

Macrobenthos at marine hotspots along the Northwest Indian inner shelf: Patterns and drivers

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Abstract

Marine hotspots are areas prioritized for conservation and monitoring, based on their sensitivity or vulnerability. Understanding the natural variability of resident organisms in such critical areas is integral for deciphering human-induced perturbations to formulate appropriate management strategies. Five marine hotspots along NW India, comprising three active harbours and two marine protected areas, were surveyed seasonally to understand the macrofaunal distribution patterns and functional traits. Among the 33 macrobenthic taxa, Polychaeta constituted the dominant taxon. Spatial variability was prominent due to differences in terms of polychaete species types, relative abundances and functional trait matrices. Monsoonal hypoxia altered the macrobenthic species and functional composition. CCA revealed a combination of natural (texture, DO, salinity) and anthropogenic (PHc, SS, ammonia) hydro-sedimentological variables as key drivers for the polychaete distribution patterns. The results are expected to improve the understanding of the variability and functioning of polychaete taxocommunity within the ecologically and economically significant “marine hotspots”.

Keywords: Benthos, Polychaetes, Marine hotspots, Abiotic factors, Hypoxia, Northwest Indian shelf.

1. Introduction

Hotspots are select areas, mostly terrestrial, that are prioritised for conservation measures based on its inherent exceptional biodiversity or exposure to high levels of threat (Zacharias and Gregr, 2005). Of late, marine hotspots especially coral reef areas, are gaining credence as places to develop effective conservation strategies (Allen, 2008). In the marine realm, the coastal ecosystems are known to be productive yet fragile as they are most often subject to varied alterations resulting from human activities and natural processes (Aubry and Elliott, 2006). Although the tropical latitudes are known to host high marine biodiversity, their coastlines face increasing damage at an alarming rate due to anthropogenic interventions (Kundu *et al.*, 2010). This has resulted in marine diversity losses and changes in ecosystem functions. Adding to the complexity, the various manifestations of climate change also are known to impact the subtidal biota of coastal zones (Harley *et al.*, 2006), particularly the hotspots (Wernberg *et al.*, 2011). The responses of coastal organisms residing in these sensitive zones to global climatic alterations are not very well understood due to paucity of sufficient data. Besides the taxonomic composition and relative abundance that is conventionally employed to describe ecosystems, the study of functional diversity is now being proposed as more relevant in evaluating the ecosystem status and its functioning (Wouters *et al.*, 2018). Thus, the comprehensive knowledge on the taxonomic and functional diversity patterns of sensitive tropical coastal ecosystems and its drivers are vital in understanding ecosystem functioning (Wafar *et al.*, 2011) and prioritising conservation strategies.

Macrobenthos are widely used in many monitoring studies due to their sensitivity to the environmental quality status and effectiveness in reflecting the system condition (Fitch and Crowe, 2010). In this study, emphasis was put on the key taxon, Polychaeta, because (a) they are the most dominant macrobenthic group (del-Pilar-Ruso *et al.*, 2008) (b) they are potential surrogate taxocene for monitoring programs (Soares-Gomes *et al.*, 2012) as they comprise of both sensitive and tolerant species occurring in pristine to heavily disturbed environments (del-Pilar-Ruso *et al.*, 2009) and (c) they have a major functional role (Jumars *et al.*, 2015) in the benthic community, thereby permitting an evaluation of the macrobenthic ecological functioning (Otegui *et al.*, 2016).

As is the case with many emerging economies, India has a coast that is also exposed to many human interventions due to the rapidly escalating industrialization and urbanisation along its coastline. The Indian west coast, in particular, is recognized as a biodiversity hotspot and contributes to >70% of the country's marine capture fishery (Ingole *et al.*, 2009). The northwest Indian coast comprises of the large states of Maharashtra and Gujarat, which are undergoing brisk industrial

developments and contributing significantly to nation's economic growth (Sachs *et al.*, 2002). The consequential expansion of coastal urban clusters has added further anthropogenic pressure to the coastal environment. Coastal zones of the Indian continental shelf are known to sustain rich marine biodiversity (Jayaraj *et al.*, 2008). The west coast is also exposed to upwelling related low oxygen levels during monsoon. Monsoon season has a significant impact on the life cycle of the coastal macrobenthos along the tropics (Alongi, 1990) by influencing their recruitment and dispersal (Gaonkar *et al.*, 2013). The functional diversity pattern of macrofaunal assemblage is also reported to vary during the tropical monsoon regimes (Sivadas *et al.*, 2013). The environmental factors influencing the large scale biodiversity patterns and the ecological functioning of this geographic region still remain largely unexplained (Sivadas and Ingole, 2016).

The Government of India had initiated a long-term coastal monitoring programme, Coastal Ocean Monitoring and Prediction System (COMAPS), wherein "hotspots" along the vast Indian coastline are surveyed seasonally to monitor the quality of Indian coastal waters. The marine protected areas of Vadinar and Malvan and the coastal areas around major harbours of Veraval, Mumbai and Ratnagiri are five selected hotspots along the 2360 km long northwest Indian coastline (Fig. 1). The program provided the appropriate platform to identify spatio-temporal patterns in macrobenthic taxonomic and functional diversity by using polychaetes as surrogates. This is crucial for understanding the processes that influence the community structure of organisms and to interpret the possible changes associated with natural and anthropogenic impacts (del-Pilar-Ruso *et al.*, 2011).

