



## Macrobenthic functional feeding groups in a microtidal monsoonal estuary (Kodungallur–Azhikode estuary, India)

P.R. Jayachandran<sup>a,\*</sup>, S. Bijoy Nandan<sup>a</sup>, M. Jima<sup>a</sup>, Philomina Joseph<sup>a</sup>, N.D. Don Xavier<sup>a</sup>, O.K. Sreedevi<sup>a</sup>, M.P. Prabhakaran<sup>b</sup>, K.J. Joseph<sup>a</sup>

<sup>a</sup> Department of Marine Biology, Microbiology and Biochemistry, School of Marine Sciences, Cochin University of Science and Technology, Lakeside campus, Fine Arts Avenue, Kochi 682016, Kerala, India

<sup>b</sup> Department of Aquatic Environment Management, School of Fisheries Resource Management and Harvest Technology, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi 682506, Kerala, India



### ARTICLE INFO

#### Article history:

Received 4 June 2018

Received in revised form 16 November 2018

Accepted 16 November 2018

Available online 29 November 2018

#### Keywords:

Functional feeding groups

ABC plot. Taxonomic distinctness

Kodungallur–Azhikode estuary

### ABSTRACT

The functional feeding groups of macrobenthos in the Kodungallur–Azhikode estuary were studied on a monthly basis for a two year period (2009–2011). The main aim of the study was to understand the distribution pattern of macrobenthic functional feeding groups and their relationship to environmental drivers in the estuary. Malacostracan crustaceans dominated the system (60%) by numerical density, while molluscs contributed significantly to macrobenthic biomass (63%). Many species exploit the same class of resources within an assemblage of macrofaunal groups. The suspension feeding corophiid amphipod *Americorophium triaeronyx* was the most represented macrofaunal species. Other dominant macrofaunal feeding groups were the suspension feeding hydroid colonies of *Obelia bidentata*, surface deposit feeding polychaetes *Prionospio cirrifera*, suspension feeding mussels *Arcuatula senhousia*, carnivorous isopods *Cirrolana fluviatilis* and sub-surface deposit feeding polychaetes *Capitella* sp. The sampling stations were compared using taxonomic distinctness (AvTD), and variations in taxonomic distinctness (VarTD), the values of AvTD and VarTD for all stations during the entire monthly survey fell within the confidence intervals of probability funnel (95%,  $p < 0.05$ ). However, a significant variation was noticed in the values between stations (AvTD:  $F(6,161) = 3.105$ ,  $p = 0.007$ ; VarTD:  $F(6,161) = 2.489$ ,  $p = 0.025$ ). The abundance biomass curves were plotted separately for each site as well as combined for the entire estuary. The relatively high negative trend was observed in the station 5 ( $W = -0.139$ ) which indicates potential for the relatively high disturbance among all other stations. However, the W-value for the entire estuary was  $-0.079$ , which depicted moderate disturbance.

© 2018 Elsevier B.V. All rights reserved.

## 1. Introduction

Estuaries are one of the highly productive systems serving as breeding and nursery grounds for a diverse array of organisms (Donald and Michael, 2004; Jayachandran and Bijoy Nandan, 2012; McLusky and Elliot, 2004). The hydrodynamics of estuaries leads to the establishment of an environmental gradient expressed by gradual changes in salinity, the variability of sediment composition and amount of organic matter (Medeiros et al., 2016). A continuum of assemblages along the salinity gradient from the freshwater river to the sea, with shifts in the ranges of organisms, appears in response to changes in freshwater flow (Attrill and Rundle, 2002). The freshwater flux to estuaries carries substantial amounts of suspended particles, including sediment from erosion of surrounding catchments, streams, and riverbanks. The fine fractions of deposits

are easily transported and have a significant influence on sediment texture and water column turbidity of the receiving environments (Thrush et al., 2013). These highly variable environments naturally stress the ecosystem and determine the distribution of species along the estuarine gradient (Asha et al., 2016; Elliott and Quintino, 2007). In addition to natural stressors, estuaries are also subjected to a high degree of anthropogenic impact, which also exerts an influence on the distribution of species (Anu et al., 2014; Borja et al., 2000; Jayachandran et al., 2012).

Macrofaunal functional groups play a pivotal role in estuarine ecosystems, by acting as links in the carbon cycling. Their density and abundance in the estuaries are corresponding to successional dynamics in response to changes in surface sediment characteristics, total organic carbon, salinity, depth, current velocities, turbidity front and dissolved oxygen (Yu et al., 2012). They enhance bioturbation and display burrowing activities that result in the degradation or redistribution of organic matter (Fauchald and Jumars, 1979; Gaston, 1987). The functional niches of macrofaunal organisms are defined by ecological processes, demographic attributes,

\* Corresponding author.

E-mail address: [jayachandranpr@cusat.ac.in](mailto:jayachandranpr@cusat.ac.in) (P.R. Jayachandran).

and environmental factors (Fauchald and Jumars, 1979). The comprehensive information on distribution of these functional groups and associated feeding guilds can be used for benthic communities based ecosystem monitoring (Gallagher, 2008). The feeding group or guild is typically assigned based on the morphology of the mouthparts of species (Fauchald and Jumars, 1979; Gaston, 1987). The feeding guild in which an organism is found can be defined as the set of relations between food particle size and composition, food-intake mechanism and the motility patterns associated with feeding (Fauchald and Jumars, 1979). According to Thomson (1982), high primary production combined with higher current speed enables efficient filter feeding, which has been thought to be the contributing factor to the high bivalve biomass and density. However, when water currents are weak, the biomass of filter feeding bivalves decreases in favour of facultative filter feeders and deposit feeders (Thrush et al., 2004). Fauchald and Jumars (1979) noticed that selective and non-selective deposit feeders are dominated by macrofaunal polychaete communities.

Trait-based approaches are commonly used in community ecology for describing general ecological processes and for predicting future changes (Darling et al., 2012). Species traits analysis provides information regarding life-history strategies, which can broadly define biotic and abiotic interactions of organisms (Darling et al., 2012). The high prevalence of small *r*-selected species in a benthic community may be indicative of habitat instability (Schwinghamer, 1983) and results in high production relative to total biomass given the high turnover rates of organisms (Boudreau et al., 1991). In contrast, *K*-selected species although potentially having higher total biomass, may have lower relative production due to long lifespans and slow turnover rates. Abundance Biomass Curve (ABC) plots can be used for understanding the general nature of benthic communities in the estuary. Abundance Biomass Curves have been developed on the biological concept that, in a stable benthic community, interspecific competition promotes the dominance of *K*-selected species in term of biomass, and therefore the biomass curve stands above the numerical abundance curve. Our aims were to (a) study the functional feeding groups of macrobenthic communities that are exposed to different natural and man-made environmental conditions and (b) to assess the stability of benthic habitat in the Kodungallur–Azhikode estuary (KAE).

## 2. Materials and methods

### 2.1. Study area

The Kodungallur–Azhikode estuarine system covers an area of about 700 ha ( $10^{\circ} 11' - 10^{\circ} 12' N$  and  $76^{\circ} 10' - 76^{\circ} 13' E$ ) (Fig. 1). It extends into the Vembanad lake ecosystem in the south, and is connected to the Karuvannur River through the man-made Canoli canal to the north (Sreeja et al., 2016). It faces the Arabian Sea to the west and bounded by the Pullut backwaters on its east. The coastal region of the study site ( $10^{\circ} 0' - 10^{\circ} 20' N$  and  $76^{\circ} 10' - 76^{\circ} 20' E$ ) has an area of  $300 \text{ km}^{-2}$  and a high average population density of 1850 persons per  $\text{km}^2$ . It has a shallow water table and is speckled with numerous small freshwater ponds and water channels that crisscross the landscape to join either the backwaters, the main estuary further downstream or the sea directly (Sreeja et al., 2016). The Kodungallur–Azhikode estuary opens into the Arabian Sea, at Munambam through a channel with a width of 180 m and a depth of 7–8 m. Tides in the estuary are semidiurnal, with a microtidal tidal range; tidal effects extend to approximately 25 km landward of Azhikode and average annual rainfall in the area is 310 cm (Revichandran and Abraham, 1998). The estuary resembles the positive type of estuary, and freshwater input varied from  $10 \text{ m}^3 \text{ s}^{-1}$  to  $21 \text{ m}^3 \text{ s}^{-1}$  during pre-monsoon and  $123 \text{ m}^3 \text{ s}^{-1}$  to  $387 \text{ m}^3 \text{ s}^{-1}$  during south-west monsoon (Revichandran

and Abraham, 1998), and it can be referred to as a monsoonal estuary (Vijith et al., 2009). Monthly sampling was carried out in the Kodungallur–Azhikode estuary (Fig. 1) over 24 months during 2009–2011, using the research boat “R.V. King Fisher”. For seasonal analysis, months were pooled as pre-monsoon (PRM, February–May), monsoon (MN, June–September), and post-monsoon (PM, October–January) (Qasim, 2003).

### 2.2. Environmental parameters

The rainfall data for the river basin were obtained from the Indian Meteorological Department ([www.imd.gov.in](http://www.imd.gov.in)). The daily river discharge data were gathered from the Central Water Commission ([www.india-wris.nrsc.gov.in](http://www.india-wris.nrsc.gov.in)). The samples were collected using a Niskin Water Sampler (General Oceanics) of 2.5-litre capacity. A digital nephelo-turbidity meter was used to measure turbidity (Model. Systronics 132). The water column salinity was recorded in the field using an optical refractometer (Atago, Japan) and cross-checked in the laboratory by employing the Mohr–Knudsen method (Strickland and Parsons, 1972; UNESCO, 1985). Dissolved oxygen was determined by the modified Winkler method, as recommended in Strickland and Parsons (1968). The water column Chlorophyll-*a* was estimated by following the protocol of UNESCO (1966).

Sediment samples were collected on a monthly basis with a standard van Veen grab ( $0.044 \text{ m}^{-2}$ ). Sediment temperature was recorded with a mercury glass thermometer ( $0 - 100 \pm 0.01 \text{ }^{\circ}\text{C}$ ) immediately after the collection of sediment samples in the grab. Sediment samples for further analysis were collected ( $\sim 500 \text{ g}$ ) in pre-cleaned plastic bags and kept in an icebox during transportation to the laboratory. The sediment samples were dried in a hot air oven at  $95 \text{ }^{\circ}\text{C}$  before grain size analysis. Sediment grain size was determined by combined sieving and pipette method (Carver, 1971; Lewis, 1984). Another portion was dried to a constant weight around  $60 \text{ }^{\circ}\text{C}$  utilised for estimation of organic carbon (OC), by modified wet oxidation method (El-Wakeel and Riley, 1957; Nelson and Sommers, 1982; Trivedy and Goel, 1986). Organic matter (OM) content of sediment was calculated by multiplying organic carbon values by Van Bemmelen factor of 1.724 (Trask, 1939). Organic matter was expressed as grams per kilogram ( $\text{g kg}^{-1}$ ).

### 2.3. Biological parameters

Benthic samples in duplicate were collected on a monthly basis from each site in the estuary with a van Veen grab of  $0.044 \text{ m}^{-2}$  surface area. Before fixing, the larger animals were removed and the rest of the animals were narcotised with 8% of  $\text{MgCl}_2$ . Then, sediments were sieved with a 0.5 mm ( $500 \mu\text{m}$ ) mesh sieve and fixed with 5 to 7% neutral formalin. In the laboratory, the organisms were stained with Rose Bengal biological stain (0.1 g in 100 mL of distilled water) for easy identification of transparent organisms and re-sieved using 0.5 mm mesh sieve to remove the residual sediment, excess stain and formalin (Eleftherioo and Mc Intyre, 2005). Invertebrates were identified and quantified under a binocular microscope (Leica DM) with standard keys (Beesley et al., 2000; Böggemann, 2002, 2005; Day, 1967; Fauchald, 1977; Ima-jima, 1990a,b,c, 1992a,b; WoRMS, 2017). The numerical abundance was expressed in individuals per meter square ( $\text{ind m}^{-2}$ ). The wet weight of each macrofaunal group was determined by using a high precision electronic balance (Sartorius AG–ME215P, Germany with a precision of 0.01 mg). The biomass of macrofauna was expressed in  $\text{g m}^{-2}$ . The wet weight of bivalve molluscs was determined with shells removed.

