the bioturbated tanks (tanks containing sediment, water and crabs and those containing water and crabs) was 3.39 µg at. N/l at 0 hours. It increased to 3.47 µg at. N/l after 6 hours. At 12, 18 and 24 hours it was 3.54, 3.65 and 3.79 µg at. N/l respectively **[Fig 7(d)]**. These values were higher than those recorded from tanks without the crabs (tanks containing only water and those containing only sediment and water). Tanks containing only water showed a gradual decrease in the NO_3 concentrations from 3.39 µg at. N/l to 3.34 µg at. N/l. Whereas those containing sediment and water showed a decrease in the NO_3 concentration from 3.39 µg at. N/l to 3.28 µg at. N/l.

7.3.3 DISCUSSION

The crab *Dotilla myctiroides* is known to bring about sediment reworking (refer to section 7.4) due to it's burrowing activity. This process releases the nutrients from the sediment to the water column thereby enhancing it's productivity (Kristensen and Blackburn, 1987). In the present study increase in NO^3 values in the bioturbated tanks could be due to sediment reworking by the crabs. This inference is based on preliminary studies only. However, detailed studies have to be carried out to arrive to any definite conclusion.

7.4 Estimation of sediment reworking rate by the crab, *Dotilla myctiroides*

7.4.1 INTRODUCTION

Benthic organisms injest small particles by one of the three mechanisms namely: filter feeding, browsing and deposit feeding. Filter feeding organisms such as bivalves, filter the suspended materials from the water column above the sediment. The browsing organisms such as the amphipods, isopods scrape material from the surface and the sediment-water interface. The deposit feeding organisms such as annelids, bivalves, gastropods and crustaceans injest sediment particles directly by burrowing in the sediment (Parsons et al. 1977). In biogenic sediment reworking, the deposit feeders play a major role in the sediment turnover (Harkantra et al., 1989; Berkenbusch and Rowden, 1999). The turnover can take place through different bioturbational modes namely: conveyor belt mode, reverse belt mode and biodiffusive mode (Wheatcroft et al., 1994).

The burrowing activity of some organisms such as the large size polychaetes and the burrowing crabs may alter the benthic habitat within a very short time due to very high rates of sediment reworking. Roberts et al. (1981) and Colin et al. (1986) showed that *Callianassa* species could cause very high rates of sediment reworking (3.9 kg/m^2/day) thus altering the habitat. Similarly, working on a burrowing beach crab *Ocypode* species, De (1998) reported severe erosion on a sandy beach in 3 to 4 years. While Botto and Iribarne (2000) estimated sediment reworking of about 2.2 kg/m^2/day by *Chasmagnathus* species. Since the reworked material is rich in the dissolved nutrients (Tuominen

et al., 1999) and the particulate organic matter (Colin et al., 1986), it increases the nutrient level and the biological productivity of the surrounding waters. Therefore bioturbation can affect the physical, chemical, biological and geological structures of the sediment and residential faunal communities. Deposit feeders bring about manipulation in the size of the sedimentary particles which occurs when the organism injests the sediment as a whole and then expels any undigested particles in a consolidated mass called fecal pellets (Hughes et al., 1996). Rhoads and Young (1970) suggested that the pumping of the fine sediment particles and deposition of fecal pellets by deposit feeders at the sediment-water interface result in the resuspension of the sediment by very slow water movements. This may discourage the filter feeders from settling due to the apparent clogging of the filtering structures. Also the movement, ingestion and defecation of sediments by deposit feeders increases the fluffiness of the sediments.

Sediment reworking process not only recycles the dissolved nutrients in sediment-water interface but also helps in supplying the dissolved oxygen to the deeper sediment layers through pumping of seawater into tubes (Kristensen, 1985). Bioturbation and bioirrigation work simultaneously and transform the simple one-dimensional exchange between sediment pore water and the overlying water (Aller, 1983). It also results in the transport of newly deposited organic matter to the deeper levels (Aller and Yingst, 1980). Thus the nature and the rate of sediment reworking can act as a major factor in deciding the biogeochemical and transportation processes.

The present study is designed to investigate the rate of sediment reworking by the soldier crab, *Dotilla myctiroides*, by carrying out microcosm experiments in the laboratory.

7.4.2 RESULTS:

Carapace length of the various individuals collected varied from 0.4 – 1.8 cm. The sediment that was reworked from the respective burrows was weighed and found to vary between 3.4 – 15.38 g/h/individual with an average value of 7.34 g/h/individual. The sediment reworking rate showed significant positive correlation with the carapace length ($Y = 5.7846X + 1.6077$, $R^2 = 0.6098$, $n = 12$) **[Fig 7(e)]**. From the regression equation the calculated weight of the reworked sediment was found to range from 3.92 – 12.01 g/h/individual with an average of 7.33 g/h/individual. The average density of the crabs in the field is found to be 92 individuals/m^2. Therefore the reworking rate works out to be 675.28 g/h/m^2.

7.4.3 DISCUSSION:

Many studies have been carried out by several workers on sediment reworking by various organisms. Various benthic organisms can bring about bioturbation. Some of them are *Callianassa* sp. (Tamaki and Suzukawa, 1991; Rowden and Jones, 1994), *Uca* sp. (Olafsson and Ndaro, 1997), *Dotilla* sp. (Olafsson and Ndaro, 1997), *Capitella* sp. (Dauwe et al., 1998), *Chasmagnathus* sp. (Botto and Iribarne, 2000). In particular investigators have singled out the thalassinidean shrimps and the burrowing crabs as important bioturbators.

Roberts et al. (1981) and Colin et al. (1986) showed that *Callianassa* sp. could cause very high rates of sediment reworking (3.9 kg/m^2/day. While Botto and Iribarne (2000) estimated sediment reworking of about 2.2 kg/m^2/day by *Chasmagnathus* sp.

Particle reworking modifies the sediment transport (Jumars and Nowell, 1984), alters the sediment geochemistry (Aller, 1983), increases oxygenation and mineralisation (Kristensen, 1985), brings about fecal pellet accumulation (Rhoads et al., 1977). Bioturbation increases the surface area available for the exchange of nutrients and modifies the redox and adsorption-desorption characteristics of the sediment. Aller and Dodge (1974), showed that bioturbation inhibits suspension feeders due to high rate of sediment turnover. Studies by Driscoll (1975) on sediment-water interaction reported that reworking brings about a seasonal change in the organic content of the sediment. Aller and Aller (1998) have shown that solute transport during the benthic activity stimulates the microbial mnineralisation within the bioturbated zone, which in turn increases the mineralisation rates of the benthic organic matter (Aller and Yingst, 1978). Thus benthic deposit feeders are regarded as the important regenerators of nutrients for pelagic productivity (Doering, 1979).

Table 7(a): Chlorophyll-*a* (Chl-*a* mg/m^3), paheophytin (Phaeo mg/m^3) and primary production (Pp mgC/hr/m^3 in water column of study site).

Months	Surface Chl-a	Surface Phaeo	Bottom Chl-a	Bottom Phaeo-a	Surface Pp	Surface Pp
O	2.65	1.09	2.18	0.08	1.99	0.54
N	0.87	0.38	2.39	0.08	11.53	27.62
D	2.06	0	2.28	0	44.75	54.69
J	0.54	0	0.72	0	41.58	28.76
F	0.93	0.003	0.09	0.09	10.83	2.86
M	0.49	0.05	0.07	0.31	15.34	0.86
A	0.62	0.003	0.3	0.2	11.64	0.63
M	1.68	0.22	0.22	0.06	7.84	0.5
Mean ($\bar{x}$)	1.23	0.21	1.03	0.1	18.18	14.55
SD (±)	0.8	0.37	1.05	0.1	15.9	20.33

Table 7(b): Environmental parameters in study site

Parameters	Months								Mean (x)	SD ( )
	O	N	D	J	F	M	A	M		
Temperature (^{0}C)	26	26.5	27	27.5	28	28.5	28.8	29	27.66	1.1
Salinity (psu)	34.1	34.5	34.7	34.8	35	35.2	35.4	35	34.83	0.41
Dissolved Oxygen (ml/l)	1.28	3.91	5.26	5.3	4.85	2.42	5.04	4.8	4.1	1.48
pH	7.5	7.8	7.9	8.15	7.6	7.7	8.1	8.2	7.86	0.26
Sand %	1.6	1.5	1.4	1.7	1.8	1.9	1.7	1.8	1.67	0.17
Silt %	69.7	69.5	69.3	68.9	67.5	68.5	68.4	68.3	68.76	0.73
Clay %	28.7	29	29.3	29.4	30.7	29.6	29.9	29.9	29.56	0.61
Mean Grain size (mm)	0.015	0.016	0.014	0.015	0.015	0.016	0.014	0.015	0.015	0.0007
Sediment sorting	0.6	0.61	0.59	0.6	0.6	0.59	0.6	0.61	0.601	0.0075
Total ortganic carbon (µg/g)	23811	18971	25747	18687	21177	24603	20597	23012	22075.62	2615.07
Total organic nitrogen (µg/g)	2553	1649	2536	2093	2009	2512	2202	2304	2304	313.7
C/N	11.3	11.5	10.15	8.92	10.54	9.79	9.35	9.98	10.19	0.89