Macrobenthic studies along the Indian western continental shelf have been extensively carried at different depth ranges (Jayaraj *et al.*, 2007, 2008; Joydas and Damodaran, 2009; Ingole *et al.*, 2014, 2016; Rengaiyan *et al.*, 2017). However, this study is the first of its kind to be undertaken temporally over a large spatial extent along the northwest Indian coast covering the nearshore coastal waters. Additionally, the study aimed to provide information on the functional diversity of the inner-shelf sediments of NW India. The past studies on macrobenthic functional trait analysis in the Indian waters were confined to feeding-mode analysis (Manokaran *et al.*, 2013; Ingole *et al.*, 2014; Sukumaran *et al.*, 2016; Rehitha *et al.*, 2017), mobility and habitat type (Sivadas *et al.*, 2013). Moreover, the aforementioned studies were restricted to a limited sampling area. Of the five transects investigated in this study, Vadinar and Malvan are coralline marine protected areas, whereas Veraval, Mumbai and Ratnagiri have bustling ports. The aims of the present study were (1) to assess the polychaete species taxonomical and functional diversity and distribution patterns at spatio-temporal scales along the northwest inner shelf (2) to investigate whether the seasonal hypoxia

during the monsoon impacted the polychaete community structure and functional traits and (3) to delineate the prime environmental drivers influencing the polychaete community structure.

2. Material and Methods

2.1 Study area

The Arabian Sea, located in the northwestern Indian Ocean, is a geochemically active area of the world's oceans along the western boundary of India. Among the coastal zones of India, the northwest coast has the largest subtidal area with less than 50 m (90,000 km²) (Vivekanandan *et al.*, 2005). The onset of the annual monsoon in this zone is due to the development of a strong land-ocean thermal gradient. Seasonal winds, remote forcing and thermohaline circulation strongly influence the ecosystem of this region (Jayaraj *et al.*, 2007). The winds are stronger during the southwest monsoon season with relatively weaker winds during the premonsoon (Aboobacker *et al.*, 2011). An upwelling phenomenon leads to the development of coastal hypoxia along this region, forming a naturally oxygen-deficient system (Naqvi *et al.*, 2000).

The present study area was situated between 16° and 22° N latitude and 73° and 69° E longitude, wherein the five chosen hotspot sites situated along the northwest Indian coast were monitored seasonally. The state of Gujarat has the longest coastline of 1640 km among the maritime states of India (Solanki *et al.*, 2005), whereas the coastal stretch of Maharashtra state is 720 km (Deshmukh, 2013). Sampling was conducted at five transects: Vadinar (stations: VD1-VD4), Veraval (stations: V1-V4) in the state of Gujarat; and Mumbai (stations: MY1-MY4), Ratnagiri (stations: R1-R4), Malvan (stations: M1-M4) in the state of Maharashtra (Fig. 1). Vadinar (22°N; 69°E) is located on the southern flank of Gulf of Kachchh (GoK), which is an indentation on the northwest Indian coast. Vadinar was designated as a Marine National Park and Sanctuary (MNPS) in 1982 for preserving the coral reefs and the rich biodiversity. The ecosensitive zone of Vadinar is dotted by single point moorings (SPMs), jetties and ports catering to oil and gas industries, and salt pans. Veraval (20°N; 70°E) is one of the biggest commercial fishing centres in Asia (Misra and Kundu, 2005), where fishing, its processing and exporting constitute a significant source of income to the population (Sundararajan *et al.*, 2017). This overcrowded fishing harbour receives a large amount of domestic and industrial wastes, especially from small-scale fish processing plants. Mumbai (18°N; 72°E) is the second largest coastal city in the world and India's premier port. Various effluents and sewage generated in Mumbai region are drained into the coastal waters (Rokade, 2009). Ratnagiri (17°N; 73°E) is a thriving fishing harbour and is one of the major marine fish landing centres in India. Malvan (16°N; 73°E) was declared as a Marine Sanctuary in 1987 by

the Government of India to protect its fragile coralline ecosystem. Currently, the Malvan coast is being threatened by intensive fishing activities and a rapid growth of tourism and urbanization.