The species identified were assigned to different feeding guilds based on the information available on the feeding mode of each taxon with an examination of taxonomic features of the feeding

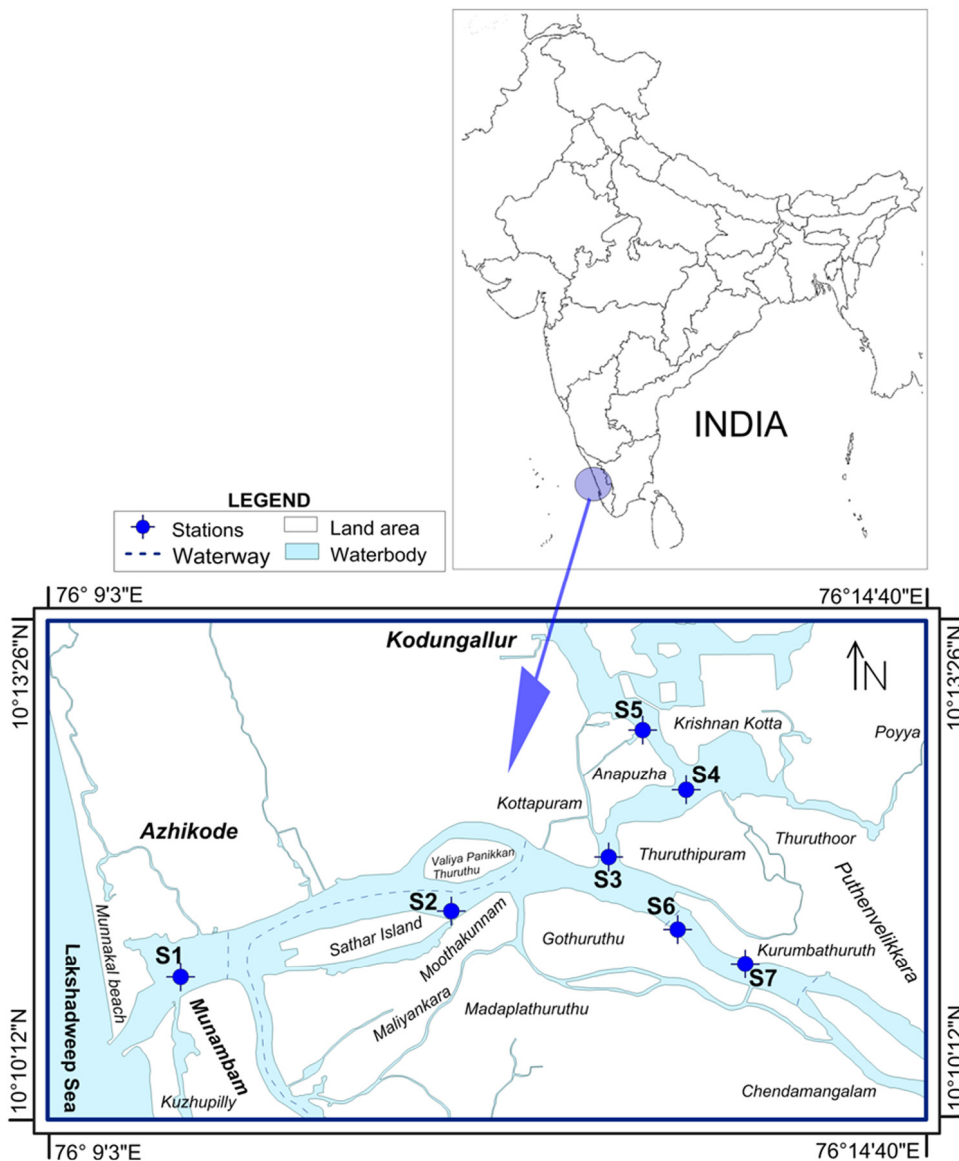


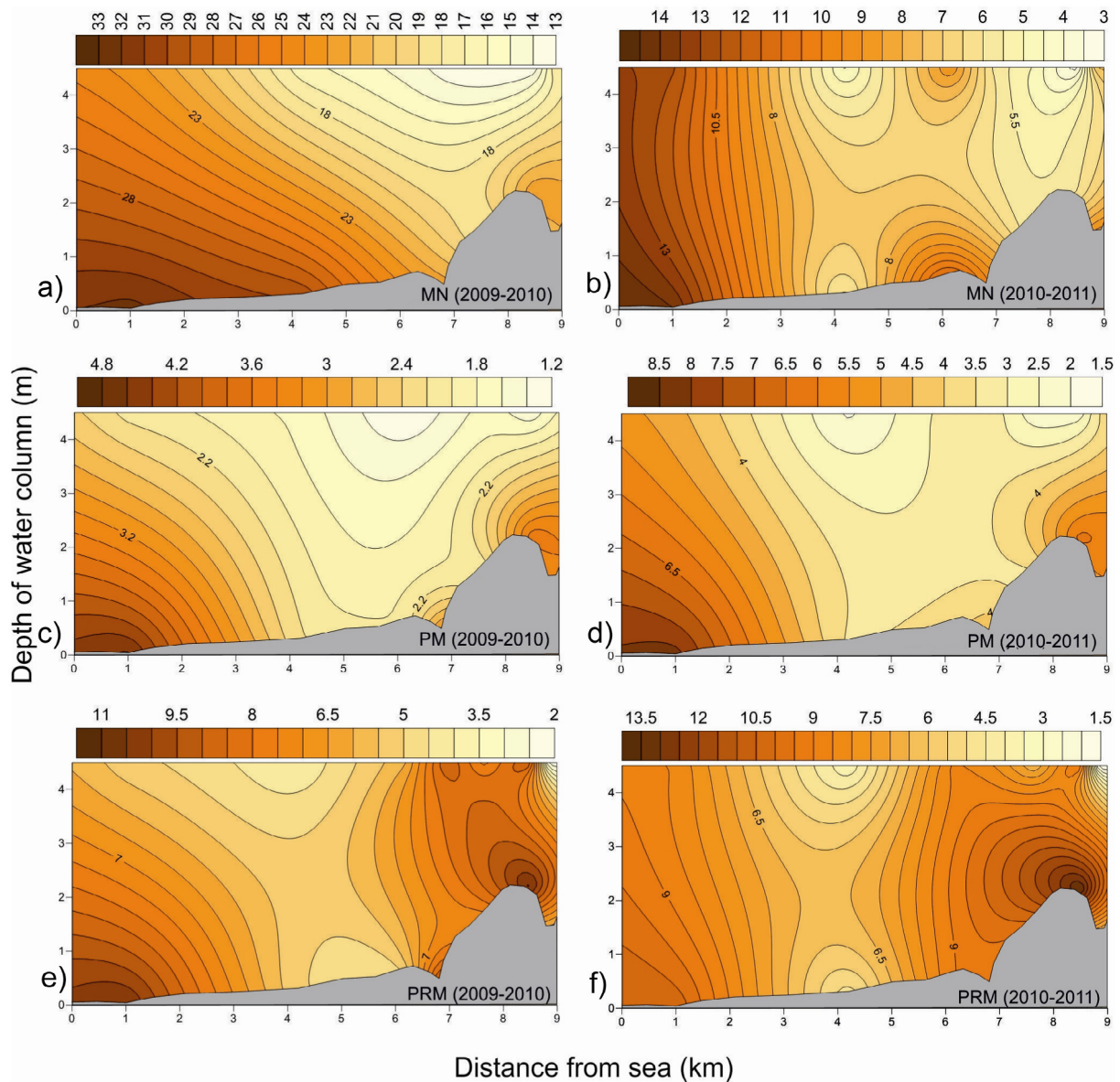
Fig. 1. Map of the sampling sites in Kodungallur–Azhikode estuary (KAE).

mechanism (Fauchald and Jumars, 1979; Macdonald et al., 2010; Jumars et al., 2015). In general, the feeding guild of macrofaunal assemblages were classified into macrophagous and microphagous. The macrophagous group was subdivided into two sub-modes herbivores (HVR) and carnivorous (CVR), while, the microphagous have been subdivided into three sub-modes such as suspension feeders or filter feeders (SF), deposit feeders (DF) and omnivorous (OVR). In this study, deposit feeders were again subdivided into sub-surface deposit feeder (SSDF) and surface deposit feeder (SDF). In case of missing information, they were add-on by using information referring to closely related species (Fauchald and Jumars, 1979; Jumars et al., 2015; Macdonald et al., 2010; MarLIN, 2017; Pagliosa, 2005).

#### 2.4. Statistical methods and analysis

Multivariate analysis and diversity indices were calculated with PRIMER v6 +PERMANOVA software package (Anderson et al., 2008; Clarke and Gorley, 2006). SPSS/PASW Statistics v18.0 (Statistical Programme for Social Sciences version v18.0) was used for statistical analysis. Golden Software Releases Surfer v11.0, ORIGIN v8.0

and MapInfo Professional v11.0 were used for graphical representation of data. PCA (Principal Component Analysis) and PCO (Principal Coordinates Analysis) in PERMANOVA+v1 were also performed (Anderson et al., 2008). TAXDTEST was conducted to evaluate the taxonomic distinctness of the macrofaunal species assemblages in the estuary (Clarke and Warwick, 1998). The procedure evaluates taxonomic distinctness (AvTD) of the sample, compares it to a regional pool of all species (including higher taxonomic levels: genus, subfamily, family, suborder, and order) and to the variation in taxonomic distinctness (VarTD). The method is robust and independent of sampling effort (Clarke and Warwick, 1998, 2001a,b). The regional species master list was compiled from WoRMS website (WoRMS, 2017). Taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) analyses are unique ways to evaluate biological assemblages. These methods have the advantage that the analyses are not influenced by sampling effort and it considers the taxonomic relationship of each species in the sample. Warwick and Clarke (1998) reported that chronically disturbed locations would exhibit greater variation and reduced taxonomic distinctness. Abundance Biomass Comparison curve (ABC curve) was used as a indicator of natural physical and biological disturbance as well as of pollution-induced disturbance in study sites and



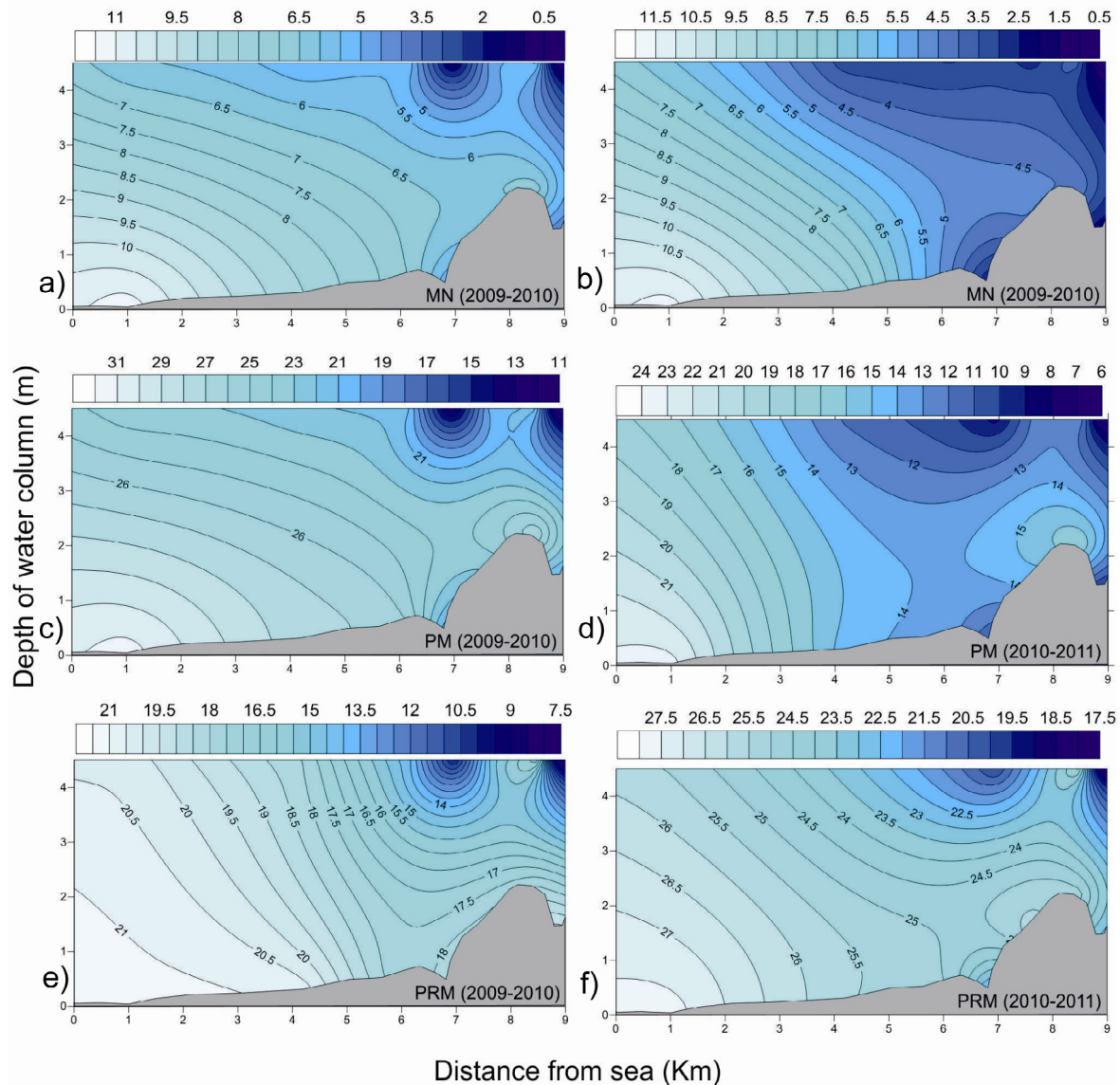
**Fig. 2.** Seasonal pattern of vertical distribution of water column turbidity (NTU) in the Kodungallur–Azhikode estuary (KAE) during the 2009–2010 and 2010–2011 period [Monsoon (MN), Post-Monsoon (PM), Pre-Monsoon (PRM)].

it does not require any reference site (Warwick, 1986). Uniformity in the distribution of abundance and biomass values represents the level of stress in the community. In undisturbed communities, the biomass curve lies above the curve for abundance. Under moderate pollution (or disturbance), the biomass and abundance curves are strictly coincident and may cross each other one or more times. In polluted conditions, the abundance curve lies above the biomass curve throughout its length. The W-value (Warwick value) was used to statistically define the relationship between trajectories and quantify the level of stress that a community experiences. When the biomass curve is above the abundance curve, the W-value will be positive. The negative W-value occurred when the abundance curve is above the biomass curve, with intermediate cases tending towards zero (Warwick and Clarke, 1998).