Table 7(c): Vertical profile of Chlorophyll -*a* (µg/g) and phaeophytin (µg/g) in sediment column 16 cm at 2 cm interval from top (a) to bottom (h). R-Reactive, I-Integrated

	O		N		D		J		F		M		A		M	
Depth	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**	**Chl-a**	**Ph-a**
0-2	0.45	3.5	0.55	4.5	0.65	5.5	0.75	6	0.6	6	0.65	6.5	0.75	7.5	0.8	7
2-4	0.4	3	0.5	3.5	0.6	5	0.7	5.5	0.85	5.5	0.9	6.5	0.85	6.5	1.1	6
4-6	0.35	3.2	0.4	3	0.55	4.5	0.65	5	0.65	5	0.7	6	0.9	6	0.6	5.5
6-8	0.3	3	0.35	3	0.5	4	0.6	4.5	0.8	4.6	0.85	5.5	0.65	5.5	0.8	5
8-10	0.25	3.1	0.3	2.9	0.45	3.5	0.55	4	0.6	4.3	0.7	4.5	0.8	5	0.9	4.5
10-12	0.22	3	0.25	2.5	0.35	3	0.5	3.5	0.35	3.2	0.6	4	0.4	4.5	0.6	4
12-14	0.2	2.5	0.2	2	0.25	2.5	0.3	3	0.32	3	0.3	3.5	0.45	4	0.4	3
14-16	0.2	2.5	0.2	2	0.2	2.5	0.2	3	0.25	2.9	0.3	3	0.3	3.5	0.3	3
R	1.75	15.8	2.1	16.9	2.75	22.5	3.25	25	3.5	25.4	3.8	29	3.95	30.5	4.2	28
I	2.37	23.8	2.75	23.4	3.55	30.5	4.25	31.03	4.12	34.5	5	39.5	4.00	42.5	5.5	38

Table 7(d): Vertical profile of paheophytin / chlorophyll-*a* and particle reworking coefficient (PRC)derived from Chl-*a*

Depth				**Months**				
(cm)	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**
0-2	7.7	8.18	8.46	8	10	10	10	8.75
2-4	7.5	7	8.33	7.85	6.47	7.22	7.64	5.45
4-6	9.14	7.5	8.18	7.69	7.69	8.57	6.66	9.16
6-8	10	8.57	8	7.5	5.75	6.47	8.46	6.25
8-10	12.4	9.66	7.77	7.27	7.16	6.42	6.25	5
10-12	12.5	10	8.57	7	9.14	6.66	11.25	6.66
12-14	12.5	10	10	10	9.37	11.66	8.88	7.5
14-16	12.5	10	12.5	15	11.6	10	11.66	10
PRC	0.045	0.052	0.07	0.087	0.158	0.267	0.496	0.636