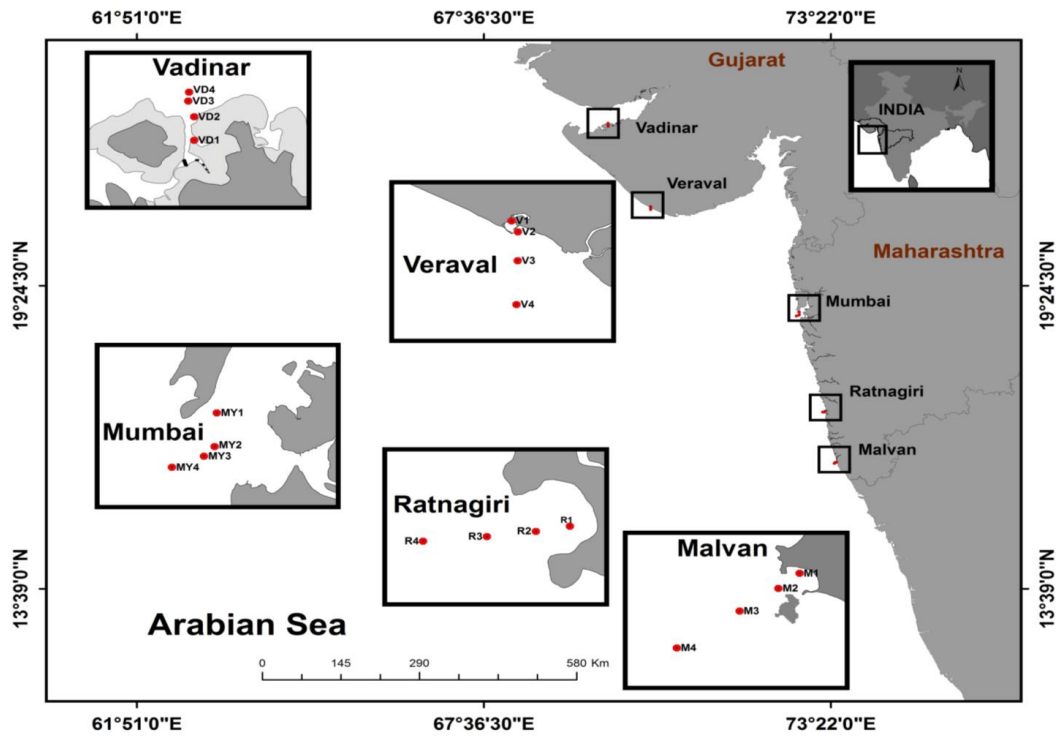


Fig. 1. Map of the investigated marine hotspots along northwest Indian coast with the station locations.

2.2 Study Design

At each latitudinal transect, four stations were sampled perpendicular to the coast along the depth gradient. Thus, station 1 was located closest to the shoreline and at shallow depths (2-5 m) and station 4 was placed farthest from the shore and in deeper waters (25-30 m). Stations 2 (8-10m) and 3 (15-20m) were located at intermediate depths. Three seasons constitute an annual weather cycle along the west coast of India with the premonsoon season of intense heat from March to May followed by the southwest monsoon season from June to September- the period of heavy rainfall when the coast experiences high wave activity (Kumar *et al.*, 2006). Lastly, the period between October to January is the postmonsoon season of fair weather conditions. Three sampling campaigns were conducted between 2013 and 2014 during premonsoon, postmonsoon and monsoon seasons respectively, to include seasonal variability within benthic habitats.

2.3 Sampling and processing

At each station, sediments were collected in quadruplicate using a van Veen grab with 0.04 m² sampling area. Altogether 240 grab samples from 20 locations were analyzed. The sediment samples were sieved through 0.5 mm mesh sieve and the animals retained were fixed in 5% formalin mixed with Rose Bengal vital stain. Benthic organisms were identified to major taxon (phylum, class or order) while the dominant taxon, Polychaeta was identified to the lowest possible taxonomic resolution, mostly species. The organisms were enumerated, averaged across replicates at each station and expressed as number of individuals per square meter (ind. m⁻²).

Post identification, polychaete species were assigned to functional categories related to their feeding mode, motility, body size, bioturbation mode and habitat. Traits were defined and categorized by referring extant literature (Macdonald *et al.*, 2010; Queirós *et al.*, 2013; Jumars *et al.*, 2015) and internet sources. Each of five functional traits was further divided into variable number of categories/modalities, forming a total of twenty three traits (Table 1).

Functional Trait	Trait Category/Modality	Codes
Feeding mode (F)		
	Predator	F.Pr
	Grazer	F.Gr
	Surface deposit feeders	F.SR-De
	Subsurface deposit feeders	F.SS-De
	Detritus feeder	F.Dt
	Suspension feeders	F.Su
	Scavenger	F.Sc
Motility (M)		
	Motile	M.M
	Discretely motile	M.D
	Sessile	M.S

Body size (S)		
	Small	S.S
	Small to Medium	S.S-M
	Medium	S.M
	Medium to Large	S.M-L
	Large	S.L
Bioturbation mode (B)		
	Upward Conveyors	B.UC
	Downward Conveyors	B.DC
	Upward/Downward conveyors	B.UC/DC
	Biodiffusors	B.Diff
	Surface modifiers	B.Surf
Habitat (H)		
	Free living	H.F
	Tubicolous	H.T
	Burrow dwelling	H.B

Table 1. List of functional traits and respective modalities with corresponding codes.

Bottom water and separate sediment samples were collected for characterization of the abiotic environment at all stations concurrently with the macrobenthic sample collection. Hydrochemical parameters like suspended solids (SS), salinity, dissolved oxygen (DO), nitrate–nitrogen (NO_3^- -N), ammoniacal nitrogen (NH_4^+ -N) were analysed using standard methods (Grasshoff *et al.*, 1999). Due to technical issues, NO_3^- -N could not be measured at V1 station during pre- and monsoon seasons. Bottom water temperature was measured using a mercury thermometer with an accuracy of $\pm 0.1^\circ\text{C}$. The sediment descriptors analysed were texture (Buchanan, 1984),

organic carbon (C_{org}) (Walkey and Black, 1934), and petroleum hydrocarbons (PHc) (IOC-UNESCO, 1982).