### 3. Results

#### 3.1. Environmental parameters

The mean annual rainfall in the catchment area of Kodungallur–Azhikode estuary (KAE) was  $297 \pm 281$  mm during the entire study period (2009–2011) and river discharge was  $252 \pm 267$  m<sup>3</sup> s<sup>-1</sup>. In a temporal scale, monsoon season (MN) showed large discharge pattern in relation with precipitation rate in the upper basins which was  $606 \pm 180$  m<sup>3</sup> S<sup>-1</sup> for the 1st year period and that for the 2nd year was  $473 \pm 62$  m<sup>3</sup> S<sup>-1</sup>. The mean turbidity value for KAE was  $9.60 \pm 11.46$  NTU and temporarily, monsoon season showed highest mean (Fig. 2 a–f). A significant variation was observed between seasons (ANOVA  $F(5,162) = 12, p = 0.000$ ). Inter-annual mean bottom salinity value for the entire estuary was  $15.78 \pm 9.90$  PSU. In a temporal scale, monsoon seasons (MN) showed a decreasing trend. Comparatively, highest mean values have been recorded during post-monsoon (PM) of the 2nd year ( $24.60 \pm 5.49$  PSU) and pre-monsoon (PRM) of the 1st year ( $24.55 \pm 5.78$  PSU) (Fig. 3 a–f). The average bottom water dissolved oxygen (DO) content for the



**Fig. 3.** Seasonal pattern of vertical distribution of water column salinity (PSU) in the Kodungallur–Azhikode estuary (KAE) during the 2009–2010 and 2010–2011 period [Monsoon (MN), Post-Monsoon (PM), Pre-Monsoon (PRM)].

entire estuary was  $4.94 \pm 1.11 \text{ mg L}^{-1}$ . Seasonally, MN ( $5.66 \pm 0.87 \text{ mg L}^{-1}$ ) and PM of the 2nd year ( $5.043 \pm 0.88 \text{ mg L}^{-1}$ ) showed peak values of DO, while lowest values were recorded during PRM ( $4.20 \pm 0.83 \text{ mg L}^{-1}$ ) and PM ( $4.43 \pm 0.86 \text{ mg L}^{-1}$ ) of the 1st year. Spatially, mean values observed at the St.1 ( $4.57 \pm 1.30 \text{ mg L}^{-1}$ ), St.2 ( $4.67 \pm 0.90 \text{ mg L}^{-1}$ ), St.5 ( $4.77 \pm 1.07 \text{ mg L}^{-1}$ ) and St.4 ( $4.87 \pm 1.05 \text{ mg L}^{-1}$ ) were comparatively low. However, the high mean bottom water DO concentration was observed at riverine stations, comprising St.7 ( $5.37 \pm 1.11 \text{ mg L}^{-1}$ ), St.6 ( $5.21 \pm 1.10 \text{ mg L}^{-1}$ ) and St.3 ( $5.13 \pm 1.15 \text{ mg L}^{-1}$ ). DO concentration showed clear variability among seasons (ANOVA  $F(5,162) = 11.21, p = 0.000$ ) (Fig. 4 a–f). Inter annual mean bottom water Chlorophyll-*a* (Chl-*a*) in the estuary was  $5.99 \pm 4.48 \text{ mg m}^{-3}$  (Fig. 5 a–f and Table 1a and b). Chl-*a* concentration in the bottom water showed a significant variation among seasons (ANOVA  $F(5,162) = 8.05, p = 0.000$ ).

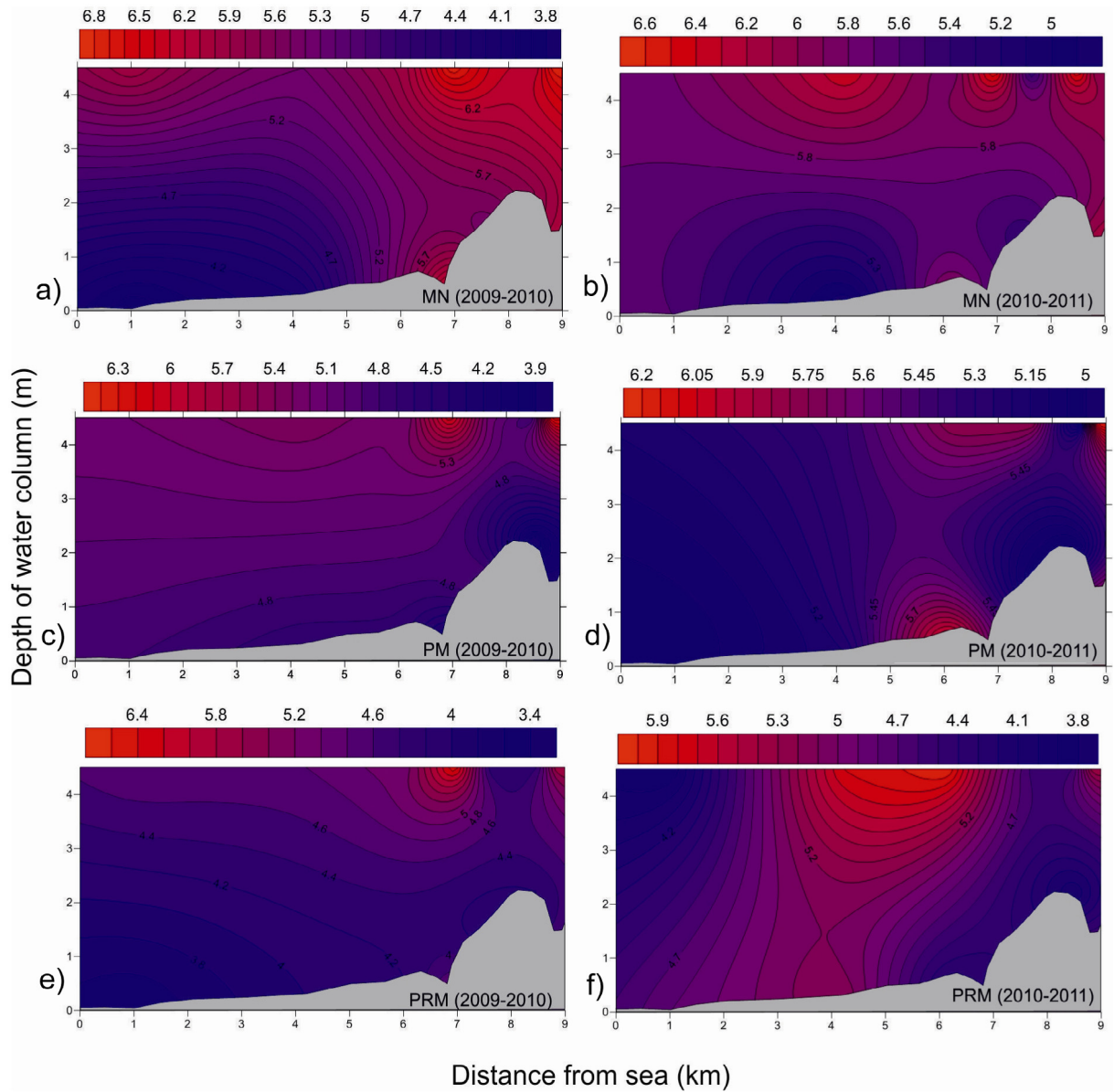
The estuarine sediment was characterised with the abundance of sand and silt with minor amounts of clay (Fig. 6 and Table 2a and b). Sand content in the estuarine sediment depicted an overall mean of  $81.61 \pm 16.59\%$ . Spatially, St.4 ( $91.15 \pm 5.45\%$ ), St.3 ( $88.18 \pm 11.74\%$ ), St.1 ( $87.50 \pm 12.39\%$ ) and St.5 ( $86.90 \pm 4.06\%$ ) exhibited comparatively higher sand fractions when compared to

**Table 1a and b**

Seasonal mean of hydrographic parameters ( $\pm$  SD) during the 2009–2010 and 2010–2011 period.

a. Hydrographic parameters ( $\pm$ SD) during 2009–2010 period			
Parameters	Monsoon	Post-monsoon	Pre-monsoon
Salinity (PSU)	$9.41 \pm 6.42$	$24.55 \pm 5.78$	$19.38 \pm 4.04$
Turbidity (NTU)	$21.11 \pm 20.58$	$3.04 \pm 1.33$	$7.42 \pm 4.64$
DO ( $\text{mg L}^{-1}$ )	$5.38 \pm 1.16$	$4.43 \pm 0.86$	$4.2 \pm 0.83$
Chl- <i>a</i> ( $\text{mg m}^{-3}$ )	$6.06 \pm 4.64$	$4.58 \pm 4.92$	$9.04 \pm 4.72$
b. Hydrographic parameters ( $\pm$ SD) during 2010–2011 period			
Parameters	Monsoon	Post-monsoon	Pre-monsoon
Salinity (PSU)	$2.6 \pm 4.47$	$14.11 \pm 8.1$	$24.6 \pm 5.49$
Turbidity (NTU)	$12.56 \pm 9.2$	$5 \pm 3$	$8.46 \pm 7.27$
DO ( $\text{mg L}^{-1}$ )	$5.66 \pm 0.87$	$5.43 \pm 0.88$	$4.54 \pm 1.17$
Chl- <i>a</i> ( $\text{mg m}^{-3}$ )	$4.27 \pm 3.37$	$3.81 \pm 1.5$	$8.16 \pm 4.26$

other stations such as St.6 ( $58.10 \pm 18\%$ ), St.2 ( $76.99 \pm 16.55\%$ ) and St.7 ( $82.43 \pm 15.08\%$ ). The silt fraction of sediment depicted a mean value of  $10.55 \pm 12.79\%$ . MN ( $6.71 \pm 9.06\%$ ) and PRM ( $7.76 \pm 12.62\%$ ) of the first year showed the lowest silt content. Silt

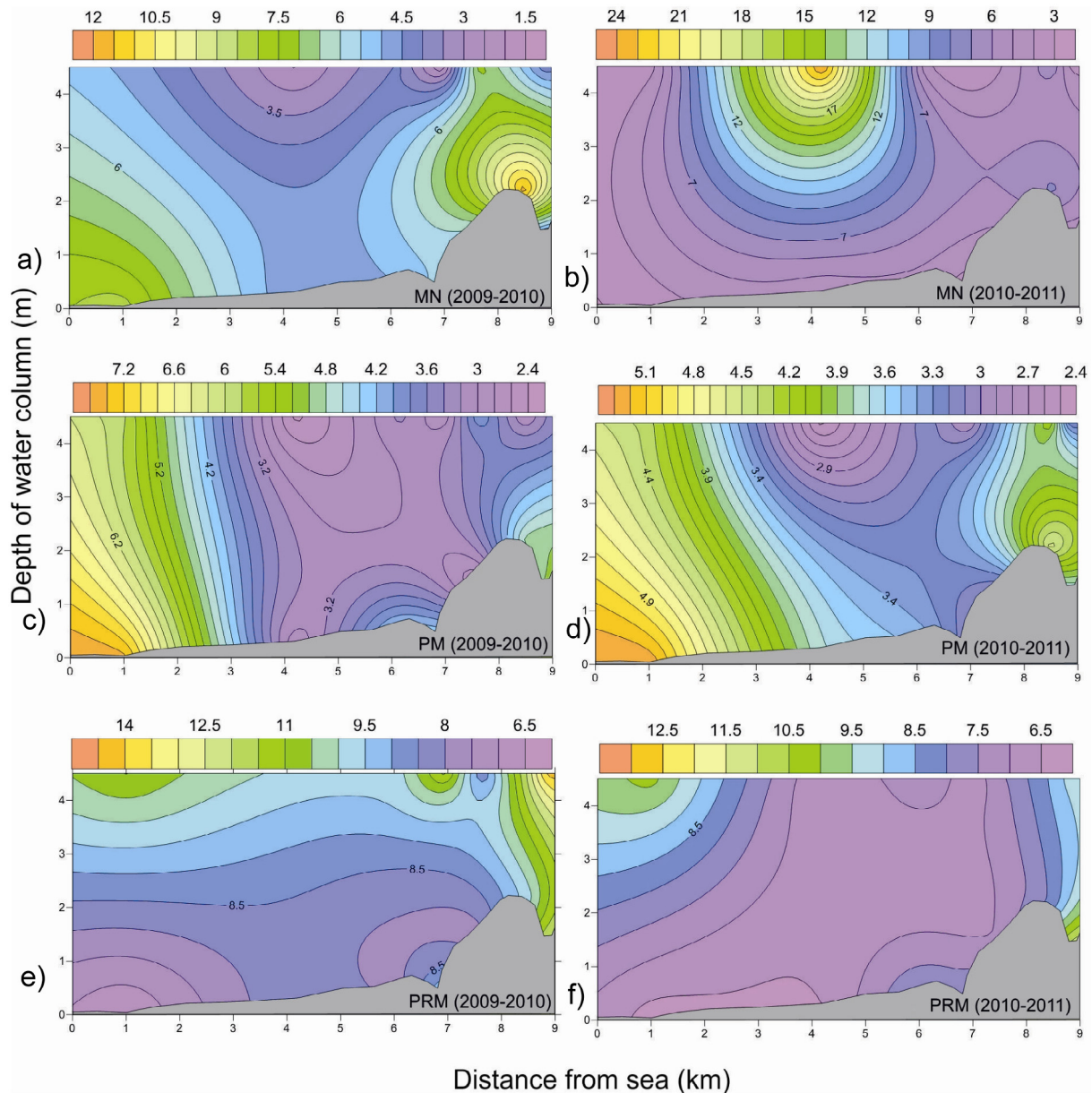


**Fig. 4.** Seasonal pattern of vertical distribution of water column dissolved oxygen ( $\text{mg L}^{-1}$ ) in the Kodungallur–Azhikode estuary (KAE) during the 2009–2010 and 2010–2011 period [Monsoon (MN), Post-Monsoon (PM), Pre-Monsoon (PRM)].