Fig. 7 (a): Monthly depth profiles of Chlorophyll-a in sediment cores at site A

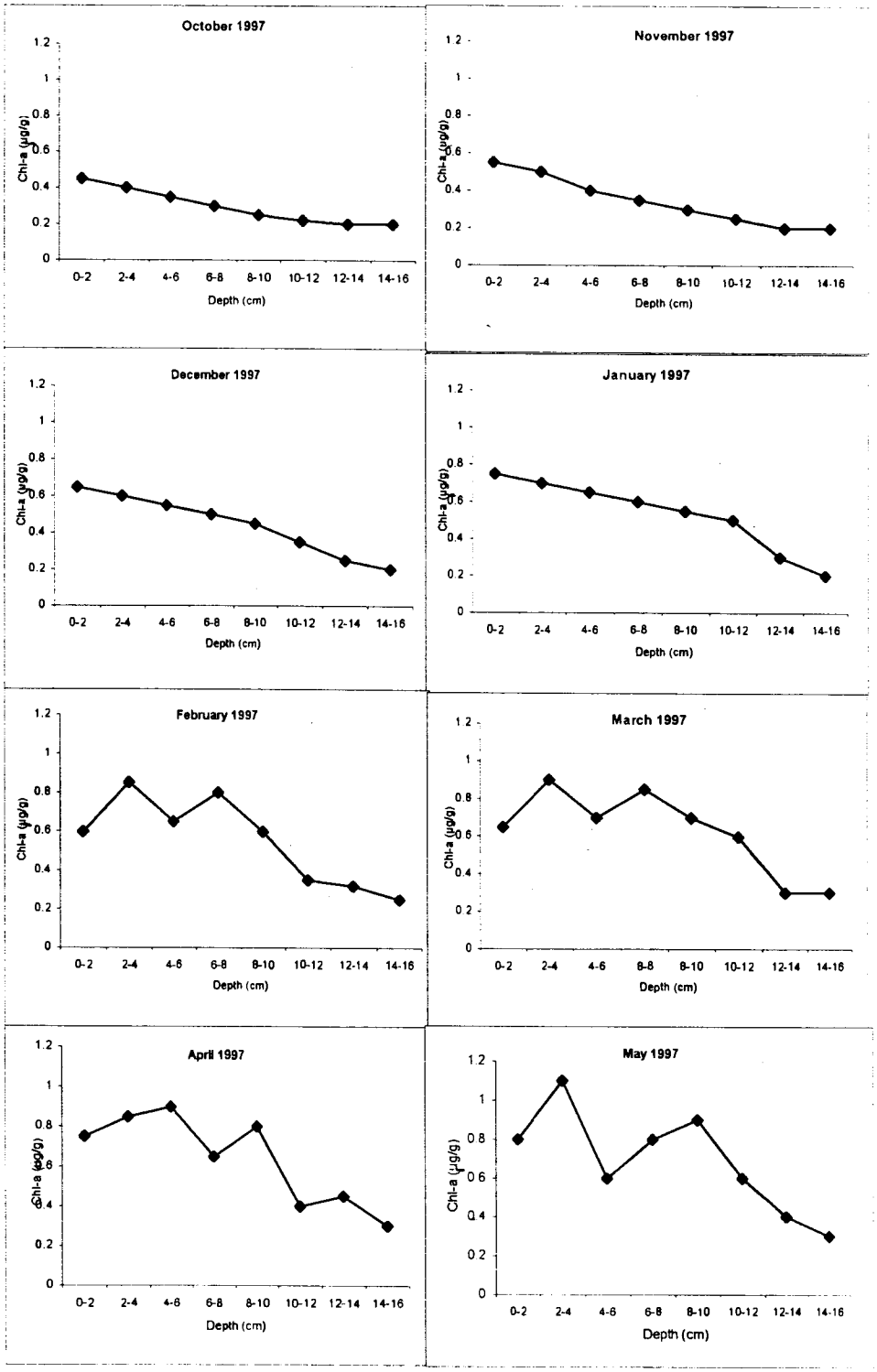


Fig. 7 (b): Monthly depth profiles of phaeopyhtin in sediment cores at site A

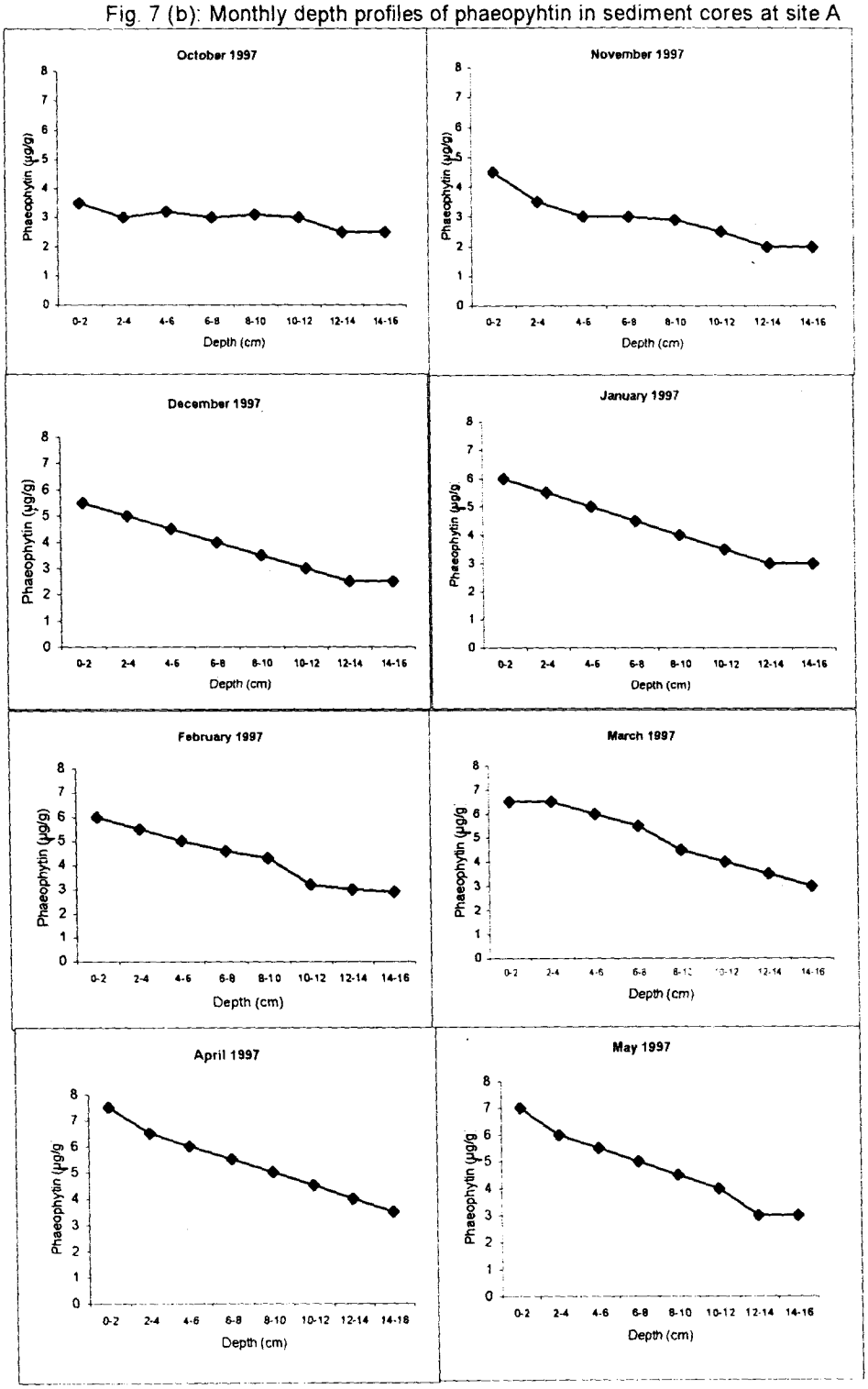
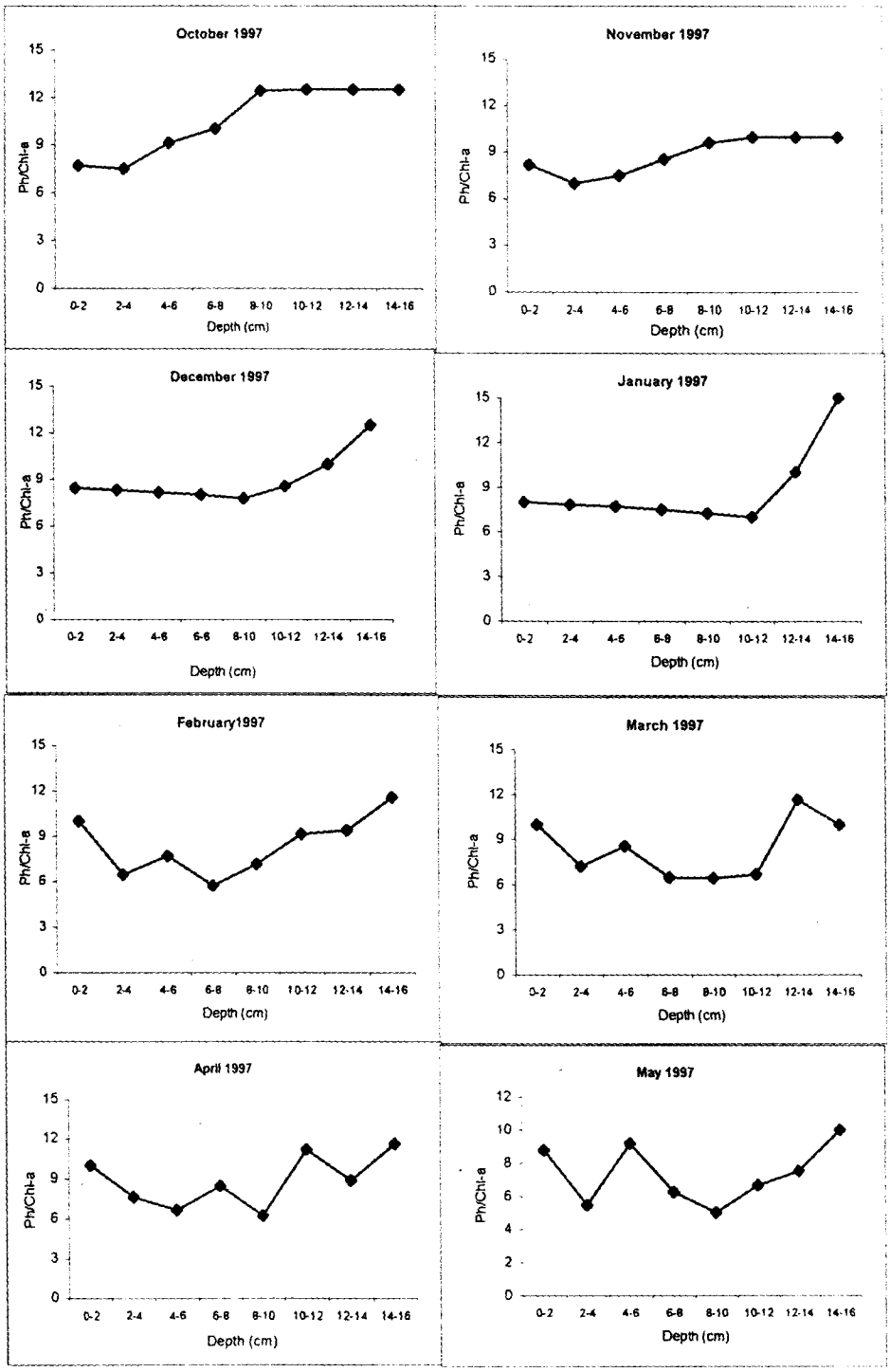


Fig.7(c): Monthly depth profiles of phaeophytin / chlorophyll-a ratio in sediment cores at site A.



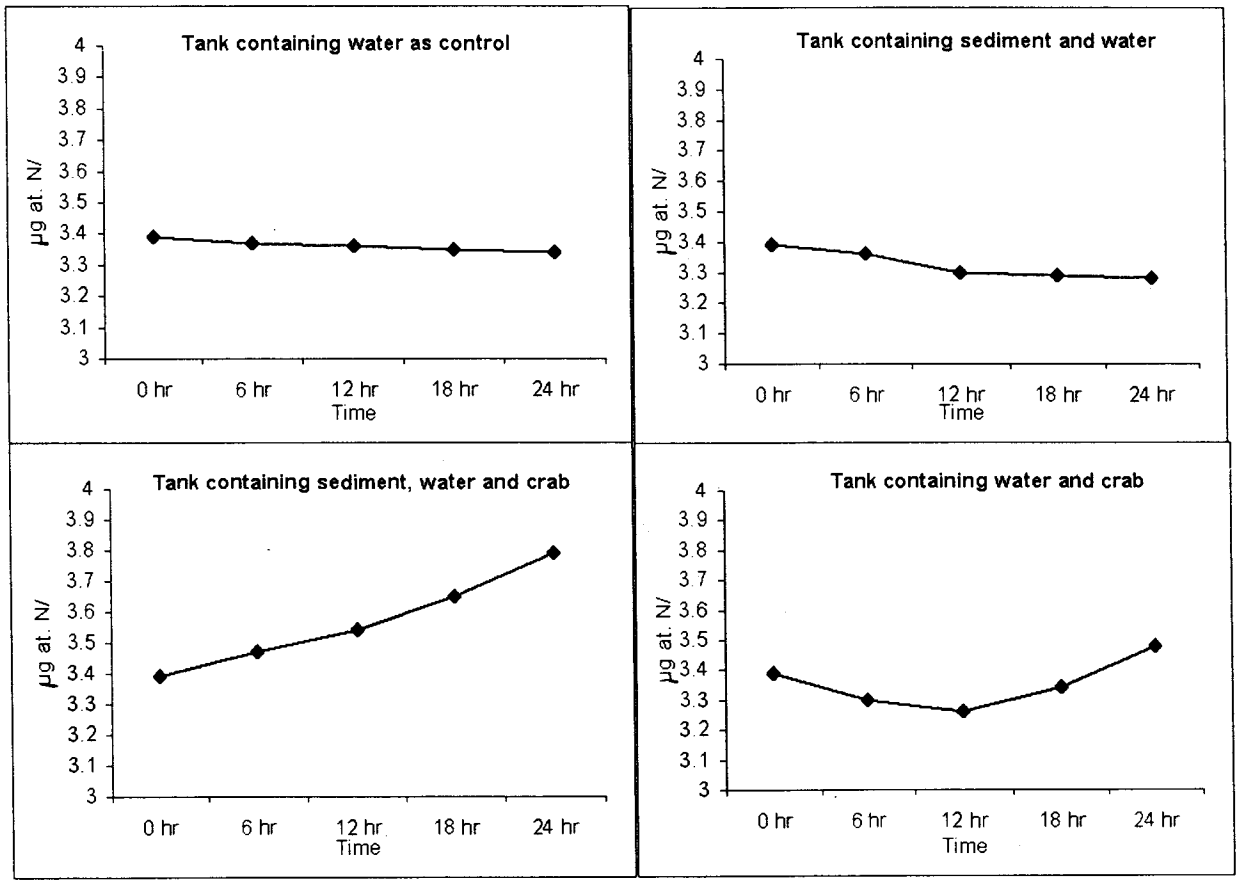


Fig. 7 (d): Nitrate variability in simulated laboratory microcosm experiments.