2.4 Data Treatment

Macrobenthic taxa abundance data of all four replicates were averaged for each station (Appendix A). From this dataset, the average polychaete species abundance data was used for further statistical analyses. A suite of univariate and multivariate analyses were performed using the statistical software PRIMER analytical package version 6 to describe the polychaete structure and organization along the northwest Indian coastal fringe. Azoic sampling stations (V1- pre and postmonsoon seasons) were excluded prior to the multivariate analyses in order to avoid the influence of these outliers on the derived inferences.

In order to determine the major abiotic parameters influencing the distribution of the stations, Principal Component Analysis (PCA) was performed on the environmental dataset.

The univariate techniques employed were Shannon–Wiener diversity index, H' (\log_2); Margalef's index, d ; and Pielou's evenness index, J' . Multivariate analyses involved non-metric multi-dimensional scaling (n MDS), where the ordination of the fourth-root transformed polychaete species abundance data using Bray-Curtis similarities was presented graphically. Two-way crossed Analysis of similarity (ANOSIM) was performed to determine significant differences in polychaete assemblages between different transects and seasons. Bonferroni correction was applied to adjust the p value. Similarity percentage (SIMPER) was applied to identify the polychaete species responsible for an observed pattern of differences in the transects. Canonical Correspondence Analysis (CCA) was employed to explore the species-environment relationship using CANOCO version 4.5 (ter Braak and Smilauer, 2002) based on a preliminary Detrended Correspondence Analysis (DCA) (Hill and Gauch, 1980). The analysis was performed on a matrix of 12 abiotic variables and 27 most abundant polychaete species (having over 0.5% of relative abundance). In order to test the significance of the ordination axes, Monte Carlo Permutation test (with 499 unrestricted permutations) was integrated.

The functional trait analysis of polychaete fauna was carried with 'fuzzy coding' (Chevenet et al., 1994). This procedure was adapted to categorize each of the polychaete species based on their affinity to the modalities of every functional trait. The affinity score was scaled from 0-3 where '0' indicated no affinity of a species to the trait category while '3' expressed a total affinity. The frequency of each modality was calculated by multiplying the affinity score with species abundance for every transect during the three sampling events. This generated 'traits by station' matrix

(Bremner et al., 2006) that was ordinated by Fuzzy Correspondence Analyses (FCA) on multidimensional plots (Chevenet et al., 1994). The correlation of every trait with principal axes that contributed for the functional variability in the study area was also provided by FCA analysis. The Functional Diversity (FD) index was calculated by using Rao's quadratic entropy (Rao, 1982; Paganelli et al., 2012). All analyses were performed under the frame of the R environment (version 3.4.4, R Core Team, 2018) using the packages *vegan* (version 2.4-6, Oksanen et al., 2018) and *ade4* (version 1.7-10, Dray and Dufour, 2007).

3. Results

3.1 Environmental variability

The spatial and temporal variability of the measured environmental variables at all five transects is depicted in Fig. 2 a-g. Bottom-water temperatures were comparatively consistent (26-30°C) across seasons at all transects except for the low temperatures at Vadinar during postmonsoon (20.7±0.6°C). Bottom water salinities at Vadinar during all seasons were markedly higher (37.4±0.3) than typical seawater. A drop in salinity during monsoon was observed at all transects along the Maharashtra coast. Extremely low levels of DO were observed at the inner stations (V1 and V2) of Veraval, more so during the premonsoon when the DO was barely detected. DO was uniformly low ($\leq 2.4 \text{ mg l}^{-1}$) at the outer stations of Veraval during the monsoon. Remarkably low DO concentrations during monsoon were also observed at outermost Mumbai station (2.7±0.2 mg. l⁻¹). Hypoxia developed at Ratnagiri (1.4±0.4 mg l⁻¹) while near hypoxic conditions were observed at Malvan (2.6±1.0 mg l⁻¹) during the monsoon. Only Vadinar had well oxygenated bottom waters (6.8±0.7 mg l⁻¹) during all sampling seasons. SS concentrations were maximum at Veraval (78±55.6 mg. l⁻¹) followed by Mumbai (60.7±34.3 mg l⁻¹) and Vadinar (44.5±17.8 mg l⁻¹), whereas relatively low values ($\leq 31.5 \pm 2.7 \text{ mg. l}^{-1}$) were displayed at Ratnagiri and Malvan. Elevated NO₃⁻-N concentrations were found at Veraval and Mumbai transects. Abnormally high concentrations of NH₄⁺-N were evident at the inner stations of Veraval (21.9-465.8 $\mu\text{mol. l}^{-1}$) whereas low values ($\leq 5.3 \mu\text{mol. l}^{-1}$) were observed at the rest of the transects during all three seasons. The maximum concentrations of sediment PHc were noted at the inner stations of Veraval during all seasons while the remaining transects displayed comparatively low values ($< 3.0 \mu\text{g. g}^{-1}$; wet wt).