**Table 2a and b**

Station-wise mean of sediment quality parameters ( $\pm$  SD) in KAE during 2009 to 2010 and 2010–2011 period.

a. Sediment quality parameters ( $\pm$ SD) in 2009–2010					
Stations	Sed. temp. ( $^{\circ}\text{C}$ )	Sand (%)	Silt (%)	Clay (%)	OM (%)
St.1	$28 \pm 1.68$	$91.03 \pm 9.87$	$4.36 \pm 4.96$	$4.62 \pm 5.28$	$0.72 \pm 0.79$
St.2	$28.5 \pm 1.7$	$84.15 \pm 11.11$	$6.92 \pm 9.7$	$8.93 \pm 4.05$	$1.81 \pm 1.12$
St.3	$28.48 \pm 1.83$	$90.49 \pm 5.66$	$2.93 \pm 2.65$	$6.58 \pm 3.86$	$1.24 \pm 1.09$
St.4	$28.56 \pm 1.61$	$92.63 \pm 4.32$	$2.63 \pm 2.44$	$4.73 \pm 2.68$	$0.59 \pm 0.39$
St.5	$29.06 \pm 1.43$	$86.67 \pm 4.38$	$6 \pm 2.31$	$7.33 \pm 4.14$	$1.23 \pm 0.72$
St.6	$28.5 \pm 1.75$	$65.5 \pm 17.31$	$20.84 \pm 14.08$	$13.67 \pm 11.9$	$3.34 \pm 1.43$
St.7	$28.77 \pm 1.88$	$84.11 \pm 18.16$	$8.98 \pm 16.67$	$6.92 \pm 5.09$	$1.59 \pm 0.93$
b. Sediment quality parameters ( $\pm$ SD) in 2010–2011					
Stations	Sed. temp. ( $^{\circ}\text{C}$ )	Sand (%)	Silt (%)	Clay (%)	OM (%)
St.1	$27.84 \pm 1.73$	$83.98 \pm 14.03$	$10.54 \pm 11.84$	$5.47 \pm 4.25$	$1.02 \pm 0.59$
St.2	$28.15 \pm 1.70$	$69.84 \pm 18.38$	$19.35 \pm 15.97$	$10.81 \pm 7.63$	$2.51 \pm 0.68$
St.3	$28.54 \pm 1.53$	$85.88 \pm 15.63$	$9.05 \pm 13.74$	$5.08 \pm 3.23$	$0.94 \pm 0.33$
St.4	$28.50 \pm 1.45$	$89.66 \pm 6.22$	$4.83 \pm 3.1$	$5.51 \pm 4.17$	$0.7 \pm 0.37$
St.5	$29.04 \pm 1.68$	$87.11 \pm 3.9$	$8.52 \pm 3.94$	$4.36 \pm 2.01$	$1 \pm 0.19$
St.6	$28.50 \pm 1.68$	$50.7 \pm 17.97$	$31.46 \pm 16.23$	$17.84 \pm 8.84$	$3.92 \pm 0.49$
St.7	$28.63 \pm 1.40$	$80.75 \pm 11.81$	$11.25 \pm 8.09$	$8 \pm 6.34$	$1.92 \pm 0.66$



**Fig. 5.** Seasonal pattern of vertical distribution of water column Chlorophyll-*a* ( $\text{mg m}^{-2}$ ) in the Kodungallur-Azhikode estuary (KAE) during the 2009–2010 and 2010–2011 period [Monsoon (MN), Post-Monsoon (PM), Pre-Monsoon (PRM)].

content was high at St.6 ( $26.05 \pm 15.82\%$ ) and St.2 ( $13.13 \pm 14.4\%$ ) whereas the lowest fractions were found at St.4 ( $3.73 \pm 2.95\%$ ) and St.3 ( $5.99 \pm 10.17\%$ ). However, the clay fraction of sediment depicted mean value of  $7.85 \pm 6.76\%$ . In spatial scale, St.6 ( $15.75 \pm 10.47\%$ ) and St.2 ( $9.87 \pm 6.05\%$ ) depicted comparatively higher percentage of clay, whereas, St.4 ( $5.1 \pm 8.35\%$ ) and St.3 ( $5.83 \pm 3.57\%$ ) were recorded as low fractions in the sediment. A significant spatial variation was observed in the sand (ANOVA  $F(6,161) = 18.10$ ,  $p = 0.000$ ), silt (ANOVA  $F(6,161) = 11.32$ ,  $p = 0.000$ ) and clay (ANOVA  $F(6,161) = 1.063$ ,  $p = 0.000$ ) fractions of the sediment. However, the silt fraction also depicted a variability among seasons (ANOVA  $F(5,162) = 3.30$ ,  $p = 0.007$ ). The average sediment organic carbon (OC) content of the KAE during the entire study was  $9.30 \pm 7.10 \text{ g kg}^{-1}$ . In spatial scale, St.6 ( $21.1 \pm 6.3 \text{ g kg}^{-1}$ ), St.2 ( $12.5 \pm 5.7 \text{ g kg}^{-1}$ ) and St.7 ( $10.2 \pm 4.7 \text{ g kg}^{-1}$ ) were noticed with higher OC content as compared to St.4 ( $3.8 \pm 2.2 \text{ g kg}^{-1}$ ), St.1 ( $5.0 \pm 4.1 \text{ g kg}^{-1}$ ), St.3 ( $6.3 \pm 4.7 \text{ g kg}^{-1}$ ) and St.5 ( $6.4 \pm 3.1 \text{ g kg}^{-1}$ ). A significant difference in OC among

the stations (ANOVA  $F(6,161) = 41.28$ ,  $p = 0.000$ ) and a weak variation among seasons were observed (ANOVA  $F(5,162) = 2.59$ ,  $p = 0.028$ ). The mean sediment organic matter (OM) in the estuary was  $16.10 \pm 12.30 \text{ g kg}^{-1}$  (Fig. 7).

The environmental variation was made clear in the principal component analysis (PCA). The first five principal components (PC) accounted for 71.4% of the variability in the ecological parameters of the seven stations. The first 2 PC accounted 46.3% of variability that was 27.9% on axis 1 (eigenvalue value, 4.86) and 18.4% for axis 2 (eigenvalue value, 3.27). Rainfall, river discharge, salinity, turbidity, DO and sediment temperature were most important determinants of differences between seasons along the first axis, whereas OC, OM, sand, silt, and clay fraction were influential along the axis 2 (Fig. 8).

### 3.2. The benthic standing crop of macrobenthos

A total of 18846 organisms were collected in the grab samples, of which, malacostracan crustaceans contributed 60% of total



Fig. 6. The mean percentage composition of sediment texture in KAE during the study (2009 to 2011) with its spatial distribution pattern.

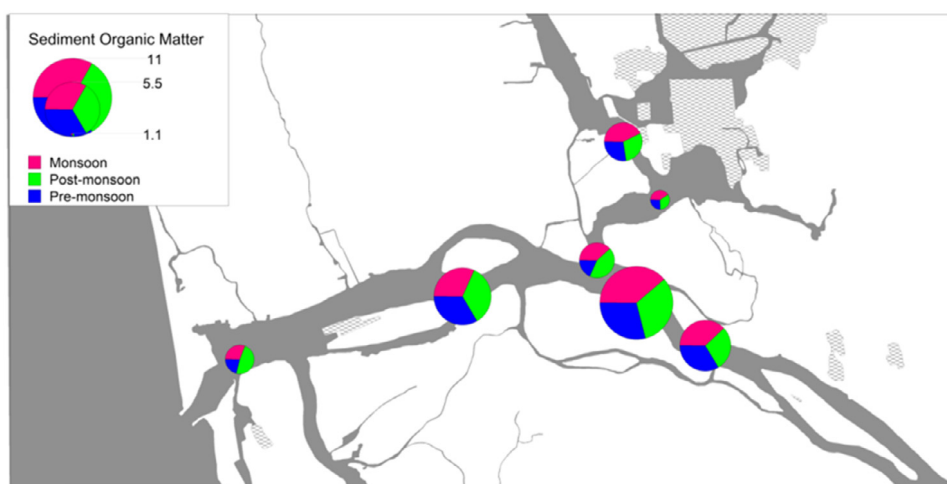


Fig. 7. The mean spatio-temporal distribution pattern of sediment organic matter in KAE during the study (2009–2011).

macrobenthic density followed by polychaetes (20%), molluscs (9%) and other groups (11%). Among the macrobenthic biomass, molluscs were the dominant group (63%) followed by malacostracan crustaceans (18%), polychaetes (17%) and other groups (2%). Malacostracan crustaceans in the present investigation were represented mainly by the amphipods and isopods, with a significant representation of decapods, cumaceans, tanaids, stomatopods and mysids. Malacostracan was the most dominant group concerning the number of individuals. The abundance of this group was the greatest at St.1 representing 85.55% of the total numbers (Table 3a–c). While it was 42.61% at St.2, 82.35% for St.3; 67.38% for St.4; 2.88% for St.5; 10.58% for St.6 and with the least value of 2.09% at St.7. Similarly, the mean biomass of malacostracans in the study period was  $5.09 \pm 15.90 \text{ g m}^{-2}$ , and that was  $3.40 \pm 9.98 \text{ g m}^{-2}$  for 1st year and  $6.78 \pm 20.09 \text{ g m}^{-2}$  for the 2nd year survey (Table 4a–c).

Polychaetes were the second dominant group regarding number of individuals, representing 20% of all organisms collected during the study, while polychaete biomass represented about 17% that of the total macrofauna. A total of 5669 polychaetes were collected during the entire study; subclass Errantia contributed 1811 organisms and subclass Sedentaria contributed 3858 individuals. The abundance of this group was the greatest at St.1 representing 7.92% of the total numbers. While it was 43.49% at St.2; 4.60% at St.3; 9.37% at St.4; 57.07% at St.5; 78.94% at St.6 and 13.18% at St.7. Mean biomass of polychaetes during the entire study was  $4.74 \pm 83$

$\text{g m}^{-2}$  and that for the 1st year was  $6.19 \pm 66 \text{ g m}^{-2}$  and  $3.23 \pm 100 \text{ g m}^{-2}$  for the 2nd year.

Among the molluscs bivalves constituted a significant group, with few representations from gastropods. In all samples, 2788 clams were collected and they contributed 9.71% to total macrofauna density. The contribution of bivalves to total macrofauna density was 8.81% and that for gastropods was 0.90%. The relative abundance of the molluscan group varied as 2.93% in St.1; 10.03% in St.2; 11.39% in St.3; 18.63% in St.4; 5.84% in St.5; 1.25% in St.6 and 1.67% in St.7. Molluscs represented about 63% of the total biomass. Mean biomass of molluscs in the grab samples varied from  $0.02 \pm 0.08 \text{ g m}^{-2}$  in St.6 to  $67 \pm 70 \text{ g m}^{-2}$  in St.3 with an average value of  $17 \pm 54 \text{ g m}^{-2}$  across all sites.

Other groups represented in the samples were hydrozoans, cirripedians, insects, Pisces, ophiuroideans and nemerteans. They contributed 11% to the total macrofaunal density. Of these, hydrozoans were well represented at some stations which contributed more than 10% to the total density. Pisces (0.49%) and cirripedians (0.24%) were also contributed to the numerical density of macrofauna in some stations of the estuary. Hydrozoans (92.61%) were the most representing members in other groups followed by Pisces (4.50%), cirripedians (2.18%), nemerteans (0.36%), ophiuroideans (0.23%) and insects (0.13%). The combined biomass of these groups varied from nil to  $17.50 \text{ g m}^{-2}$ , they accounted for 2% of the total macrofaunal biomass in the entire study with mean biomass of

**Table 3a–c**Station-wise and season-wise macrofaunal density (ind m<sup>-2</sup>) in KAE during 2009–2010 and 2010–2011 period.

a. Station-wise macrofaunal density during 2009–2010 period					
Station	Polychaeta	Malacostraca	Mollusca	Others	Total
St.1	496 ± 618	1991 ± 4166	167 ± 260	295 ± 709	2951 ± 4269
St.2	1013 ± 1916	123 ± 108	62 ± 64	131 ± 305	1333 ± 1932
St.3	576 ± 666	2693 ± 5005	706 ± 802	342 ± 899	4320 ± 4757
St.4	570 ± 510	4114 ± 8236	756 ± 793	358 ± 1015	5801 ± 8178
St.5	1208 ± 918	95 ± 78	250 ± 368	249 ± 592	1805 ± 1158
St.6	879 ± 959	157 ± 205	23 ± 32	194 ± 655	1256 ± 1028
St.7	578 ± 460	127 ± 156	108 ± 110	29 ± 64	845 ± 555
b. Station-wise macrofaunal density during 2010–2011 period					
Station	Polychaeta	Malacostraca	Mollusca	Others	Total
St.1	150 ± 217	5008 ± 16864	72 ± 80	5 ± 13	5237 ± 16812
St.2	667 ± 884	1523 ± 5111	341 ± 810	7 ± 14	2540 ± 5216
St.3	375 ± 453	14331 ± 28684	1648 ± 1207	5 ± 13	16362 ± 28281
St.4	299 ± 220	2155 ± 3244	975 ± 878	79 ± 221	3512 ± 3366
St.5	2720 ± 4542	102 ± 129	150 ± 154	2113 ± 4535	5087 ± 6077
St.6	761 ± 806	61 ± 61	2 ± 7	3 ± 7	830 ± 803
St.7	445 ± 605	32 ± 48	21 ± 26	2033 ± 7011	2534 ± 6950
c. Season-wise macrofaunal density during 2009–2011 period					
Seasons	Polychaeta	Malacostraca	Mollusca	Others	Total
Mon.09–10	1006 ± 1404	1261 ± 3205	409 ± 667	12 ± 43	515 ± 1007
Pos.09–10	656 ± 756	2231 ± 6244	276 ± 478	515 ± 1007	158 ± 439
Pre.09–10	619 ± 553	494 ± 1073	203 ± 403	76 ± 349	6 ± 11
Mon.10–11	552 ± 751	5575 ± 19274	375 ± 718	1740 ± 5384	
Pos.10–11	1285 ± 3181	4169 ± 12230	312 ± 499		
Pre.10–11	485 ± 501	204 ± 444	688 ± 1174		