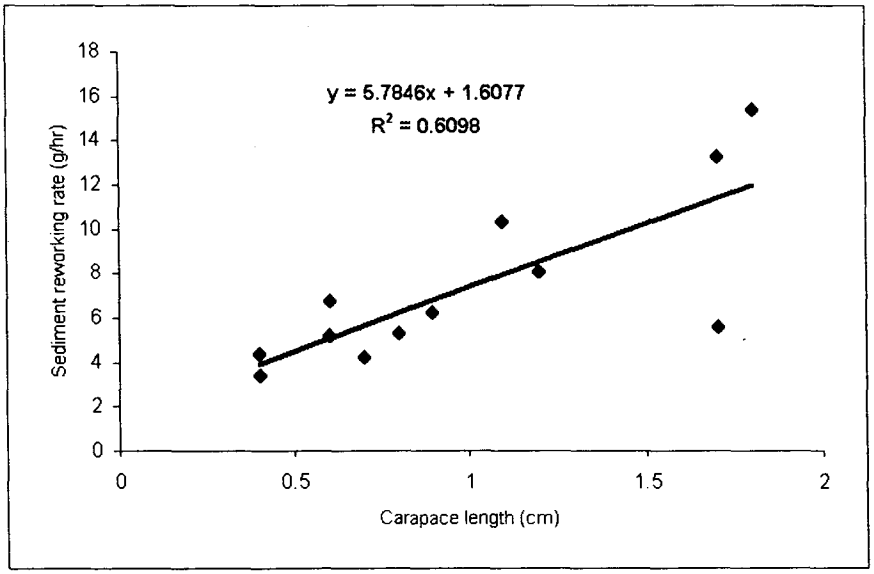


Fig. 7 (e): Relationship between size of the crabs (*Dotilla myctiroides*) and the reworking rate.

CHAPTER 8

SUMMARY AND CONCLUSIONS

SUMMARY

The coastal ocean represents an area of transition where land, air and sea interact to form a wide variety of diverse habitats and ecosystems viz. In the cosatal ocean, estuaries are regarded as complex ecosystems, involving interactions of physical and bio-geochemical processes both spatially and temporally. They are the most productive ecosystems in the world and act as conduits for dissolved and particulate effluents discharged from centers of population, industries and from land drainage to the adjacent coastal environment. While some components are consumed or retained within the estuarine environment, rest of it are transported into the adjoining coastal waters. The coastal ecosystems are also places of hectic human activity, resulting in interference due to rapid development.

Estuaries, as the transition zones of the world's fresh and marine waters, rank on a landscape scale among the most prominent ecotones on earth. Rapid changes and steep gradients of environmental factors, particularly salinity are the hallmarks of these systems (Schlacher and Wooldridge, 1996). These factors and other biological features of the transition zone between the sea and the freshwater have long attracted the interest of marine biologists. Identifying the factors and important processes governing population size and the structure of communities is a central problem in ecology.

One of the aims of benthic ecologist is to understand the ecological processes which is achieved by examining the interrelationship between environmental parameters and benthic community structure (Holland et al.,

1987), anthropogenic impacts (Frouin, 2000) and modelling of the ecosystem (Longhurst, 1978). A better management of living resources in estuaries can be achieved by understanding the ecological processes. Estuaries form an ideal ecosystem in which to observe such interactions due to their wide range of environmental parameters especially salinity and sediment properties (Jones et al., 1990).

Benthic invertebrates are used extensively as indicators of estuarine environmental status and trends because numerous studies have demonstrated that benthos respond predictably to many kinds of natural and anthropogenic stress (Pearson and Rosenberg, 1978; Dauer, 1993; Tapp et al., 1993; Wilson and Jeffrey, 1994). Many characteristics of benthic assemblages make them useful indicators (Bilyard, 1987), the most important of which are related to their exposure to stress and the diversity of their response. Organic wastes such as sewage when introduced into the environment may cause changes in the enclosed bays and estuaries (Bozzini, 1975). Monitoring benthic assemblages in such areas is essential to understand complex ecosystems such as those in estuaries, because it provides a mechanism to view community response to disturbance, gives insight about food resource availability and food-web interactions and may be useful for assessing differences in ecosystem structure and function over space and time.

Benthic organisms continuously restructure or bring about mixing of the sediments by means of locomotion, injestion, ejestion and respiration. This process of mixing the sediment grains is referred to as "bioturbation" and is

recognised as one of the major processes altering the primary structure of sedimentary deposits on millimeter to meter scales. These benthic organisms, play an important functional role in estuaries and other aquatic ecosystems. They alter geochemical conditions at the sediment-water interface, promote decomposition and nutrient recycling, and transfer energy to other food web components (Rhoads, 1974; Boesch et al., 1976; Aller, 1982; Tenore et al., 1984; Schaffner et al., 1987). Benthic community trophic structure is a potentially valuable criterion for integrating and assessing ecological responses along estuarine gradients (Brown et al., 2000).

Ecological studies have a wide range of applications. To begin with, any ecological study based on spatial and temporal variations will give us a baseline data of that particular area under study. Secondly, this baseline data can be useful in comparing with earlier data, if any, from the same area and thus helps in assessing the changes that have occurred over the time scale. Knowledge of all these is useful in understanding the natural fluctuations and the changes caused by human / anthropogenic impact. In addition, these studies help us in assessing the ecosystem dynamics and energy flow from one trophic level to the other and also in resource management. Finally, with the abiotic and biotic data obtained one can arrive to a model, that can be used in predicting any future ecosystem changes or perturbations.

So far, no work had been carried out on the biochemical composition of the sediments from the sites under study. Also macrobenthic species succession was studied using multivariate techniques. In addition, pollution studies were

carried out along a gradient of organic enrichment to see the effect of sewage on macrobenthic community. Finally, assessment of bioturbation activities was carried out using chlorophyll *a* as an indicator. Besides these preliminary studies on nutrient flux in laboratory microcosm and estimation of the sediment reworking rate for the soldier crab, *Dotilla myctiroides* were carried out. All these issues mentioned above have not been studied so far from the coastal waters of Goa.

In the framework of the present concern for future global environmental changes, the primary interest was to evaluate the changes in the macrofaunal community structure due to natural and anthropogenic changes in the environment. In addition, benthic organisms bring about changes in the sedimentary environment which further contributes in structuring of benthic communities.

Hence, in this study an attempt was made to collect extensive benthic data together with other physico-chemical parameters in the Mandovi and Zuari estuaries and adjoining coastal waters for a period of one year (1997-1998). Studies pertaining to the above would significantly contribute to the ecological and biogeochemical understanding of the tropical Mandovi-Zuari estuarine system, which is one of the largest riverine networks on the southwest coast of India and which is of major importance to life in Goa.

Six stations – three in Zuari estuary (Z1, Z2 and Z3), two in Mandovi estuary (M1 and M2) and an offshore station A, were selected based on the salinity and sediment characteristics.

OUTLINE OF THE THESIS

The research work presented in the thesis is divided into 7 chapters as described below.

CHAPTER 1:

INTRODUCTION

This chapter gives general information about benthic macroinvertebrates and bioturbation and summarises previous work carried out. The importance of ecologicsl studies is stressed upon. It also gives the objectives of the research/study and also evaluates the importance of these organisms in the marine and estuarine environment. The problems and lacunae are pointed out.

CHAPTER 2:

MATERIALS AND METHODS

In this chapter, the study area is described giving a full account of the geographical features, the climate and the station positions.

The materials and the methods used for the environmental parameters such as grain size, organic carbon, organic nitrogen, chlorophyll-*a*, proteins, carbohydrates, lipids in the sediment and salinity, pH, temperature, dissolved

oxygen of the water have been described. Also, the methods used for studying the macrofauna have been discussed. The statistical analyses used have been discussed in this chapter. Besides these, mean, standard deviation (SD) and the community structure indices such as that for species diversity (H'), evenness (J), species richness (SR), and dominance (D) and species rank abundance (SRA) have been described.

Methods used to identify macrofauna estimate, biomass and other environmental parameters like salinity, temperature, dissolved oxygen, BOD5, pH of interstitial water and organic carbon, grain size, chlorophyll *a* of sediment (as mentioned earlier) have been studied. This was to study the changes in macrofaunal community along enrichment gradient.

Also, methods used to study the vertical trend of chlorophyll-*a* in the sediment, nutrient flux experiments and sediment reworking rate by *Dotilla myctiroides*, that were studied to assess bioturbation activities have been discussed in this chapter.

CHAPTER 3:

THE ENVIRONMENT

This chapter highlights the hydrological and the sediment parameters analysed.