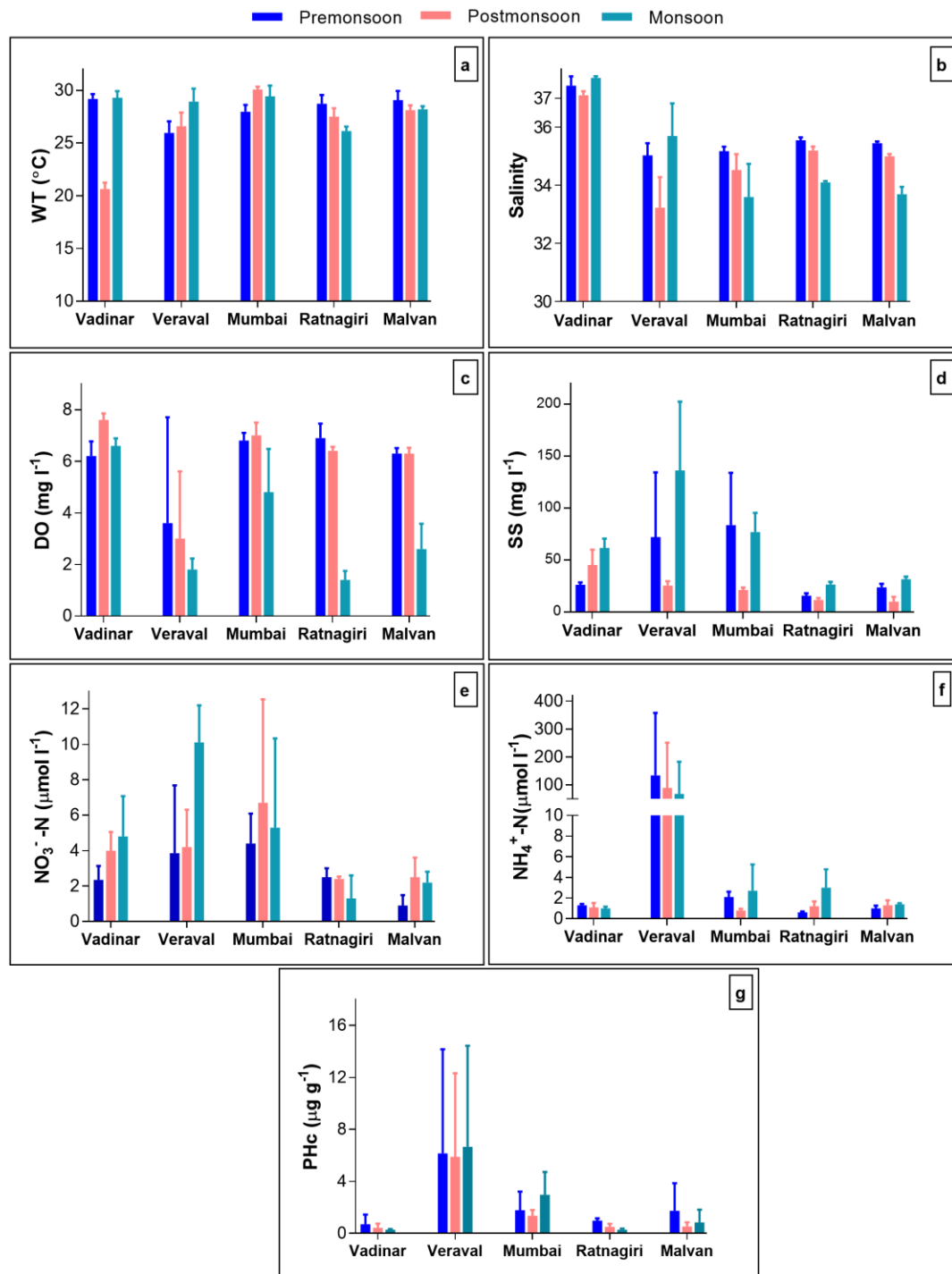


Fig. 2. Variations in hydro-sedimentological parameters (avg±SD) at the five transects during premonsoon, postmonsoon and monsoon seasons. Water temperature (a), Salinity (b), DO (c), NO₃⁻-N (d), NH₄⁺-N (e), SS (f), PHc (g).

Among the textural descriptors, silt fraction dominated Mumbai and Veraval transects ($\geq 80\%$) and was the major contributor ($< 50\%$) at other transects as well during every season (Fig. 3a-c). The nearshore stations of Ratnagiri (R1, R2) and Malvan (M1) were mainly sandy ($> 75\%$) while the rest of the zones had minor sand proportion ($\leq 16.5\%$). Comparatively, the clay percentage at all transects was negligible ($\leq 11.7\%$). Organic carbon values (calculated by dry weight) fluctuated between $0.9 \pm 0.2\%$ (Vadinar) and $2.8 \pm 0.2\%$ (Malvan). Elevated C_{org} concentrations were present in the sediments of inner stations of Veraval (V1 and V2; $> 1.8\%$) and outer stations of Ratnagiri (R3 and R4; $> 2.7\%$) and Malvan (M2-M4; $> 3.3\%$). However, the observed organic carbon values in the sandy inner stations of Ratnagiri and Malvan during all seasons were $\leq 1\%$.