**Table 4a–c**Station-wise and season-wise macrofaunal biomass (g m<sup>-2</sup>) in KAE during 2009–2011 period.

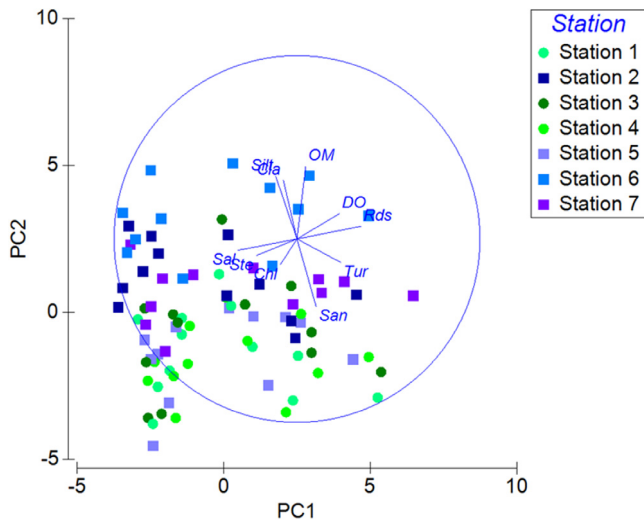
a. Station-wise macrofaunal biomass during 2009–2010 period					
Station	Polychaeta	Malacostraca	Mollusca	Others	Total
St.1	5.08 ± 6.1	1.2 ± 2.26	8.76 ± 27.35	0.07 ± 0.12	15.1 ± 28.74
St.2	4.82 ± 5.75	0.31 ± 0.53	0.05 ± 0.08	–	5.18 ± 5.75
St.3	12.5 ± 20.35	10.11 ± 10.67	43.06 ± 53.89	0.24 ± 0.6	65.91 ± 65.84
St.4	2.93 ± 3.25	10.98 ± 20.99	37.34 ± 40.32	1.58 ± 4.11	52.82 ± 48.75
St.5	10.34 ± 7.98	2.45 ± 7.83	11.44 ± 39.08	0.11 ± 0.39	24.34 ± 37.6
St.6	4.14 ± 5.14	0.28 ± 0.66	0.04 ± 0.12	1.46 ± 5.05	5.92 ± 6.65
St.7	2.83 ± 3.17	0.72 ± 1.8	0.07 ± 0.13	0.15 ± 0.22	3.77 ± 3.58
b. Station-wise macrofaunal biomass during 2010–2011 period					
Station	Polychaeta	Malacostraca	Mollusca	Others	Total
St.1	2.68 ± 5	14.19 ± 40.1	3.54 ± 10.14	–	20.41 ± 43.13
St.2	5.09 ± 5.73	1.77 ± 5	2.42 ± 6.16	1.19 ± 3.96	10.47 ± 11.09
St.3	4.75 ± 8.27	19.09 ± 27.9	91.8 ± 77.56	0.32 ± 1.11	115.95 ± 81.41
St.4	1.92 ± 1.52	3.9 ± 4.6	46.41 ± 58.1	–	52.23 ± 58.1
St.5	4.72 ± 5.45	2.82 ± 8.97	0.08 ± 0.08	0.91 ± 2.35	8.53 ± 9.39
St.6	3.47 ± 3	0.8 ± 1.77	–	1.06 ± 3.67	5.32 ± 5.53
St.7	1.29 ± 1.41	1.65 ± 5.09	0.01 ± 0.02	0.63 ± 1.38	3.58 ± 5.35
c. Seasonal macrofaunal biomass during 2010–2011 period					
Seasons	Polychaeta	Malacostraca	Mollusca	Others	Total
Mon.09–10	6.62 ± 7.03	7.04 ± 15.31	17.79 ± 36.56	0.21 ± 0.81	0.74 ± 3.3
Pos.09–10	5.26 ± 12.33	1.93 ± 5.98	18.47 ± 41.42	0.59 ± 2.67	0.54 ± 1.72
Pre.09–10	6.38 ± 8.84	2.2 ± 5.19	6.93 ± 22.91	0.47 ± 2.36	0.79 ± 2.81
Mon.10–11	2.89 ± 4.74	9.82 ± 30.6	24.37 ± 58.7		
Pos.10–11	3.25 ± 4.06	7.44 ± 16.37	19.71 ± 49.35		
Pre.10–11	4.02 ± 6.07	2.2 ± 5.28	18.12 ± 37.48		

0.56 ± 132 g m<sup>-2</sup>. Meanwhile, 0.56 ± 2.47 g m<sup>-2</sup> during the 1st year and 0.60 ± 2.33 g m<sup>-2</sup> for the 2nd year.

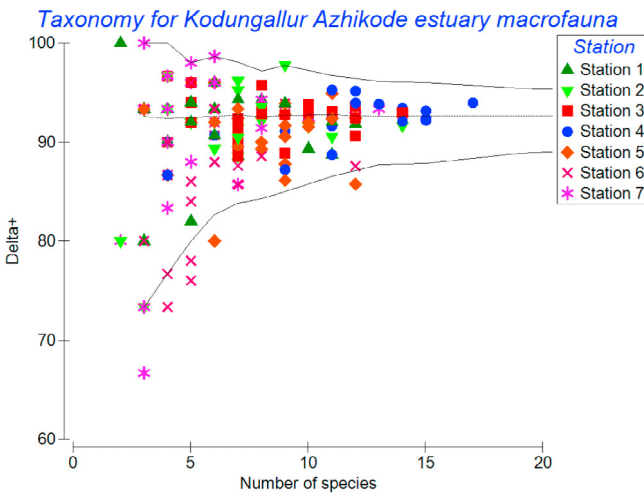
### 3.3. TAXDTEST analysis

The sampling stations were compared using taxonomic distinctness (AvTD) and variations in taxonomic distinctness (VarTD). In general, the values of AvTD and VarTD for all stations during the entire monthly survey fell within the confidence intervals of probability funnel (95%,  $p < 0.05$ ). However, a significant variation was noticed in the values among stations (AvTD:  $F_{(6,161)} =$

3.105,  $p = 0.007$ ; VarTD:  $F(6,161) = 2.489$ ,  $p = 0.025$ ). High values in variation in taxonomic distinctness were often caused by lack of certain types of habitats at some locations. The change in taxonomic distinctness plot has a broader probability funnel. Few stations were slightly more significant and on the border of the variation in taxonomic distinctness with 95% probability limits. Stations 1, 5, 6 and 7 occasionally move out from the 95% confidence intervals of probability funnel. However, stations 1, 3 and 4 (STA group) depicted less variation. The variation in taxonomic distinctness (range 0 to about 800) corroborates habitat and species distribution heterogeneity in the region (Figs. 9a&9b).



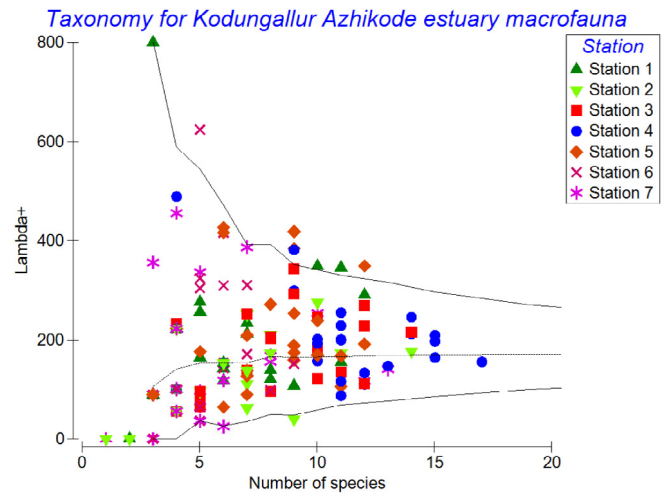
**Fig. 8.** Two-dimensional principal component analysis (PCA) ordination of selected normalised environmental variables in KAE on a spatial basis (Sal: salinity, Tur: bottom water turbidity, DO: bottom water dissolved oxygen, OM: sediment organic matter, Ste: sediment temperature, San: sand, Silt: silt, Cla: clay, RDi: river discharge).



**Fig. 9a.** Confidence funnels for taxonomic distinction (AvTD) randomised TAXDTEST analysis of benthic community assemblage compared to different stations in KAE.

### 3.4. Abundance biomass comparison (ABC) curves

The ABC curves for KAE was plotted for each sampling sites separately as well combined. In ABC plot,  $W$ -values can be ranged between  $-1$  to  $+1$  for macrofaunal assemblages and when the biomass curve lies above the abundance curve of ABC plot, it gets positive values that indicates undisturbed benthic communities with the dominance of  $K$ -selected species. Similarly, comparatively right ecological conditions were indicated in the positive  $W$  value for the sampling sites in the middle zone of the estuary, such as St.3 ( $W = 0.075$ ) and St.2 ( $W = 0.051$ ). However, when communities were characterised as moderately stressed, the abundance and biomass curves became very close or intersect, represented by  $W$ -values close to zero. Such conditions were observed for St.1 ( $W = -0.009$ ), St.4 ( $W = -0.011$ ), St.6 ( $W = -0.079$ ) and St.7 ( $W = -0.079$ ) indicating moderate disturbances. In contrast to that, negative  $W$ -values (when the abundance curve lies above the biomass curve) depict the disturbed benthic communities with the



**Fig. 9b.** Confidence funnels for variation in taxonomic distinction (VarTD) randomised TAXDTEST analysis of benthic community assemblage compared to different stations in KAE. Funnel boundaries describe the upper and lower 95 percent confidence limits using 1000 permutations of selecting species randomly from a comprehensive master species list for the null distribution.

dominance of  $r$ -selected species in the assemblages. In the present study, the relatively high negative trend was observed in the St.5 ( $W = -0.139$ ) which indicates the potential for high disturbances. However, the  $W$ -value for the entire estuary was  $-0.079$  indicating the moderate disturbances (Fig. 10a–h).

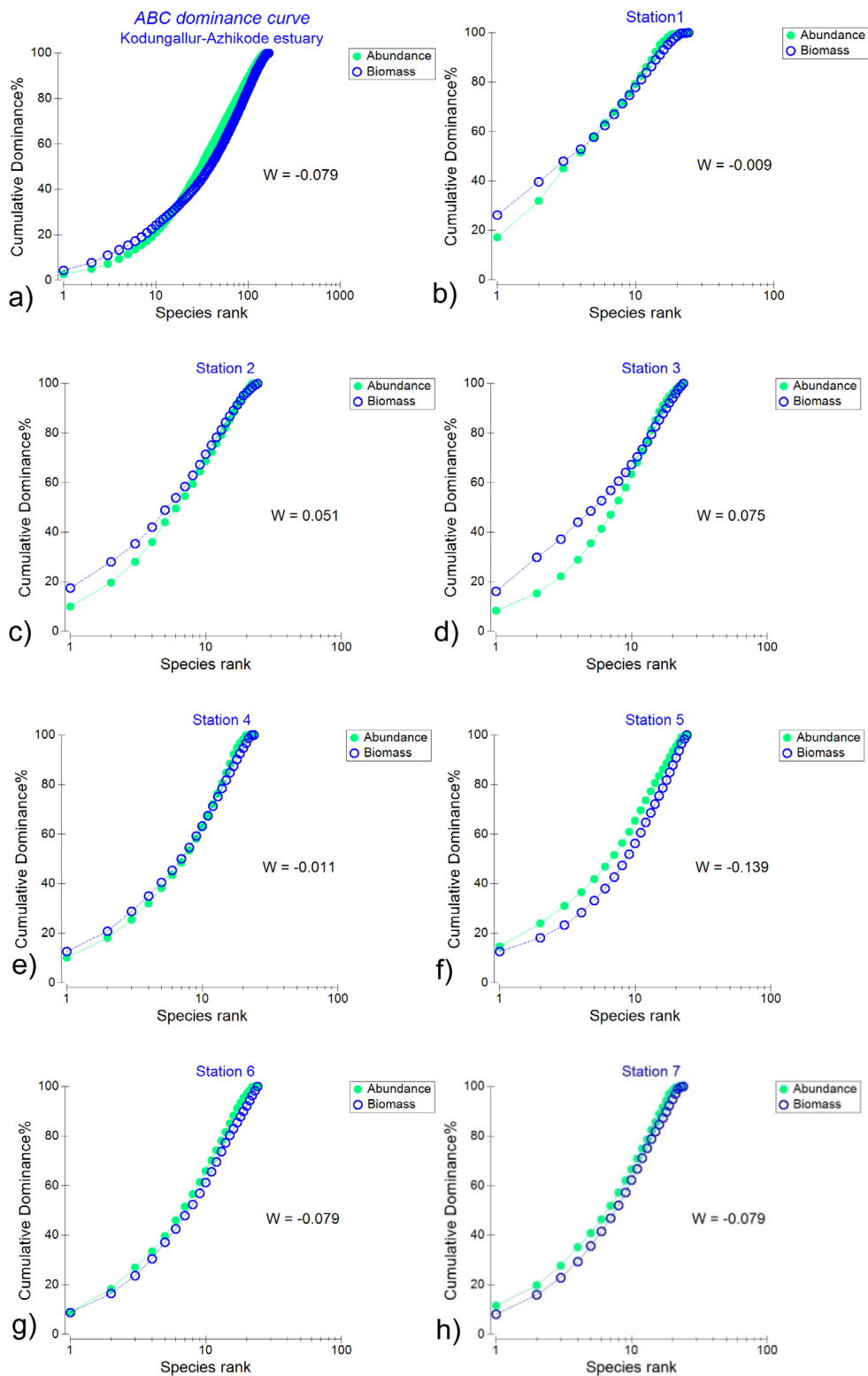
### 3.5. Feeding guild composition of macrofauna

Suspension feeding amphipod *Americorophium triaenonyx* under the family Corophiidae was the most represented macrofaunal species. Other dominant macrofaunal members were suspension feeders (SF) from the hydroid colony of *Obelia bidentata*, surface deposit feeders (SDF) of sedentarian polychaete like *Prionospio cirrifera*, suspension feeder (SF) bivalvelike *Arcuatula senhousia*, carnivorous (CVR) isopod like *Cirolana fluvialtilis* and sub-surface deposit feeder (SSDF) sedentarian polychaete like *Capitella* sp. (Fig. 11 & Table 5).

During the first year period, macrofaunal assemblage showed the dominance of suspension feeders (SF) with 41.56% followed by 20.58% of sub-surface deposit feeder (SSDF), 20.23% of HVR, 10.51% SDF and 7.13% CVR. During the 2nd year period, SF dominated with 66.14% of total density followed by 12.35% of SSDF, 9.34% of HVR, 6.92% of SDF and 5.16% CVR with sporadic occurrence of wood boring isopods. Based on hierarchical cluster analysis and SIMPROF test the St.3, 4 and 1 grouped as STA and rest of the stations 2, 5, 6 and 7 were grouped as STB. The stations in group STA dominated with 70.41% of SF followed by 17.09% HVR, 4.81% SSDF, 4.76% CVR and the rare occurrence of 0.32% SRL. While group STB dominated with 39.74% SSDF, 25.27% SF, 20.62% SDF, 8.55% CVR and 5.82% HVR. In the seasonal pattern, MN and PM periods were grouped in the SIMPROF test and formed SSB group while PRM has made another group SSA. Stations in the SSB dominated with 57.79% SF, 14.69% SSDF, 13.69% HVR, 8.30% SDF and 5.46% CVR while SSA dominated with 50% SF, 20.02% SSDF, 13.23% HVR, 8.49% SDF and 8.27% CVR.

### 3.6. Feeding guild of Polychaetes

In this investigation following Fauchald and Jumars (1979), the feeding guilds of polychaetes were classified as carnivorous (CVR), surface deposit feeders (SDF), subsurface deposit feeders



**Fig. 10a–h.** (a) Abundance biomass comparison (ABC) curves of macrofaunal assemblage in Kodungallur–Azhikode estuary and (b–h) each station plotted separately. The W statistic is positive when abundance curve remains below biomass curve and is negative when the two curves cross.

(SSDF), filter feeders or suspension feeders (SF) and omnivores (OVR). As Fauchald and Jumars (1979) have furnished information at the family level, the assigning of all the species encountered in the study to a particular feeding guild confirmed after examining the mouthparts. The available food resources in the sediments are thereby utilised and partitioned between these trophic guilds.