A total of 13 parameters were studied on the water and sediment samples. Over an annual cycle the mean temperature was seen to be 29.04^{0}C, mean salinity 12.77 psu, mean dissolved oxygen 5.06 ml/l and mean pH 6.89 for the

water samples. Whereas for the sediment, mean value for chlorophyll *a* was 0.92 µg/g, mean grain size was 2.07 mm, mean sediment sorting coefficient was 0.24ø, mean total organic carbon was 2759.30 mg/g, mean total nitrogen 334.11, mean protein was 8.57 µg/g, mean carbohydrates was 355.95 µg/g and mean lipids was 117.27 µg/g. The mean for the carbon : biopolymeric fraction (C:BPF) was calculated to be 236.1. All these 13 parameters showed significant difference between sites and seasons. Environmental data were closely related to the monsoon behaviour in this region.

CHAPTER 4:

COMMUNITY STRUCTURE

This chapter deals with the study of the community structure. This involves estimating the species density, diversity, evenness, richness, dominance, biomass estimation and species numbers. All these aspects have been highlighted in this chapter along with studying the species succession. Also description of the families of different faunal groups studied is given along with the faunal list.

There was significant difference in population distribution by seasons and not by sites. The population was significantly higher during premonsoon than the other seasons. This change was largely due to seasonality and site position in the estuaries.

A total of 67 species was recorded of which 18 were new to the locality. Polychaetes formed the dominant taxa followed by molluscs and crustacea.

Significantly high biomass was observed at the site with sandy substratum, which indicated moderately sorted low-energy site with relatively intermediate organic carbon and salinity. Significant high species diversity was observed at site having a muddy substratum, indicating a moderately sorted low-energy site, with a relatively high organic carbon and high salinity. Well sorted sediments offer small range of grain sizes and interstitial spaces and thus provide fewer niches and hence contain less diverse fauna (Nichols, 1970; Grebmeir et al., 1989), which agrees with our observation and supports earlier work done (Coleman et al., 1997. Finer sediments supported high species diversity corroborating with earlier findings (Mountford et al., 1997). The fauna comprised of 26 species of polychaetes belonging to 15 families, 15 species of bivalves belonging to 9 different families, 4 species of gastropods belonging to 4 families, 13 species of amphipods and several other groups. All the families have been described in this chapter.

The tropical estuarine soft-bottom species succession varied both temporally and spatially and showed three distinct seasonalities. This dynamic process was mainly influenced by the southwest monsoon and the local biotic and abiotic factors at specific sites. The species succession observed here largely support the models put forth by Clement (1916), Connel and Slayter (1977) and Rhoads and Boyer (1982).

Comparison of the present data with that reported earlier (Parulekar et al., indicates that the general trend in the abundance and biomass of fauna has changed considerably. Changes in macrofaunal community structure can occur

due to change in salinity as a result of monsoon, sediment scouring and colonisation of adults and juveniles of various species.

CHAPTER 5:

INFLUENCE OF ENVIRONMENTAL PARAMETERS ON THE BENTHIC COMMUNITY STRUCTURE

This chapter highlights study carried to test the hypothesis that salinity and sediment properties significantly affect the soft bottom benthic community structure.

For this, the benthic and environmental data was subjected to various statistical techniques. ANOVA and interaction study revealed that salinity and sediment properties (percentage of sand, silt and clay, mean grain size, sediment sorting, organic carbon and chlorophyll *a*) were the main parameters that influenced the differences in community structure between seasons and sites. Multiple regression analyses indicate that a combination of sediment properties (mean grain size, sediment sorting, percent sand, silt and clay and organic carbon) and bottom water characteristics were the significant parameters explaining 61 - 88% of the variation in the estimate of species diversity at sites A, M1, Z2 and Z3.

CHAPTER 6:

EFFECT OF ORGANIC ENRICHMENT ON THE MACROFAUNAL COMMUNITY STRUCTURE

In this chapter the effects of organic enrichment from a sewage disposal site on the macrobenthic invertebrates is emphasised. Techniques such as Pearson-Rosenberg Model (PRM), abundance biomass comparison (ABC) curve, benthic community structure indices and cluster analysis were used to discriminate and diagnose the pollution gradient.

In the present study, the faunal numbers and biomass at the disposal point was maximum with less number of species. As we moved away from this point the diversity increased but density fell. Also, the fauna comprised mainly the deposit feeder *Capitella capitata* (90 – 95%), indicating organic enrichment of the area. Away from this site, *Capitella capitata* numbers decreased and bivalves which are filter-feeders were seen. The most abundant of them was *Tellina ala*. The species abundance biomass curve (SAB curve) was in agreement with the Pearson-Rosenberg Model as suggested by Pearson and Rosenberg (1978). Abundance and Biomass comparison curves closely coincided and crossed each other at the sewage disposal site indicating moderate organic pollution. Also cluster classification revealed two clusters – one of the polluted site and the other of the non-polluted sites.

CHAPTER 7:

ASSESSMENT OF BIOTURBATION ACTIVITIES

This chapter deals with the assessment of bioturbation activities which the benthic organisms bring about in the sedimentary environment For this, chlorophyll-*a* trend in the sediment core was seen, sediment reworking rate by *Dotilla myctiroides* was calculated and nutrient flux experiments were carried out. Relatively on most of the occasions higher chlorophyll *a* values were observed on the top layer of the sediment core (0-2 cm) and high pigment values were observed from post to premonsoon. Chlorophyll *a* profile did not exhibit an exponential decrease with depth as expected. However, irregular profiles of chlorophyll-*a* observed may be caused by variable seasonal input, temperature dependant activities and mixing by benthic organisms. The reworking rate showed significant positive correlation with the carapace length. The sediment reworking rate works out to be 675.28 g/h/m^2. Thus population of such species may transport enourmous quantity of particles over the surface and hence alter the structural and geotechnical characteristics of the substratum. Microcosm experiments in the laboratory showed increase of nutrient value in the sediment-overlying waters in bioturbated aquarium tanks with crabs than in non-bioturbated aquarium tanks without the crabs. High nutrient values are largely due to sediment reworking and defecation by the crabs and addition of diet in the tanks as their feed. However these are only preliminary studies and more work needs to be carried out in order to firmly establish the facts.

CONCLUSIONS

- Food Index or the ratio of carbon of the biopolymeric fraction to the total organic carbon (C-BPF:TOC), which forms food for the benthic organisms, was calculated for the first time in these estuaries. High Food Index at site M1supported high benthic diversity and productivity.
- A total of 67 species were identified from the study sites.
- Of the total species recorded, 18 were new to the locality.
- Fauna was dominated by polychaetes (*Prionospio pinnata* and *Clymene annandalei*), mollusc (*Meretrix casta*) and crustacean (*Urothoe platydactyla*).
- Comparison with benthic data recorded 25 years earlier, showed a clear decrease in the macrofaunal density, biomass and species number, mainly due to mining activities.
- Seasonality of species succession was seen largely due to southwest monsoon.
- 13 environmental parameters were studied. Salinity, dissolved oxygen and total organic nitrogen were the major significant factors that influenced the species diversity, biomass and population.
- Species Abundance Biomass (SAB) curves obtained from the study were in agreement with the Pearson Rosenberg Model.
- Abundance and Biomass Comparison (ABC) curves obtained closely coincided and crossed each other at the sewage disposal site indicating moderate organic pollution.

- Vertical profile of chlorophyll *a* indicated bioturbation activities.
- Sediment reworking by the crab *Dotilla myctiroides*, in the tanks, enhanced the nutrient flux to the water column.

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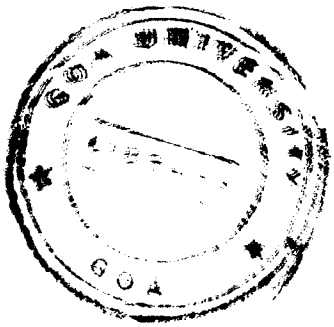
* - Publications from Thesis

Nimi R. Rodrigues 05/04/04
(Candidate)

S.N.Harkantra 8/4/04
(Research Guide)

VARIABLES	SEASON	SITE Z3	
		MEAN	SD
Spesies diversity	1	2.07(ns)	0.51
	2	1.87	0.39
	3	1.96	0.44
Total biomass	1	*1.26[b]	5.83
	2	1.47[c]	2.42
	3	1.13[a]	1.01
Population density	1	764.5[b]	758.6
	2	997[c]	682.17
	3	466[a]	159.4
Species number	1	5.05(ns)	1.29
	2	5.33	1.5
	3	4.57	2.3



Pattern of species succession of soft-bottom macrofauna in the estuaries of Goa, west coast of India

Sadanand N. Harkantra* and Nimi R. Rodrigues

Biological Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403 004, India

Multivariate techniques, chord normalized expected species shared (CNESS) and principal component analyses of hypergeometric probability of species matrices (PCA-H) were applied to soft-bottom macrofauna data of Goa estuaries, west coast of India, to assess the pattern of species succession at different sites. These analyses revealed three groups of species that produced three-stages or triangular species succession pattern, corresponding to the three seasons, namely post-, pre- and southwest monsoon. Each site exhibited a different pattern of species succession and compostion. A total of 58 species were recorded among which 18 were new to the local fauna. Dominant species that controlled the orientation of this succession were Polychaetes (*Prioniospio pinnata*, *Clymene annandalei*, *Nereis capensis*), Bivalves (*Meretrix casta*, *Cardium flavum*), Amphipoda (*Urothoe platydactyla*), Echiurida (*Thalassema* sp.) and Nema-

*For correspondence. (e-mail: sadanand@darya.nio.org)

toda at different sites. Species succession was mainly influenced by the southwest monsoon and the local biotic and abiotic factors at specific sites.