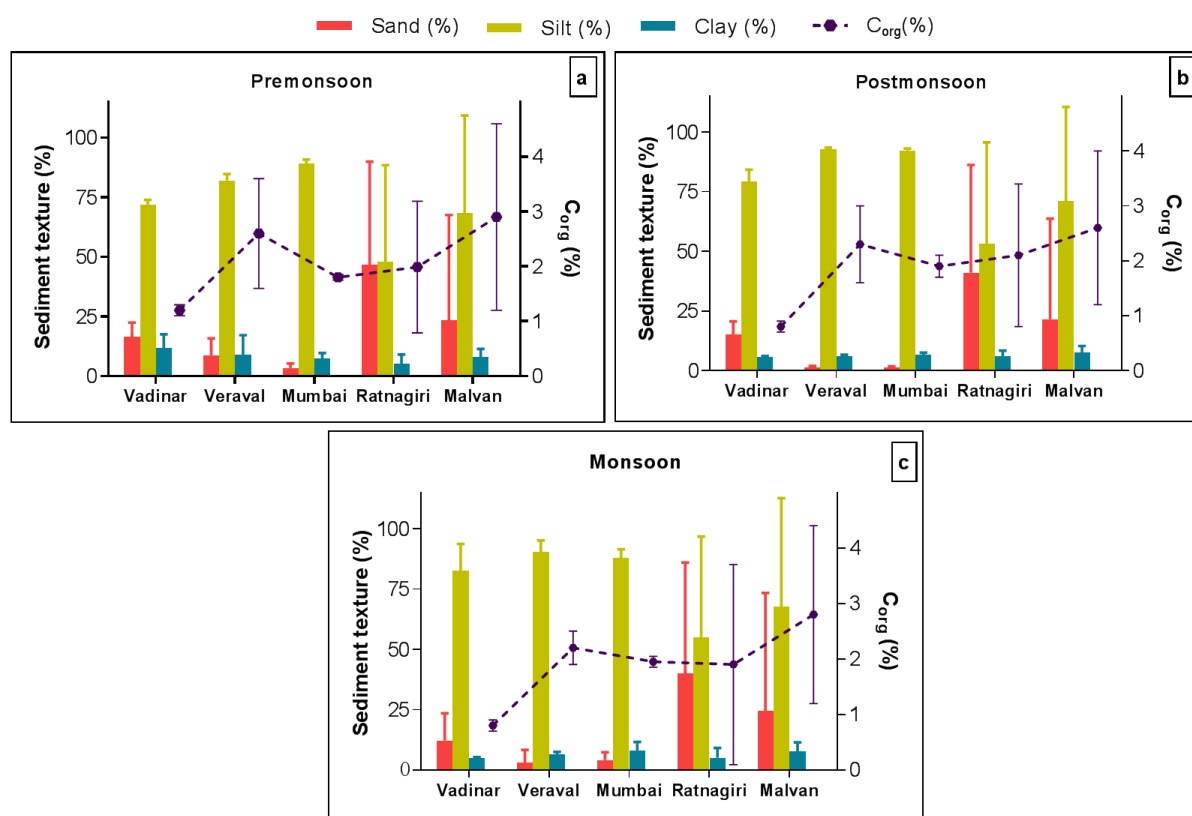


Fig. 3. Sediment texture and organic carbon (%) (avg \pm SD) at the five transects during premonsoon (a) postmonsoon (b) and monsoon (c) seasons.

The PCA performed with environmental data indicated that 51.5% of the total variability was explained by the first two axes (Fig. 4). The first principal component (PC1) was mainly influenced by the sediment characteristics (% sand, % silt and % clay and % C_{org}). The main contributors responsible for separation along axis 2 (PC 2) were hydrological parameters (SS,

salinity, DO and $\text{NH}_4^+\text{-N}$), sediment PHc and depth. The sandy inner stations of Ratnagiri and Malvan transects (R1, R2, M1) with lower depths were clearly isolated from the rest of the stations that were dominated by finer sediments. Inner stations of Veraval (V1 and V2) having the maximum concentrations of sediment PHc, SS and $\text{NH}_4^+\text{-N}$ were positioned apart from the rest. Similarly, Vadinar stations were grouped together on account of their comparatively higher salinities and DO concentrations. Also, the PCA plot indicated that the Veraval and Mumbai transects were associated with high $\text{NO}_3^-\text{-N}$ values. Spatial variation between the zones was evident, whereas no temporal trend was observed in the PCA plot (Fig. 4).