The polychaete species represented in the present study was assigned to one of four feeding guilds such as carnivorous (CVR), surface deposit feeders (SDF), sub-surface deposit feeders (SSDF) and suspension feeders (SF). The composition and structure of the polychaete feeding guilds were investigated using the species abundance data for understanding the spatiotemporal changes.

**Table 5**  
The mean feeding guild composition (ind m<sup>-2</sup>) of macrobenthic groups in the Kodungallur–Azhikode estuary (KAE).

Class	Order	Family	Feeding guild	St.1	St.2	St.3	St.4	St.5	St.6	St.7	
Malacostraca	Decapoda	Penaeidae	CVR	1	1	3	7	4	3	17	
		Hymenosomatidae	SDF	1	2	12	9	2	4	5	
		Leucosiidae	SDF	0	0	10	3	0	4	1	
		Portunidae	CVR	2	0	1	8	0	0	0	
		Alpheidae	CVR	0	1	2	0	0	1	5	
		Diogenidae	CVR	3	0	0	0	0	0	0	
		Luciferidae	SF	0	0	0	0	2	0	0	
		Amphipoda	Maeridae	SDF	0	0	0	2	0	0	0
			Melitidae	SDF	36	1	0	5	5	0	0
			Corophiidae	SF	6617	720	7434	2599	30	26	29
	Eriopisidae		CVR	86	40	35	37	14	23	2	
	Ischyroceridae		SF	0	0	0	0	0	1	0	
	Gammaridae		CVR	0	0	12	1	0	3	0	
	Aoridae		HVR	132	17	132	154	27	7	5	
	Cumacea		Bodotriidae	SDF	3	5	0	3	0	0	1
			Isopoda	Anthuridae	CVR	46	4	87	74	11	3
	Tanaidacea		Idoteidae	HVR	0	1	1	4	0	2	0
		Sphaeromatidae	SRL	1	0	0	0	0	0	0	
		Cirolanidae	CVR	214	16	779	304	2	28	12	
		Apseudidae	SDF	13	16	4	2	1	5	4	
		Stomatopoda	Squillidae	CVR	0	0	0	0	0	0	1
		Mysida	Mysidae	SF	3	0	0	0	1	1	0
		Polychaeta	Eunicida	Lumbrineridae	CVR	57	33	14	27	56	82
Onuphidae				CVR	1	2	21	13	17	0	3
Syllidae				CVR	19	37	29	25	0	23	5
Phyllodocida			Nereididae	CVR	57	122	64	67	567	128	48
	Nephtyidae		CVR	0	0	0	0	13	2	0	
	Phyllodocidae		CVR	0	0	0	0	9	0	0	
	Goniadidae		CVR	3	0	5	6	9	0	0	
	Glyceridae		CVR	9	34	1	31	30	6	12	
	Pilargidae		CVR	0	0	0	1	0	0	0	
	Sabellida		Oweniidae	SSDF	7	0	0	3	7	0	0
Serpulidae	SF		0	0	3	0	0	0	0		
Spionida	Spionidae		SDF	47	303	43	96	525	292	135	
Terebellida	Terebellidae		SF	3	9	130	36	0	0	1	
Scolecida (Infraclass)	Opheliidae		SSDF	2	0	0	0	0	2	0	
	Capitellidae		SSDF	122	300	169	136	731	287	281	
Bivalvia	Veneroida		Corbiculidae	SF	2	0	22	265	63	1	9
			Veneridae	SF	86	23	560	188	76	5	10
			Psammobiidae	SF	3	2	3	1	21	3	5
	Anomalodesmata		Cuspidariidae	SF	0	9	0	6	1	2	15
			Mytilidae	SF	1	143	458	389	0	0	3
			Ostreoida	Ostreidae	SF	5	4	19	11	14	2
Gastropoda	Neogastropoda		Nassariidae	SDF	11	13	104	35	18	0	16
			Muricidae	CVR	1	0	0	0	0	0	0
Actinopterygii	Perciformes	Gobiidae	CVR	2	23	2	23	77	3	2	
Ophiuroidea	Ophiurida	Ophiotrichidae	SF	2	0	0	0	0	0	0	
Hydrozoa	Leptothecata	Campanulariidae	SF	143	38	168	180	1064	95	0	
Cirripedia	Sessilia	Balanidae	SF	1	0	1	14	38	0	9	
Insecta	Diptera	Chironomidae	SDF	0	0	2	0	0	0	2	
Nemertea	Nemertea	Nemertea	CVR	0	7	0	1	1	0	2	

Annual data showed a dominance of SDF polychaetes during both years followed by SSDF. Seasonally, group SSB (MN & PM) was dominated with SDF (51.95%) and followed by SSDF (34.57%), CVR (12.23%) and SF (0.25%). In seasonal group, SSA (PRM) was dominated with SF (38.63%), SDF (28.56%), SSDF (23.51%) and CVR (9.25%). Stations in the group STA (St.1, 3 & 4) were dominated with SF (52.49%), SSDF (33.28%), SDF (28.42%), and CVR (14.23%) while STB (St.2, 5, 6 & 7) was dominated with SDF (53.40%), SSDF (34.25%), CVR (11.46%) and SF (0.89%). More clearly, St.1 (43.83%) and St.7 (47.38%) were dominated with SSDF, St.3 with SF (63.21%) and St.2 (58.32%), St.4 (35.27%) St.5 (50.39%) and St.6 (59.95%) were dominated with SDF (Fig. 12).

### 3.7. Feeding guild of malacostracan crustaceans

Following the classification of Macdonald et al. (2010) and Fauchald and Jumars (1979), the feeding guilds of malacostracans in the present study were represented by carnivorous (CVR), surface deposit or detritus feeders (SDF), suspension feeders (SF),

herbivores (HVR), and sporadic occurrence of wood boring isopod (Lignivorous; LIG). Among the malacostracan communities, suspension feeders dominated in all stations. STA group of stations and St.2 in the STB was highly dominated by SF. While, in riverine stations, SF was comparatively less in number (St.5, 6 & 7). St.5 (STB) was dominated with HVR, and other stations (St.6 and 7) depicted an increase in the population of CVR and HVR.

### 3.8. Feeding guild of molluscs and other groups

In the present study, all bivalve species collected were suspension feeders (SF). The single dominant gastropod, *Nassodonta insignis* was surface deposit feeder (SDF). Carnivorous (CVR) gastropod, *Murex trapa* was collected twice from estuarine mouth region. Suspension feeders dominated in abundance of other group by the suspension feeding hydroid colony of *Obelia bidentata*, echinoderm *Ophiothrix* sp., *Balanus improvises* along with four carnivorous fishes under the family Gobiidae, nemerteans and surface deposit feeding chironomid larvae (Fig. 13a–f).

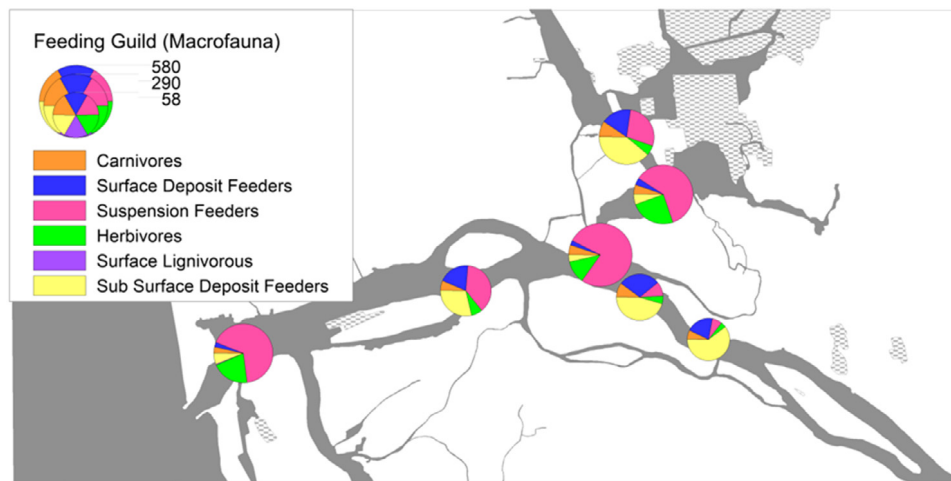


Fig. 11. Mean percentage contribution of different feeding guild in KAE during 2009–2011 period, bubble size indicates relative abundance and pie slices indicate contribution of each group.

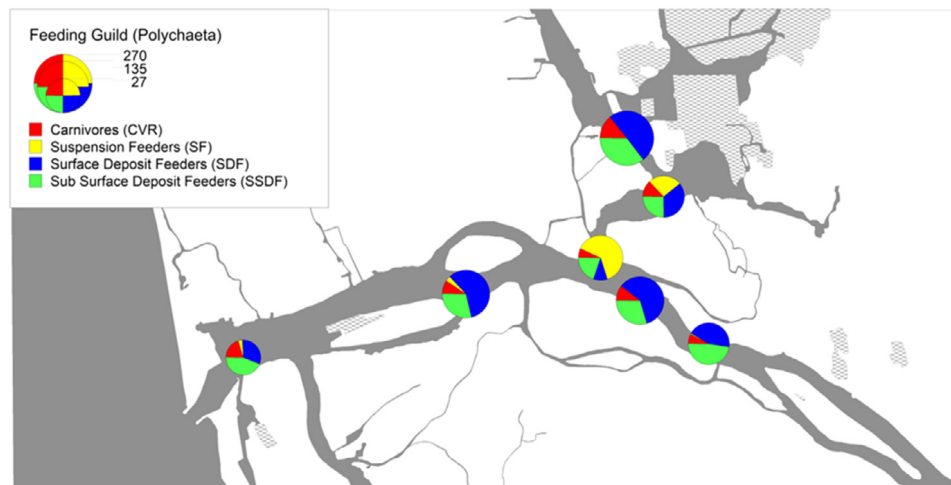


Fig. 12. Mean percentage contribution of different feeding guild of polychaetes in KAE during 2009–2011 period, bubble size indicates relative abundance and pie slices indicate contribution of each group.

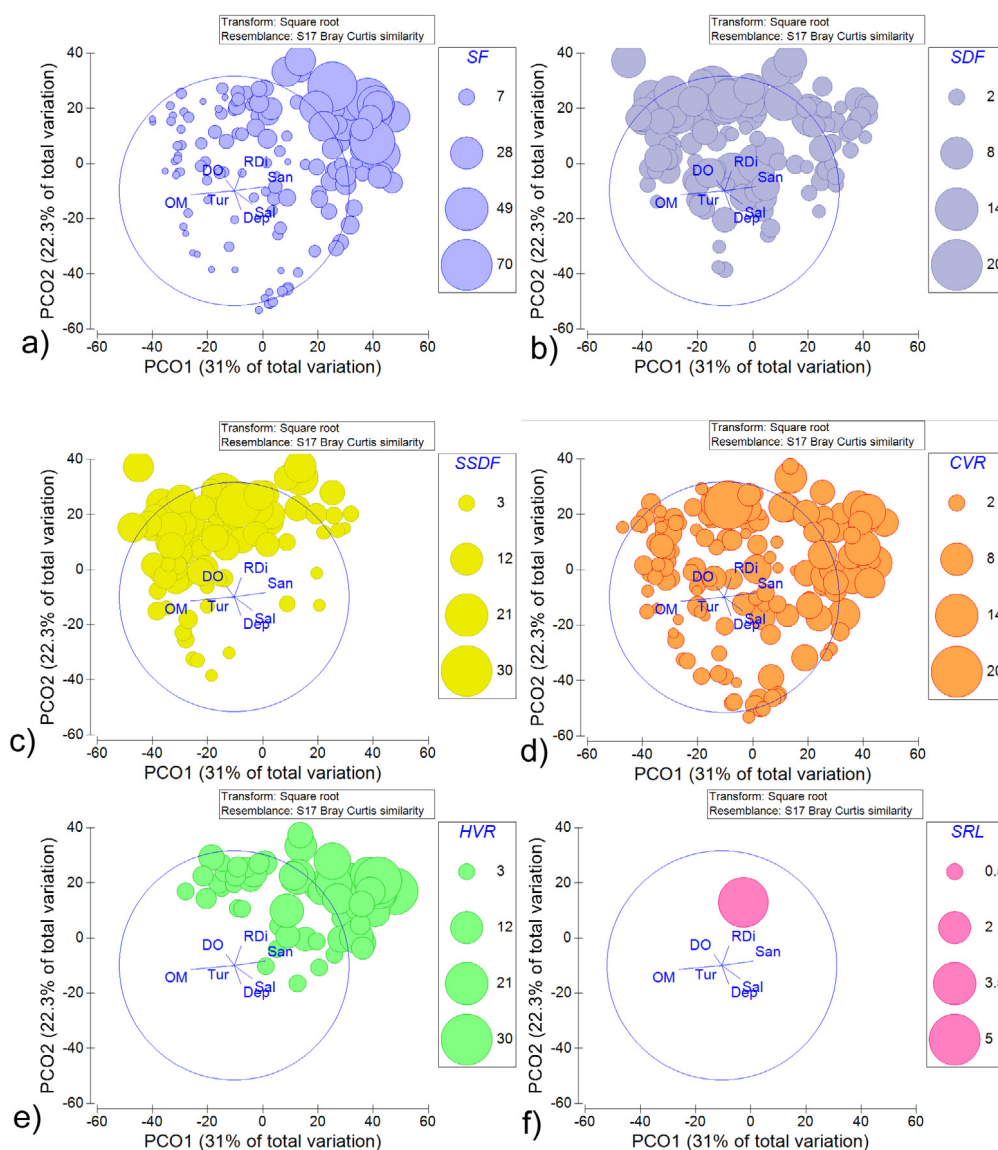
## 4. Discussion

### 4.1. Functional groups in the macrofaunal assemblages

The feeding guild of benthic communities is assigned based on their feeding characteristics, and such grouping of taxa by a particular function is useful for addressing ecosystem level questions (Fauchald and Jumars, 1979; Pagliosa, 2005). It enables transfer of information on the food source, food type and feeding mode of a particular community to simplified taxonomic data. It is useful for addressing questions regarding carbon flow in the estuarine environment (Fauchald, 1977; Word, 1978). Suspension feeding communities were dominated in the system with *Americorophium triaenonyx*, *Arcuatula senhousia* and *Obelia bidentata*. However, the population of surface deposit feeders (*Prionospio cirrifera*), sub-surface deposit feeder (*Capitella* sp.) and carnivorous (*Cirrolana fluviatilis*) dominated in some zones of the estuary depending on the suitable substrate type and other ecological factors. The burrowing population of isopod, *Sphaeroma annandalei* was also observed in the benthic samples (SRL). Many species of suspension feeding communities like molluscs and malacostracan crustaceans are less tolerant to degraded environmental conditions and they avoid such environments that are linked to eutrophication process

(Joseph et al., 2019). Among the suspension feeders, even though amphipod *A. triaenonyx* population dominated, sessile suspension feeders like bivalves were also abundant in the middle zone of the estuary. Their increased distribution was attributed to the availability of suitable substratum type and a good source of food materials. However, sometimes consistent with siltation and sudden salinity fluctuations during heavy river discharge resulted in a substantial mortality in suspension feeding population. The massive amount of suspended silt and clay in the water column was found to be detrimental to suspension feeding populations like bivalves; by affecting their filtration mechanism and interfering particle selection (Oliver et al., 2018b; Thrush et al., 2004). Similarly, suspension feeder like *O. bidentata* colonised in sandy substratum with a clear water column. Surface deposit feeders like those that of *Nassodonta insignis* population was found tolerant to low saline conditions in both organic matter enriched muddy and sandy sediments (Jayachandran et al., 2018; Oliver et al., 2018a).