A number of hypotheses of soft-bottom faunal species succession have been discussed[1–14]. Ecological succession consists of the sequence of changes in community structures that occur after a site has been disturbed[11]. It can be considered as a local progression of species invasion and occupancy[12]. Rhoads and Boyer[9] defined soft-bottom benthic succession as a significant directional change in pattern of animal–sediment interaction, rather than changes in species composition. Clements'[12] view is that succession was driven by changes in external environment. Species succession largely depends on the life-history strategies and recruitment process[2]. Species which have *r*-selected and opportunistic traits will be found during early stages, while species which have less opportunistic and *k*-selected traits will be found at later stages[2]. Based on many views, Connell and Slayter[13] have formulated three models of succession – facilitation, tolerance and inhibition. Facilitation is based on biotic habitat modification by each group of species that enhances the settlement of subsequent groups. The tolerance mechanism centres on differences in species resource-utilization pattern and life histories. Inhibition involves suppression of settlement and/or growth of other species by those already established in the disturbed area. This fundamental ecological process of species-succession models of facilitation, tolerance and inhibition has been studied in a number of soft-bottom environments in temperate waters[1–14]. Though there are some studies on soft-bottom macrofauna in Indian estuaries[15–19], no such approach was made. The multivariate techniques, chord normalized expected species shared (CNESS) and principal component analyses of hypergeometric probability of species matrices (PCA-H) were applied to soft-bottom macrofauna data of Goa estuaries to assess the pattern of species succession at different sites, in order to examine the various hypotheses mentioned above.

The Mandovi and Zuari estuarine system of Goa is located on the central west coast of India (Figure 1). Spatio-temporal variations in abiotic and biotic parameters in this estuarine system are affected by tropical southwest monsoon; riverine and tidal flows make them ecologically complex ecosystems[15–17,20,21]. The average annual rainfall of Goa is about 3000 mm, of which nearly 80% occurs during the southwest monsoon period (June–September), while relatively stable conditions prevail during post-monsoon (October–January) and pre-monsoon (February–May) periods. The study sites M1, M2 and Z1, Z2 are located upstream of Mandovi and Zuari estuaries, respectively (Figure 1). The depth varied between 3.5 and 4.5 m, whereas salinity varied from 1.5 to 33.0 psu. The substrata were sandy in Mandovi sites and muddy in Zuari sites. The organic carbon values ranged

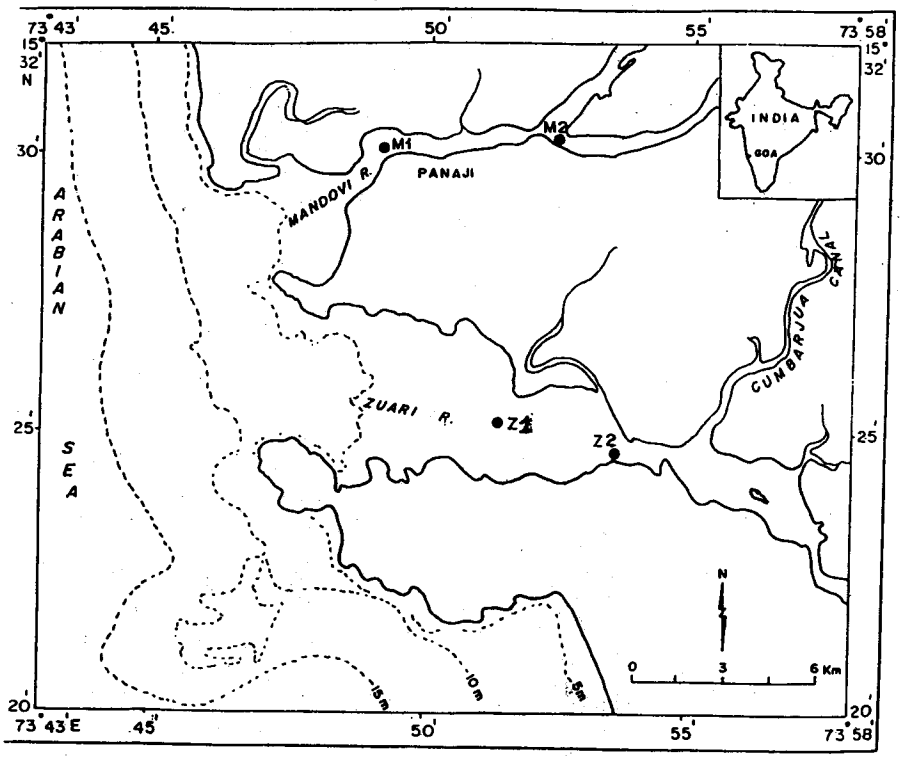


Figure 1. Map showing location of the study area.

Table 1. Species density *n*/0.04 m^2 (average of triplicate samples) at different sites and months, which has contributed more than 2% of the sample. First column and row indicate species code (refer figure code) and month respectively

	O	N	D	J	F	M	A	M	J	J	A	S
M1												
Dn	4.0	0.0	17.3	1.0	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nc	3.0	7.0	15.0	0.0	6.0	2.5	16.5	2.0	2.0	3.0	12.0	35.0
Mc	0.0	5.0	0.3	0.0	0.0	3.0	0.0	0.0	0.0	4.5	6.0	0.0
Pm	0.0	3.0	0.0	0.0	3.0	0.0	4.5	3.0	6.0	0.0	0.0	6.0
Up	1.0	0.0	1.6	0.3	115.5	0.0	16.5	14.0	0.0	1.0	1.0	0.0
N	0.0	2.0	0.3	0.0	0.0	12.0	0.5	2.0	1.0	0.0	0.0	8.0
Th	0.0	2.0	0.3	0.3	0.0	0.5	3.5	0.0	0.5	0.0	2.0	467.0
M2												
Pp	4.5	0.0	0.3	0.0	0.0	0.0	0.0	1.5	2.5	0.5	0.0	16.5
Ga	0.5	0.0	0.6	1.0	1.0	5.0	1.0	0.5	0.0	0.5	0.0	0.0
Nc	0.0	0.0	1.0	2.0	0.0	0.0	0.0	2.0	0.0	0.0	6.5	4.5
Mc	3.5	1.3	21.3	0.0	4.0	30.5	0.0	238.0	0.0	17.5	16.5	4.0
Cfl	0.5	1.0	0.0	0.0	0.0	0.0	25.0	0.0	1.0	0.0	0.0	0.0
Up	0.0	0.6	0.0	1.0	1.5	0.0	0.0	0.0	0.0	0.5	0.0	6.5
Z1												
Pp	20.0	3.0	5.3	20.0	6.5	12.0	9.0	0.0	0.5	2.0	13.5	46.5
Ni	1.5	1.6	0.3	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	5.5
Sc	0.5	0.0	4.3	5.0	7.0	9.0	8.0	0.0	0.0	0.0	0.0	0.0
Ga	2.0	0.6	0.6	10.0	0.5	4.0	3.0	0.5	2.5	0.0	0.0	0.0
Cc	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	1.0
Ca	0.5	0.6	3.6	9.0	8.0	0.0	0.0	6.0	13.0	0.0	0.0	2.0
Up	0.5	1.0	0.0	0.0	4.0	4.0	1.0	0.5	0.0	0.5	0.5	0.3
N	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	0.0
Th	0.0	0.0	0.0	0.0	1.5	0.0	4.0	1.0	1.0	0.0	0.0	1.0
Cf	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	8.5	0.0
Z2												
Pp	1.0	7.0	4.3	28.0	8.5	54.0	0.0	5.0	0.5	1.0	2.0	2.5
Ni	0.0	0.0	0.0	2.0	0.0	0.0	0.0	2.0	0.0	6.0	0.0	2.0
Ga	0.0	2.0	13.0	2.5	9.0	1.0	0.0	1.5	0.0	0.0	0.0	0.0
Cc	1.0	3.0	0.0	0.0	0.5	13.0	1.0	4.0	0.0	0.0	3.0	18.5
Ca	6.5	7.0	0.0	24.0	0.0	2.0	8.0	22.0	10.0	12.0	9.5	4.0
N	0.0	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Th	0.0	3.0	0.0	3.0	1.5	0.0	0.0	0.5	0.5	0.0	0.0	2.0

from 0.15 to 3.5% and showed higher values at sites in the Zuari estuary.