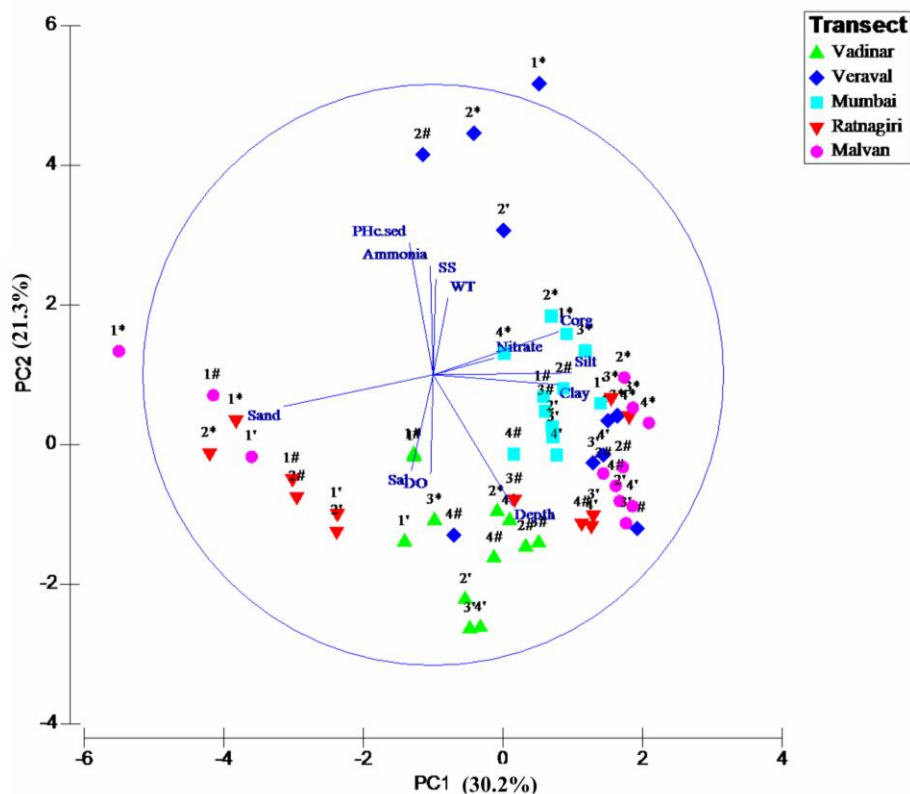


Fig. 4. Principal Component Analysis (PCA) of environmental variables at four stations (1-4) along the five transects during premonsoon (#), postmonsoon (') and monsoon (*) seasons.

3.2 Characteristics of macrobenthic and polychaete communities

3.2.1 Macrobenthic assemblages

Overall, 33 major benthic taxa were identified from the entire study area during the three surveys (Appendix A). Polychaetes dominated (62%) the benthic community of northwest inner

shelf, followed by amphipods (13.4%), gastropods (6.5%) and bivalves (5.2%). Besides foraminiferans (4%) and cumaceans (3%), the remaining 6% macrobenthos was comprised of 27 other smaller groups with density $\leq 1\%$. Distribution of some macrobenthic groups was region-specific viz. Oligochaeta and Ascidiacea were restricted to Veraval and Vadinar transects respectively, whereas Phoronida and Polyplacophora were present exclusively at Mumbai. No macrobenthos were detected at station V1 during premonsoon and postmonsoon. Polychaeta was the only major group that was present at all stations and was the dominant taxon at each transect. Though amphipods were present within all transects, they were absent at some individual stations. The maximum overall macrobenthic abundance (14539 ind.m⁻²) was recorded from Ratnagiri during postmonsoon whereas the minimum (252 ind.m⁻²) was observed at Vadinar during the monsoon (Fig. 5a). The most diverse macrobenthic community were present at Vadinar (26 taxa) while the least taxonomic diversity occurred at Veraval (17 taxa) (Appendix A).

3.2.2 Polychaete assemblages

Specimens of the dominant taxon, Polychaeta, were identified to 140 species belonging to 99 genera, 42 families and 12 orders in all. The best represented polychaete families in terms of relative densities over the entire northwest coast were Spionidae (33.2%), Sabellidae (20.8%), Cossuridae (12.4%) and Capitellidae (5.7%). Besides these, the other broadly distributed families were Hesionidae, Polynoidae, Sabellidae (absent in Mumbai), Longosomatidae, Magelonidae (absent in Vadinar) and Onuphidae (absent in Veraval).

The most speciose families present in the current investigation were Spionidae (13 species), Ampharetidae (9 species), Lumbrineridae (8 species), Sabellidae (7 species), Hesionidae and Paraonidae (6 species each). The rare and region specific families and the corresponding species encountered were Polycirridae (*Amaeana* sp., *Polycirrus* sp.), Fabriciidae (*Pseudofabriciola capensis*) from Vadinar; Polygordiidae (*Polygordius* sp.), Poecilochaetidae (*Poecilochaetus serpens*) from Veraval; Paralacydoniidae (*Paralacydonia paradoxa*) from Mumbai; Chaetopteriidae (*Spiochaetopterus* sp.) from Ratnagiri and Serpulidae (*Spirobranchus kraussii*), Amphinomidae (*Linopherus* sp.) from Malvan respectively. The analysis indicated 6 potential new species namely *Amaeana* sp., *Polycirrus* sp. from Vadinar, *Streblospio* sp. and *Polygordius* sp. from Veraval, *Kirkegaardia* sp. from Mumbai, *Spiochaetopterus* sp. from Ratnagiri region due to presence of unique morphological characteristics. Also, *Kirkegaardia* sp. forms the first record of the genus from the Indian west coast. A new species, *Heterospio indica* (Parapar *et al.*, 2016) was described during the course of the present investigation (Appendix A).

The spatial and seasonal trends in polychaete density closely mirrored that of macrobenthos (Fig. 5a and b). Transects that had the maximum number of species were Ratnagiri (60) Malvan (51) and Vadinar (43) followed by Mumbai (34). The number of species recorded at Veraval (28) were low (Appendix A).