In the spatial scale, stations with sandy sediment (STA) dominated with suspension feeders while sub-surface deposit feeders (SSDF) were abundant in muddy sediments (STB). Suspension feeders (SF) were dominated in the estuary with maximum population intensity during monsoon; however, other dominant communities like SSDF increased their relative abundance during pre-monsoon. It could be due to the formation of comparatively stable benthic



**Fig. 13a–f.** PCO ordinations of environmental data superimposed with bubble plots of estimated different feeding guild (SF, SDF, SSDF, CVR, HVR & SRL) of macrofauna in KAE.

biotope with increased organic matter deposit supplemented by heavy river discharge during the monsoon. It was observed that BOD level of the water column was found to increase with suspended particles or surficial detritus loading in the estuary. However many of these surface deposit feeders (SDF) and sub-surface deposit feeders can survive within such increased BOD levels. Species which are tolerant to such high level of BOD are considered as an indicator species of pollution such as species of polychaetes and oligochaetes. Thus, the assemblage of SDF increased in proximity to wastewater discharge points and sub-surface deposit feeders that dominated at the site with high organic enrichment. They were also responding to high concentrations of hydrogen sulphide other than high organic matter, which is an unacceptable condition for other species (Word, 1978). Ecologically stable environments support a more diverse range of feeding groups than disturbed conditions (Word, 1978); similarly in benthic biotope with heterogeneous sediment support different communities compared to homogeneous substrate type (Pearson and Rosenberg, 1978). In the present study, SDF polychaetes dominated in the estuary with other groups of SSDF.

In the estuary, the most diverse feeding guild was exhibited by polychaete assemblages and they depicted an apparent variation

on the seasonal pattern. The pre-monsoon season was dominated by SDF and SSDF polychaetes species, while SF polychaetes were the dominant population for other periods (SSA). It is also evident that in sandy sediment (STA) substratum in the estuary was dominated by SF while muddy sediment (STB) was controlled with SDF and SSDF communities. In Cochin estuary, among the polychaete feeding guild, SSDF were dominated along with SDF and CVR (Geetha et al., 2015). However, the present study depicted the least contribution from SF communities to entire macrofaunal polychaete feeding guild in the STB group of stations, while SF and SDF communities dominated in sandy sediments of STA group.

The opportunistic species can change their feeding mode depending on prevailing environmental conditions which results in higher abundance and dominance of such species (Maurer et al., 1999). In a gradient of organic matter in the estuarine sediments, high levels of organic matter result in a shift from suspension feeding to deposit feeding communities along with some carnivore communities (Pearson and Rosenberg, 1978). However, the further increase in the eutrophication process also leads to complete removal of suspension feeding communities (Lenihan, 1999). In such conditions, some of the species were found unaffected over

a wide geographical range of polluted systems, similar to their distribution in normal environmental conditions, such species are regarded as an indicator species (Pearson and Rosenberg, 1978). Within organically enriched areas in the estuary, SSDF like capitellid polychaetes occurred commonly, along with some species of spionid polychaetes such as *Prionospio cirrifera* and are considered as indicators of organic enrichment.

The distinct number of macrofaunal species in estuarine environment possesses characteristics of indicator species for the anthropogenic disturbances. Mainly because they are continuously exposed to contaminations and the diverse responses relative to the invertebrates tolerances, feeding modes and trophic interactions (Pearson and Rosenberg, 1978). Also, macrofaunal species are sedentary or sessile and they cannot evade adverse conditions from overlying water mass. So they are getting chronic exposure to unfavourable conditions in their short lifespan which enables them a rapid response to environmental variations that may be otherwise imperceptible (Word, 1978). Among other macrofaunal communities, polychaetes exhibit the maximum tolerance level to ecosystem perturbations. They are the most tolerant taxa in oxygen-depleted conditions than other macrofaunal taxa like bivalves and malacostracan crustaceans (Diaz and Rosenberg, 1995).

According to Sánchez-Moyano and García-Asencio (2010) large polychaete reefs are considered as an indicator to increase sewage contamination and chlorination process. Similarly, in the present study also observed an increasing assemblage of tube-dwelling polychaetes like *Diopatra neapolitana*; followed by an episodic river discharge events. According to Bailey-Brock (1984), the packing of sediments provides substratum strength for tube dwellers and borrowers and the high organic matters of the trapped materials serve as food sources for selective and burrowing detritivores. However, the structurally uniform muddy sediments of increased organic matter promotes accumulation of toxic metals and depletion of oxygen content and ultimately results in the exclusion of species from that area (John et al., 2002). The polychaete diversity was maximum observed with moderate organic carbon in the sediment (Sivadas et al., 2011). However, the low abundance of polychaetes in an area having more than 3% organic matter with high silt and clay content which attributes to avoidance of organisms to abundant organic matter and suboxic levels (Harkantra et al., 1982). Similarly, the reduction of polychaete diversity and increased abundance of deposit feeders also indicated the deterioration of the estuarine health (Geetha et al., 2015).

The abundance of opportunistic species also indicate organic matter accumulation in an area (Ansari et al., 1986; Pearson and Rosenberg, 1978; Rygg, 1985), such unhealthy benthic habitats are also represented by reduced macrofaunal species diversity, abundance and biomass with an increase in the dominance of small-bodied pollution tolerant species (Albayrak et al., 2006; Dauer, 1997). All the STB group stations in the estuary depicted similar condition by the dominance of opportunistic small bodied polychaete species like *P. cirrifera* and *Capitella* sp. It is suggested that, in a stressed environment the conservative species were replaced by opportunistic species with small body size and short generation time (Warwick, 1986). The aggregation of tube-dwelling polychaetes like *D. neapolitana* and *Pista indica* in the estuary support number of opportunistic species around their colonies by providing microhabitats through the accumulation of organic sediment and stabilising sediment of mat-like structures (McCave, 1976). Therefore, the study suggests that use of ecological communities as a whole to characterise the degree of pollution was found much more useful than single species monitoring.

Bioturbators, including deposit feeders and burrow builders can alter the physico-chemical nature of sediments and this may influence faunal zonation. Disturbance of the sediment by active burrower and deposit feeders, which ingest sediment and cause

high volumes of turnover of the sediment, may inhibit or promote colonisation by other animals (Peterson, 1991). Bioturbation may also decrease biological oxygen demand by allowing oxygen to penetrate lower sediment layers and thus promoting increased biological activity. The large organisms may also facilitate high productivity, leaching of nutrients from sediment, aeration and geochemistry of substratum through the formation, maintenance and ventilation of burrows (Braeckman et al., 2011). These organisms therefore can be considered ecosystem engineers, as they play a vital role in the maintenance of regional biodiversity (Stephen et al., 2004) by adding heterogeneity to the structure of benthic habitats (Levinton, 1995; Patel and Desai, 2009).

#### 4.2. Macrofaunal response to anthropogenic and natural disturbances

In the present study depicted a moderately disturbed condition in abundance biomass curves (ABC). This assessment method was described initially by Warwick (1986), by plotting separate k-dominance curves for species abundances and species biomass on the single graph for comparison. The disturbed ecological communities are usually dominated by smaller sized r-selected or opportunistic species with a short lifespan often become the biomass dominants as well as the numerical dominants (Clarke, 1990). The detailed analysis in ABC plot for each station separately demonstrated relatively good conditions in the middle zone of estuary especially in the mixing zone with the southern and northern arms. The relatively high potential for ecological disturbance was observed in the northern station in Kottapuram region, where water column experiencing high water residence time and cage farming of carnivorous fishes. The northernmost station in the estuary was dominated by small-bodied opportunistic polychaete species such as *Prionospio cirrifera* and *Capitella* sp. However, the majority of other stations in the estuary exhibited moderately disturbed condition in ABC plot. Similarly, slightly disturbed conditions were recorded in the southern part of Vembanad wetland ecosystem in ABC analysis (Asha, 2017). TAXDTEST depicted relatively higher variation in taxonomic distinctness in the stations 2, 5, 6, and 7. Taxonomic distinctness ( $\Delta+$ ) and variation in taxonomic distinctness ( $\Delta+$ ) analyses are unique ways to evaluate biological assemblages. Warwick and Clarke (1998) reported that chronically disturbed locations would exhibit greater variation and reduced taxonomic distinctness. The most of the benthic communities have been adapted to available ecological niches and habitats, where the community composition varies depending on the dynamics of biotic and abiotic factors (Remane, 1934). Though, each species in estuarine benthic communities have a level of tolerance to such components and if the level of threshold exceeded, then that species will no longer be present. Besides, each benthic species requires a minimum amount of critical resources to survive and in depleted conditions, such taxa will disappear or its population parameters will change (Abdul Jaleel, 2012; Asha et al., 2016; Jayachandran et al., 2015; Kristensen, 1988; Levin et al., 1996; Nybakken and Bertness, 2005).

#### 5. Conclusion

The dominance of suspension feeding population can be taken as a relatively good ecological condition in a water body. However the increased opportunistic species population and moderate disturbance status in ABC curve indicating the potential for high ecological disturbance in the estuary. Some zones in the estuary including cage farming sites are under high ecological risk that needs an immediate action for ecosystem management and conservation.

## Acknowledgments

This work forms part of the research project entitled “Ecology and fish production potential of the Kodungallur–Azhikode back water ecosystem” funded by the Kerala State Council for Science, Technology and Environment (KSCSTE), India and the authors are thankful for their financial assistance. Authors are also thankful to the Head, Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology for providing necessary facilities. Three anonymous reviewers are acknowledged for their constructive criticism. P.R. Jayachandra is thankful to Dr. Graham Oliver, National Museum of Wales, U.K. for his scientific support.