Four sites were sampled monthly, from October 1997 to September 1998 (Figure 1). Sites positions were noted by hand-held GPS (± 15). Triplicate samples were obtained at each site with a 0.04 m^2 van Veen grab up to the depth of 15–20 cm. Sediment samples from the grab were preserved in a 10% sea-water formalin and Rose Bengal stain mix. Later, these samples were sieved through 0.5 mm mesh sieve, with samples retained on the sieve, being transferred to plastic containers and preserved in 5% sea-water formalin[22]. Macrofauna were identified to species level and each species was counted under a stereo zoom microscope. Population density was converted to 0.04 m^2. Food and feeding habits of the species were ascertained from the literature. New faunal distance matrices, CNESS and PCA-H were used[14,23]. Succession of species was analysed using the Combinatorial Polythetic Agglomerative Hierarchial Clustering 96 (COMPAH 96) software of Gallagher[23]. Species versus month matrices were arranged for each site, as there was significant difference in environmental parameters and community structure (ANOVA test). Actual mean density data (Table 1) and species which contributed more than 2% of the samples were considered for this analysis[14,23]. Sample size (*m*) was determined as half of the minimum total population in a sample[14,23–25]. These techniques are similar to nonmatrix multidimensional scaling (NMDS) of chord distance, which was found to be the best among the eight procedures tested for ecological data[24]. Details about this analysis and techniques have been described elsewhere[14,23].

A total of 58 species was recorded (Table 2), among which 19 were new to the local benthic fauna. Species density varied from sites to months, with highest density being of Echiurida, *Thalassema* sp. 467/0.04 m^2, which was recorded in the month of September 1998 at site M1 (Table 1). Polychaetes formed the dominant taxa follo-

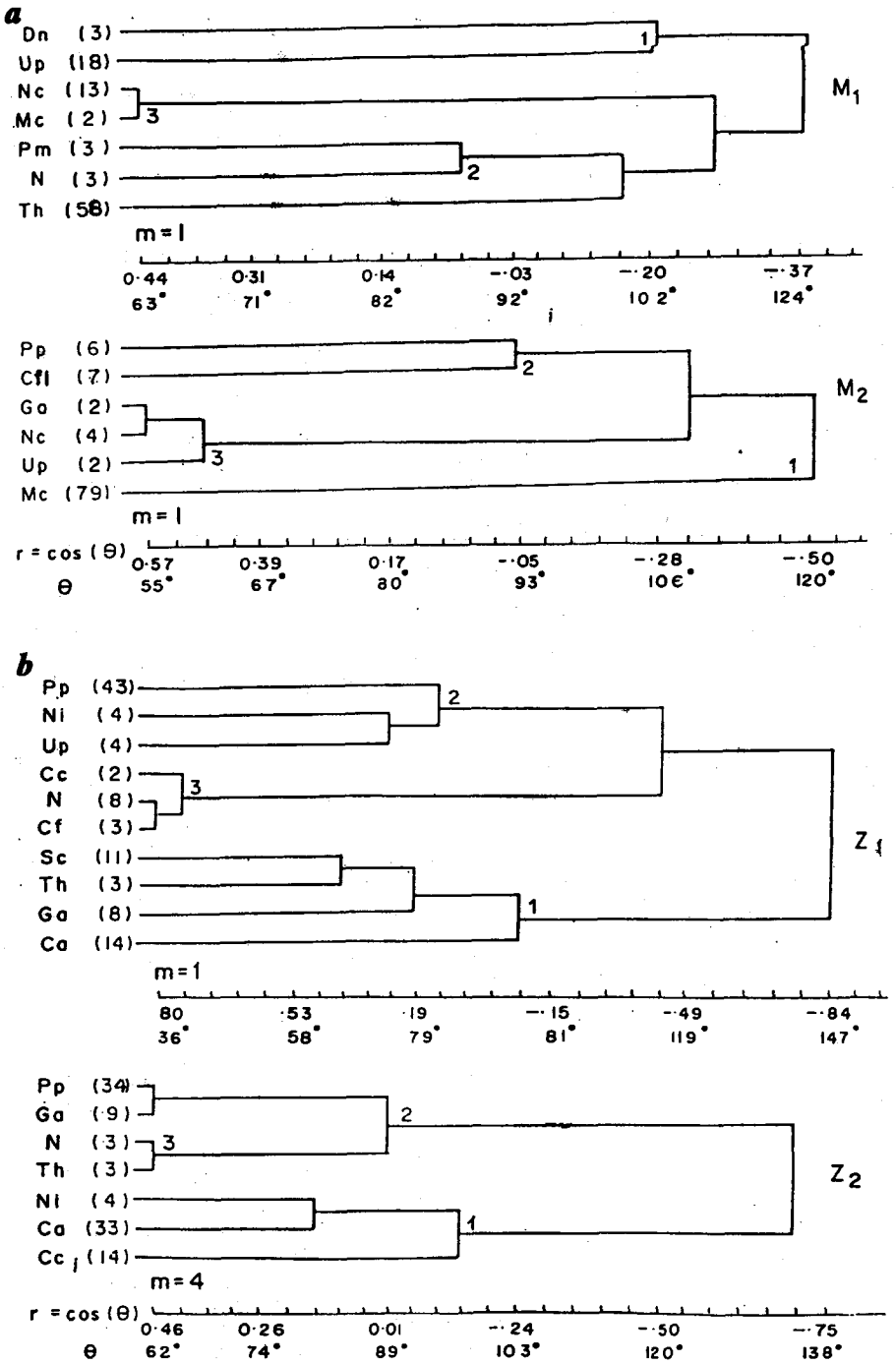


Figure 2 *a* and *b*. Single linkage clustering of columns of the hypergeometric probability (H) matrices at different sites, indicating species with frequencies at $m = 1, 4$ using Pearson's r. Clustering with Pearson's r is mathematically equivalent to clustering the species vectors displayed in Figure 3 using $\cos\phi$ similarity, where ϕ is the angle between species vectors in 12-dimensional ordination space. The three successional stages 1, 2 and 3 and the $\cos\phi$ (= Pearson's r) and ϕ value at which these clusters fuse are indicated. Numbers in parantheses are the percentage of contribution of species to CNESS analyses. Ca, *Clymene annandalei*; Cc, *Cossura coasta*; Cfl, *Cardium flavum*; Cf, *Cerethedia fluviatalis*; Dd, *Dendrostomum* sp.; Dn, *Diopatra neapolitana*; Th, *Thalassema* sp.; Ga, *Glycera alba*; Mc, *Meretrix casta*; N, Nematoda; Nc, *Nereis capensis*; Ni, *Nephthys inermis*; Pp, *Prionospio pinnata*; Sc, *Sternaspis scutata*; Up, *Urothoe platydactyla*.

wed by molluscs and crustaceans. Figure 2 *a* and *b* shows clusters of species based on the $\cos\phi$ between the species vectors in the Gabriel covariance plot. Only 6–10 species contributed to more than 2% of the CNESS variation among the samples of 58 species recorded (Tables 1 and 2; Figures 2 and 3). The stages of succession of species

formed three distinct clusters of the species vector shown as 1, 2 and 3. Stages 1, 2 and 3 represent post-, pre- and southwest monsoon season species samples. The orientation of the species vectors in 12-dimensional sample space was seen in three groups, each oriented at different angles between 36 and 147° to others (Figure 2 *a* and *b*). These three groups indicate three stages of succession, which produced the triangular pattern of seasonal samples (Figure 2 *a* and *b*). Cluster analyses also describe the composition of the three successional stages and show the percentage of proportional contribution of each species to CNESS distance among the samples. Stages 1, 2 and 3 were composed of different species at different sites (Figure 2 *a* and *b*). The most important species that controlled the orientation of the samples were the grazer amphipod, *Urothoe platydactyla* (18%) at site M1, filter feeder bivalve, *Meretrix casta* (79%) at site M2 and head-down burrowing sub-surface deposit feeder, *Clymene annandalei* at sites Z1 (14%) and Z2 (33%) during succession stage 1 of the post-monsoon season. Onset of succession was largely due to the first stage of recruitment which occurred after the southwest monsoon disturbance and re-establishment in stability of the environment. The first shift in the successional topology was from stage 1 to stage 2. Stage 1 species do not facilitate or inhibit stage 2 in this sequence, because their population has declined before stage 2 species recruit. The cause for this shift in succession to topology was the pre-monsoon second stage of recruitment state. The important species that controlled the orientation of stage 2-premonsoon period were Echiurida, *Thalassema* sp. (58%) at site M1, filter feeder bivalve, *Cardium flavum* (7%) at site M2 and *Prionospio pinnata* at site Z1 (43%) and Z2 (34%). Defaunation of macrofauna occurred largely due to a sudden decline in salinity and sediment disturbance during stages 2 and 3, which was brought about by the southwest monsoon. Stage 3, southwest monsoon succession was distinguished from stage 2 primarily by the presence of low salinity-tolerant species. The important species that controlled the orientation of stage 3 were the polychaete, *Nereis capensis* at site M1 (13%) and M2 (4%), Nematoda at site Z1 (8%) and Z2 (3%). These three important species each formed by a different successional stage 1, 2 and 3, account for 89% at site M1, 90% at site M2, 65% at site Z1 and 70% at site Z2 of the total variation in CNESS distance among the samples. Apart from this, other species also contributed in controlling the orientation of different stages (Figures 2 *a* and *b*). High percentage composition of different species at different sites and seasons (Figure 2 *a* and *b*) also indicates the spawning periodicity and recruitment process.