## References

- Abdul Jaleel, K.U., 2012. Macrobenthos of the continental margin (200–1000m) of south eastern Arabian Sea with special reference to polychaetes. In: Cochin University of Science and Technology, Cochin University of Science and Technology, Kochi, p. 238.
- Albayrak, S., Balkis, H., Zenetos, A., Kurun, A., Kubanç, C., 2006. Ecological quality status of coastal benthic ecosystems in the Sea of Marmara. *Mar. Pollut. Bull.* 52, 790–799.
- Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK.
- Ansari, Z.A., Ingole, B.S., Parulekar, A.H., 1986. Effect of high organic enrichment of benthic polychaete population in an estuary. *Mar. Pollut. Bull.* 17, 361–365.
- Anu, P.R., Jayachandran, P.R., Sreekumar, P.K., Bijoy Nandan, S., 2014. A review on heavy metal pollution in Cochin backwaters, southwest coast of India. *Int. J. Mar. Sci.* 4, 92–98. <http://dx.doi.org/10.5376/ijms.2014.04.0010>.
- Asha, C.V., 2017. Assessing the structural and functional ecology of benthic fauna in Vembanad estuarine system. Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science And Technology, India, p. 735.
- Asha, C.V., Retina, I.C., Suson, P.S., Nandan, S., Bijoy, S., 2016. Ecosystem analysis of the degrading Vembanad wetland ecosystem, the largest Ramsar site on the south west coast of India — Measures for its sustainable management. *Reg. Stud. Mar. Sci.* 8, 408–421.
- Attrill, M.J., Rundle, S.D., 2002. Ecotone or ecocline: ecological boundaries in estuaries. *Estuar. Coast. Shelf Sci.* 55, 929–936.
- Bailey-Brock, J.H., 1984. Ecology of the tube-building polychaete *Diopatra leuckarti* Kinberg, 1865 (Onuphidae) in Hawaii: community structure, and sediment stabilizing properties. *Zool. J. Linn. Soc.* 80, 191–199.
- Beesley, P.L., Ross, G.J.B., Glasby, C.J., 2000. Polychaetes & Allies: The Southern Synthesis. Environment Australia, Australia.
- Böggemann, M., 2002. Revision of the Glyceridae Grube 1859 (Annelida: Polychaeta). *Abh. Senckenb. Natforsch. Ges.* 555, 1–249.
- Böggemann, M., 2005. Revision of the Goniadidae. *Abh. Natwiss. Ver. Hambg. (Neue Folgen)* 39, 1–354.
- Borja, A., Franco, J., Pérez, V., 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. *Mar. Pollut. Bull.* 40, 1100–1114.
- Boudreau, P.R., Dickie, L.M., Kerr, S.R., 1991. Body-size spectra of production and biomass as system-level indicators of ecological dynamics. *J. Theoret. Biol.* 152, 329–339.
- Braeckman, U., Provoost, P., Moens, T., Soetaert, K., Middelburg, J.J., Vincx, M., Vanaverbeke, J., 2011. Biological vs. physical mixing effects on benthic food web dynamics. *PLoS One* 6, e18078.
- Carver, R.E., 1971. *Procedures in Sedimentary Petrology*. Wiley-Interscience, New York; Sydney.
- Clarke, K.R., 1990. Comparisons of dominance curves. *J. Exp. Mar. Biol. Ecol.* 138, 143–157.
- Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual/tutorial. PRIMER-E, Plymouth.
- Clarke, K.R., Warwick, R.M., 1998. A taxonomic distinctness index and its statistical properties. *J. Appl. Ecol.* 35, 523–531.
- Clarke, K.R., Warwick, R.M., 2001a. A further biodiversity index applicable to species lists: variation in taxonomic distinctness. *Mar. Ecol. Prog. Ser.* 216, 265–278.
- Clarke, K.R., Warwick, R.M., 2001b. Change in marine communities: an approach to statistical analysis and interpretation. Natural Environment Research Council, Plymouth, UK.
- Darling, E.S., Alvarez-Filip, L., Oliver, T.A., McClanahan, T.R., Côté, I.M., 2012. Evaluating life-history strategies of reef corals from species traits. *Ecol. Lett.* 15, 1378–1386.
- Dauer, D.M., 1997. Dynamics of an estuarine ecosystem; long-term trends in the macrobenthic communities of Chesapeake Bay. *Oceanol. Acta* 20, 291–298.
- Day, J.H., 1967. A monograph on the Polychaeta of Southern Africa, Part 1 (Errantia) and II (Sedentaria). Trustees of the British Museum (Natural History), London.
- Diaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioral responses of benthic macrofauna. *Oceanogr. Mar. Biol.* 33, 245–303.
- Donald, M.S., Michael, E., 2004. *The estuarine: ecosystem ecology, threats, and management*. Oxford OX26DP, Great Clarendon Street.
- El-Wakeel, S.K., Riley, J.P., 1957. The determination of organic carbon in marine muds. *J. Conseil Int. Explor.* 22, 180–183.
- Eleftheriou, A., Mc Intyre, A., 2005. *Methods for the study of marine benthos*. Blackwell Science Publishers Oxford.
- Elliott, M., Quintino, V., 2007. The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. *Mar. Pollut. Bull.* 54, 640–645.
- Fauchald, K., 1977. The polychaete worms. In: *Definitions and keys to the orders, families and genera* Natural History Museum of Los Angeles County: Science Series, Vol. 28. pp. 1–188.
- Fauchald, K., Jumars, P.A., 1979. The Diet of Worms: A study of polychaete feeding guilds. In: Barnes, M. (Ed.), *Oceanogr. Mar. Biol.*. Aberdeen University Press, pp. 193–284.
- Gallagher, E.D., 2008. Benthic feeding guilds and functional groups. <http://ocw.umb.edu/environmental-earth-and-ocean-sciences/eos-630-biological-oceanography/course-schedule.html>.
- Gaston, G.R., 1987. Benthic polychaeta of the Middle Atlantic Bight: feeding and distribution. *Mar. Ecol. Prog. Ser.* 36, 251–262.
- Geetha, P.N., Bijoy Nandan, S., Thasneem, T.A., 2015. Community ecology and taxonomy of polychaetes from a tropical estuary, south west coast of India. In: Gupta, V.K., Anil, K.V. (Eds.), *Animal Diversity. Natural History and Conservation* Daya Publishing House® A division of Astral International Pvt. Ltd, pp. 15–40.
- Harkantra, S.N., Rodrigues, C.L., Parulekar, A.H., 1982. Macrobenthos of the shelf off Northeastern Bay of Bengal. *Indian J. Geo-Mar. Sci.* 11, 115–121.
- Imajima, M., 1990a. Spionidae (Annelida, Polychaeta) from Japan: II. In: *The Genus Prionospio (Aquilaspio)*. *Bull. Nat. Sci. Mus., Japan*.
- Imajima, M., 1990b. Spionidae (Annelida, Polychaeta) from Japan: III. In: *The Genus Prionospio (Minuspio)*. *Bull. Nat. Sci. Mus., Japan*.
- Imajima, M., 1990c. Spionidae (Annelida, Polychaeta) from Japan: IV. In: *The Genus Prionospio (Prionospio)*. *Bull. Nat. Sci. Mus., Japan*.
- Imajima, M., 1992a. Spionidae (Annelida, Polychaeta) from Japan: IX. In: *The Genus Aonidella*. *Bull. Nat. Sci. Mus., Japan*.
- Imajima, M., 1992b. Spionidae (Annelida, Polychaeta) from Japan: VIII. In: *The Genus Scolelepis*. *Bull. Nat. Sci. Mus., Japan*.
- Jayachandran, P.R., Bijoy Nandan, S., 2012. Assessment of trophic change and its probable impact on tropical estuarine environment (the Kodungallur-Azhikode estuary, India). *Mitig. Adapt. Strat. Gl.* 17, 837–847.
- Jayachandran, P.R., Bijoy Nandan, S., Sanu, V.F., Anu, P.R., Jima, M., Midhun, A.M., Don Xavier, N.D., Philomina, J., Asha, C.V., 2018. Authentication of *Nassodonta insignis* H. Adams, 1867 (Gastropoda: Nassariidae) from the Kodungallur - Azhikode backwater, southwest coast of India using mitochondrial COI marker. *Indian J. Geo-Mar. Sci.*
- Jayachandran, P.R., Bijoy Nandan, S., Sreedevi, O.K., 2012. Water quality variations and nutrient characteristics of Kodungallur-Azhikode Estuary, Kerala, India. *Indian J. Geo-Mar. Sci.* 41, 180–187.
- Jayachandran, P.R., Prabhakaran, M.P., Asha, C.V., Bijoy Nandan, S., Akhilesh.Vijay., 2015. First report on mass reproductive swarming of a polychaete worm, *Dendronereis aestuarina* (Annelida, Nereididae) Southern 1921, from a freshwater environment in the south west coast of India. *Int. J. Mar. Sci.* 5.
- John, S.G., Rudolf Shiu-sun, W., Ying Ying, O., 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. *Mar. Ecol. Prog. Ser.* 238, 249–279.
- Joseph, P., Bijoy Nandan, S., Jayachandran, P.R., 2019. New species of *Victoriopisa* Karaman & Barnard, 1979 (Crustacea: Amphipoda: Eriopisidae) from Vembanad backwaters, Southwest coast of India. *Zootaxa* 4433, 69–70.
- Jumars, P.A., Dorgan, K.M., Lindsay, S.M., 2015. Diet of worms emended: an update of polychaete feeding guilds. *Annu. Rev. Mar. Sci.* 7, 497–520.
- Kristensen, E., 1988. Benthic fauna and biogeochemical processes in marine sediments: microbial activities and fluxes. In: Blackburn, T.H., Sørensen, J. (Eds.), *Nitrogen cycling in coastal marine environments*. John Wiley and Sons Ltd, Chichester, pp. 275–299.
- Lenihan, H.S., 1999. Physical-biological coupling on oyster reefs: How habitat structure influences individual performance. *Ecol. Monograph* 69, 251–275.
- Levin, L., Caswell, H., Bridges, T., DiBacco, C., Cabrera, D., Plaia, G., 1996. Demographic responses of estuarine polychaetes to pollutants: Life table response experiments. *Ecol. Appl.* 6, 1295–1313.
- Levinton, J., 1995. Bioturbators as ecosystem engineers: Control of the sediment fabric, inter-individual interactions, and material fluxes. In: Jones, C.G., Lawton, J.H. (Eds.), *Linking Species & Ecosystems*. Springer US, Boston, MA, pp. 29–36.
- Lewis, D., 1984. *Practical scientology* Hucthinson Ross publishing company Pennsylvania.
- Macdonald, T.A., Burd, B.J., Macdonald, V.I., van Roodselaar, A., 2010. Taxonomic and feeding guild classification for the marine benthic macroinvertebrates of the Strait of Georgia. In: *Can. Tech. Rep. Fish. Aquat. Sci.*, British Columbia.
- MarLIN, 2017. Marine Life Information Network, Available online <http://www.marlin.ac.uk>. Marine Biological Association of the UK.

- Maurer, D., Nguyen, H., Robertson, G., Gerlinger, T., 1999. The infaunal trophic index (ITI): Its suitability for marine environmental monitoring. *Ecol. Appl.* 9, 699–713.
- McCave, I.N., 1976. Organism-sediment relationships. In: McCave, I.N. (Ed.), *The benthic boundary layer*. Springer US, Boston, MA, pp. 273–295.
- McLusky, D.S., Elliot, M., 2004. *The estuarine ecosystem – ecology, threats and management*. Oxford University Press.
- Medeiros, C.R., Hepp, L.U., Patrício, J., Molozzi, J., 2016. Tropical estuarine macrobenthic communities are structured by turnover rather than nestedness. *PLoS One* 11, e0161082.
- Nelson, D.W., Sommers, L.E., 1982. *Methods of soil analysis*. Madison, Wisconsin.
- Nybakken, J.W., Bertness, M.D., 2005. *Marine Biology: an ecological approach*. Pearson Education, Inc., publishing as Benjamin Cummings.
- Oliver, P.G., Hallan, A., Jayachandran, P.R., Joseph, P., Sanu, V.F., Bijoy Nandan, S., 2018a. Taxonomy of myid bivalves from fragmented brackish-water habitats in India, with a description of a new genus *Indosphenia* (Myidae, Myoidea, Myidae). *ZooKeys* 799, 21–46. <http://dx.doi.org/10.3897/zookeys.799.25843>.
- Oliver, P.G., Jayachandran, P.R., Bijoy Nandan, S., 2018b. *Cuspidaria cochiniensis* Preston, 1916 transferred to the Corbulidae (Mollusca, Bivalvia) and assigned to the genus *Cuneocorbula*. *Mar. Biodivers.* 48, 1223–1227.
- Pagliosa, P.R., 2005. Another diet of worms: the applicability of polychaete feeding guilds as a useful conceptual framework and biological variable. *Mar. Ecol.* 26, 246–254.
- Patel, S.J., Desai, B.G., 2009. Animal-sediment relationship of the crustaceans and polychaetes in the intertidal zone around Mandvi, Gulf of Kachchh Western India. *J. Geol. Soc. India* 74, 233–259.
- Pearson, T., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol.* 16, 229–311.
- Peterson, C.H., 1991. Intertidal zonation of marine invertebrates in sand and mud. *Am. Sci.* 79, 236–249.
- Qasim, S.Z., 2003. *Indian estuaries*. Allied Publication, Mumbai.
- Remane, A., 1934. Die Brackwasserfauna. *Verh. Dtsch. Zool. Ges.* 36, 34–74.
- Revichandran, C., Abraham, P., 1998. Mixing and flushing time scale in the Azhikode estuary, south west coast of India. *Indian J. Geo-Mar. Sci.* 27, 163–166.
- Rygg, B., 1985. Effect of sediment copper on benthic fauna. *Mar. Ecol. Prog. Ser.* 25, 83–89.
- Sánchez-Moyano, J.E., García-Asencio, I., 2010. Crustacean assemblages in a polluted estuary from South-Western Spain. *Mar. Pollut. Bull.* 60, 1890–1897.
- Schwinghamer, P., 1983. Generating ecological hypotheses from biomass spectra using causal analysis: a benthic example. *Mar. Ecol. Prog. Ser.* 13, 151–166.
- Sivadas, S., Ingole, B., Nanajkar, M., 2011. Temporal variability of macrofauna from a disturbed habitat in Zuari estuary, west coast of India. *Environ. Monit. Assess.* 173, 65–78.
- Sreeja, K.G., Madhusoodhanan, C.G., Eldho, T.I., 2016. Coastal zones in integrated river basin management in the West Coast of India: Delineation, boundary issues and implications. *Ocean Coast. Manage.* 119, 1–13.
- Stephen, W., Melanie, C.A., Michael, A.K., Frode, O., Morten, T.S., Sarah, L.D., Hazel, R.N., 2004. Importance of bioturbators for biodiversity maintenance: indirect effects of fishing disturbance. *Mar. Ecol. Prog. Ser.* 275, 1–10.
- Strickland, J.D.H., Parsons, T.R., 1968. *Practical handbook of seawater analysis*. J. Fish. Res. Board Can. 167, 311.
- Strickland, J.D.H., Parsons, T.R., 1972. *A practical handbook of seawater analysis*. In: *Bull. Fish. Res. Board. Can.*, Canada.
- Thomson, D.H., 1982. Marine benthos in the eastern Canadian high Arctic: multivariate analyses of standing crop and community structure. *Arctic* 35, 14.
- Thrush, S.F., Hewitt, J.E., Cummings, V.J., Ellis, J.I., Hatton, C., Lohrer, A., Norkko, A., 2004. Muddy waters: elevating sediment input to coastal and estuarine habitats. *Front. Ecol. Environ.* 2, 299–306.
- Thrush, S.F., Townsend, M., Hewitt, J.E., Davies, K., Lohrer, A.M., Lundquist, C., Cartner, K., 2013. The many uses and values of estuarine ecosystems. *Manaaki Whenua Press, Landcare Research, Lincoln*, pp. 226–237.
- Trask, P.D., 1939. *Recent Marine Sediments*. In: *Am. Assoc. Pet. Geol. Publ.*, Tulsa, Oklahoma, USA, p. 736.
- Trivedy, P.K., Goel, P.K., 1986. *Chemical and Biological Methods for Water Pollution Studies*. In: *Series in Methodology, Environmental Publications, Karad*.
- UNESCO, 1966. *Determination of Photosynthetic Pigments in Sea Water*. In: *Monographs on Oceanographic methodology*, vol. 1.
- UNESCO, 1985. *The International System of Units (SI) in Oceanography*. In: *IAPSO Pub. Sci.*, (32) Paris, France.
- Vijith, V., Sundar, D., Shetye, S.R., 2009. Time-dependence of salinity in monsoonal estuaries. *Estuar. Coast. Shelf Sci.* 85.
- Warwick, R.M., 1986. A new method for detecting pollution effects on marine macrobenthic communities. *Mar. Biol.* 92, 557–562.
- Warwick, R.M., Clarke, K.R., 1998. Taxonomic distinctness and environmental assessment. *J. Appl. Ecol.* 35, 532–543.
- Word, J.Q., 1978. The infaunal trophic index. *SCCWRP 1978 Annual report, Southern California Coastal Research Project*. El Segundo, CA, pp. 13–39.
- WoRMS, WoRMS, 2017. *World Register of Marine Species*. Available from <http://www.marinespecies.org> at VLIZ. Accessed 2017-06-20. <http://dx.doi.org/10.14284/170>.
- Yu, O.H., Lee, H.-G., Lee, J.-H., 2012. Influence of environmental variables on the distribution of macrobenthos in the han river estuary, Korea. *Ocean Sci. J.* 47, 519–528.