The species association was better analysed with a covariance bi-plot (Figure 3) and shows three groups of species vectors, indicated by 1, 2 and 3. The species vectors do not form a continuum, but fall into three discrete groups. The species vectors gives a picture of the association among the succession of species. In the PCA-H analyses (Figure 3), the variation in CNESS was explained by the first two axes (as percentage). Axis 1 depicts the difference between the post- and pre-monsoon sampling months, with dominant species primarily contributing to the orientation of the axis. Similarly, axis 2 was formed by the difference between the pre- and southwest monsoon season sample months. The estuarine soft-bottom species succession varied both temporally and spatially, and showed three distinct seasonalities over a period of 12 months. No two stages were similar, each site exhibited different species succession and composition (Figures 2 and 3).

The patterns of benthic faunal succession found in this study exhibit elements of each of the models mentioned earlier. A variety of abiotic and biotic factors like hydrodynamic, salinity, sediment properties, competition for food and space, spawning period, recruitment process, prey–predator relationship might have affected this pattern, including human perturbation[1–14]. For example, the initial establishment of population by early colonizing species or opportunistic species with *r*-selected traits *C. annandalei* (Polychaete, Maldanidae, head-down burrowing sub-surface deposit feeder) was followed by increase in dominance of less opportunistic species or *k*-selected traits, *P. pinnata* (Polychaete, Spionidae, surface-deposit feeder) at sites Z1 and Z2, and was a tolerance model[13].

Table 2. List of species recorded in the study sites

Polychaetes – *Prionospio pinnata* Ehlers; *P. cirrifera* Wiren; **Nephthys inermis* Ehlers; **N. dibranchis* Grube; **N. oligobranchia* Southern; *Glycera alba* Rathke; **Goniada emerita* Audouin & Milne-Edwards; *Lumbriconereis heteropoda* Marenzeller; **Clymene annandalei* Southern; **Heteromastus similis* Southern; **Maldane sarsi* Malmgren; *Nereis capensis* Willey; *Diopatra neapolitana* Delle Chiaje; **Onuphis eremita* Audouin & Milne-Edwards; **Sabella melanostigma* Schmarda; **Terebella ehrenbergi* Grube; **Cossura coasta* Kitamori; **Scoloplos marsupialis* Southern; *Eunice tentaculata* Quatrefages; **Sternaspis costata* Marenzeller; **Magelona rosea* Moore; **Arabella iricolor* Montagu; **Cirratulus filiformis* Keferstein

Molluscs – *Meretrix casta* (Chemnitz); *Paphia malabarica* (Chemnitz); *P. textile* (Gmelin); *Perna viridis* Linne; *P. indica* (Hanley); *Cardium flavum* Linne; **Gafrarium tumidum* Roding; *Tellina bruguieri* Hanley; **Lutraria arcuata* Deshayes; *Cerithidea fluviatilis* (Potiez & Michaud); *Turritella attenuata* Reeve; *Villorita cyprinoides* (Grey); *Arca granosa* Lamarck; *Solen truncatus* Wood

Crustaceans – *Metapenaeus dobsoni* (Miers); *Sphaeroma annandalei* Stebbings; *S. Walkeri* Stebbings; *Gastrasoccus simulans* W. H. Tattersall; *Ampelisca brevicornis* (Costa); **Urothoe platydactyla* Rabindranath; *Diogene affinis* Henderson; *Portunus sanguinolentus* (Herbst); *Paradiastylis* sp., *Eurydice* sp., *Cyathura* sp., *Scottolana* sp.

Others – *Boleopthalmus dussimieri* Cuv. & Val.; *Edwardsia tinctrix* Annandale; *Cavernularia* sp., *Sertularia* sp., *Nemertea* sp., *Dendrostomum* sp., *Ophiothrix* sp., *Thalassema* sp., Nematoda

Asterisk indicates new species to the local fauna.

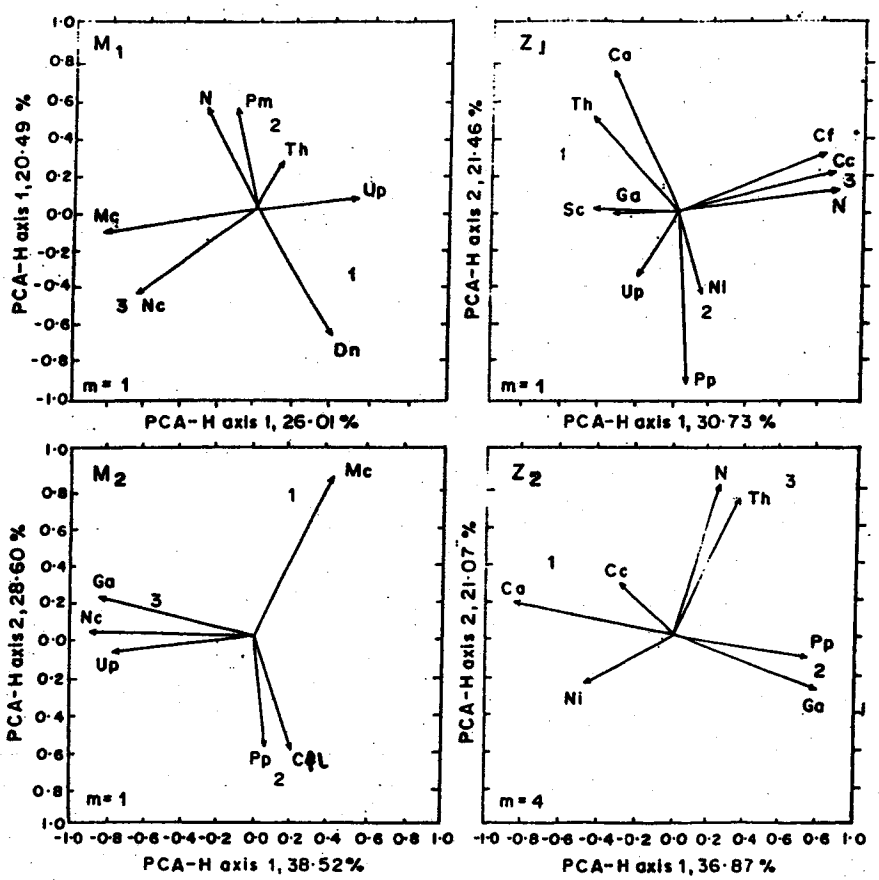


Figure 3. Three-dimensional covariance plot of species vectors. Angles between vectors indicate the temporal association among species, with acute angle indicating species with frequencies at $m = 1, 4$ that are highly correlated in time. Three groups of species comprising successional stages 1, 2 and 3 are labelled.

This was mainly due to the use of different level of food resources and different life-history strategies[2,7,8,25–28]. If the decline of the initial colonizers (*C. annandalei*) was due to resource depletion and intra-interspecific competition, then the subsequent domination by a different species (*P. pinnata*) was mainly due to more efficient exploitation of food and/or space resources[5,9,26–28]. Biotic habitat modification by earlier species may also enhance the settlement of subsequent species, which suggests that facilitative mechanisms of succession can occur in soft-bottom communities[5,7,8]. However, the extent to which these interactions shape successional patterns has to be tested by manipulative experiments[5,7,8]. Similarly, early succession of grazer Amphipoda, *U. platydactyla* and later by deposit feeder Echiurida, *Thalassema* sp. at site M1 can be explained by tolerance and facilitative models[5,7,8]. The model of inhibition[5,7,8] holds good at site M2, where we observed a succession by the filter feeder bivalves, *M. casta* and *C. flavum* during post- and pre-monsoon. These species can occupy all niches and keep-off all the later-arriving species[29]. Species succession of *N. capensis* at M1 and M2 sites and Nematoda at sites Z1 and Z2 during southwest monsoon was largely due to presence of earlier stage tolerant species and defaunation of other non-tolerant species. This succession was not a fresh recruitment[29]. Defaunation was mostly due to adult/larval mortality or migration to nearby areas, physical disturbance, etc. Some of the other explanations could be sudden changes in the environmental parameters such as lowering of salinity that may trigger gonadal release from the benthic invertebrates[30] in the water column, thereby increasing the larval abundance. Larval forms may also undergo adaptive strategies like cyst formation, postponement of larval settlement, etc. during these severe conditions[29–31]. These larvae will settle once the condition is favourable[29–31]. Though the seasonality was clear at all the sites, species composition differed among sites and seasons (Figures 2 and 3). This was mainly due to a significant difference in environmental parameters and benthic community structure among the sites and seasons. It is clear from the foregoing account that the species succession was mainly brought about by the southwest

monsoon and local abiotic and biotic factors, which largely agrees with the concept of Rhoads and Boyer[9], Clements[12], and Connel and Slatyer[13].

The pattern of succession differed from season to site in the Mandovi and Zuari estuarine complex. The study was limited to 12 months, with three seasons. Whether seasonality of species succession repeats in a similar pattern has to be ascertained from the long-term monitoring of the macrobenthos. Manipulative experiments are needed to understand the species interactions and influence of biotic factors. Based on our study, we designate *C. annandalei, M. casta, U. platydactyla* as opportunistic or *r*-selected species. *P. pinnata, C. flavum, Thalassema* sp. are considered as equilibrium or *k*-selected species and *N. capensis* and Nematoda as stress-tolerance species and taxa, respectively.

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