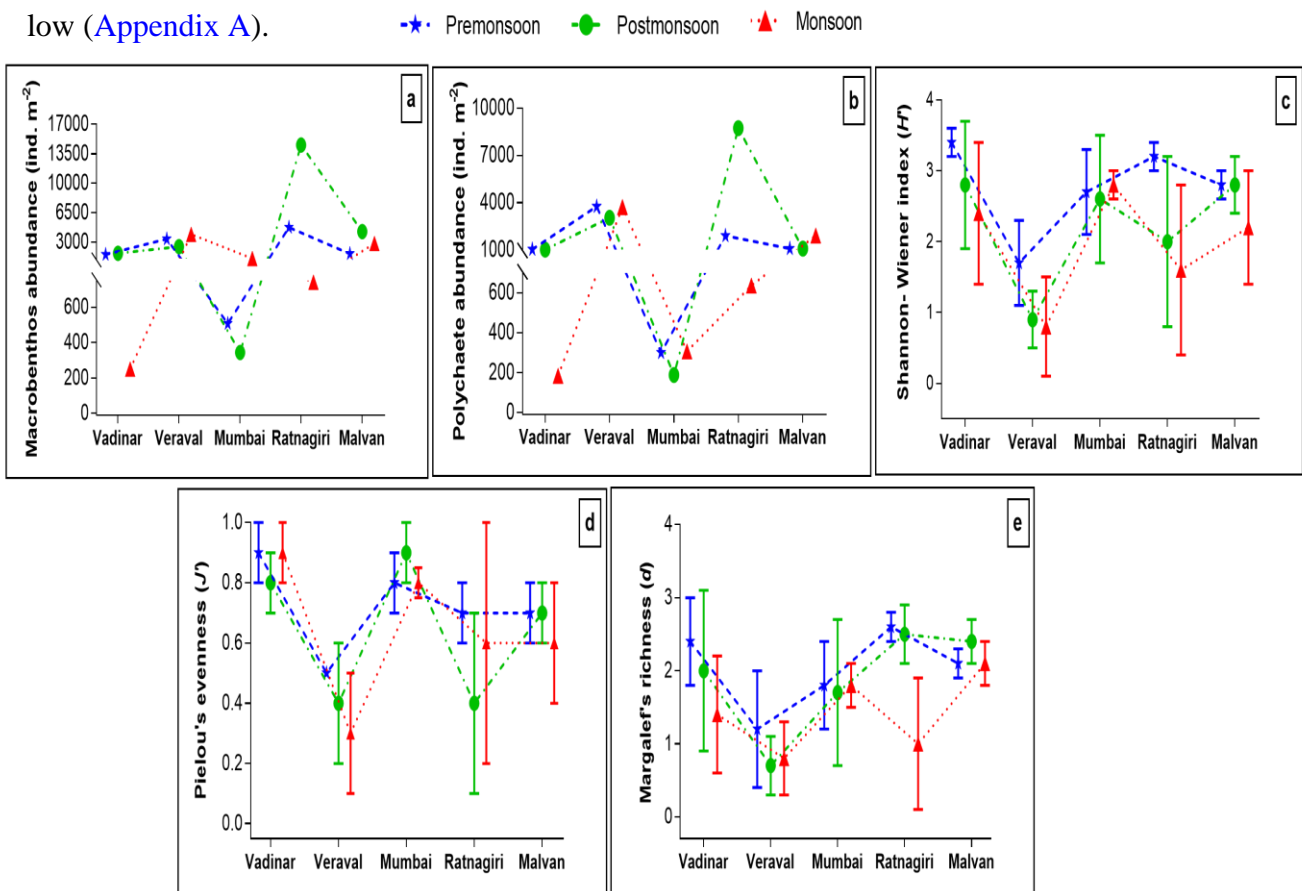


Fig. 5. Total macrobenthic abundance (a), Polychaete abundance (b), *H'*-Shannon Wiener index (c), *J'*- Pielou's evenness (d) and *d*- species richness (e) (avg ± SD) along five transects during premonsoon, postmonsoon and monsoon seasons. Standard deviation bars for macrobenthic and polychaete abundance were omitted for clear representation.

3.3 Univariate and Multivariate analyses

Spatially, Shannon–Wiener diversity *H'* (log₂) values >2.0 were recorded at all transects during the premonsoon. The exception to this was the Veraval transect where the values obtained during all seasons were ≤2.0. Mumbai had comparable diversity values across all seasons (Fig. 5 c). The Pielou's evenness index, *J'* and Margalef's richness index, *d* values were lowest at Veraval.

Seasonal variations in J' and d values were generally minor across seasons in the study area (Fig. 5 d-e).

The n MDS analyses based on average abundance data of polychaete species, indicated that spatial variations were more prominent than seasonal (Fig. 6). The well illustrated spatial variation among all the zones by n MDS was further corroborated by two-way crossed ANOSIM. The ANOSIM results indicated substantial difference in polychaete community composition between transects (Global $R=0.737$, $p= 0.0001$) (Table 2). Further, the pairwise tests revealed that all possible pairs of transects were significantly different from each other. The statistical difference between the three seasons were observed to be not significant (Global $R=0.086$). Pairwise test between the three seasons indicated significant differences only between the premonsoon and monsoon.

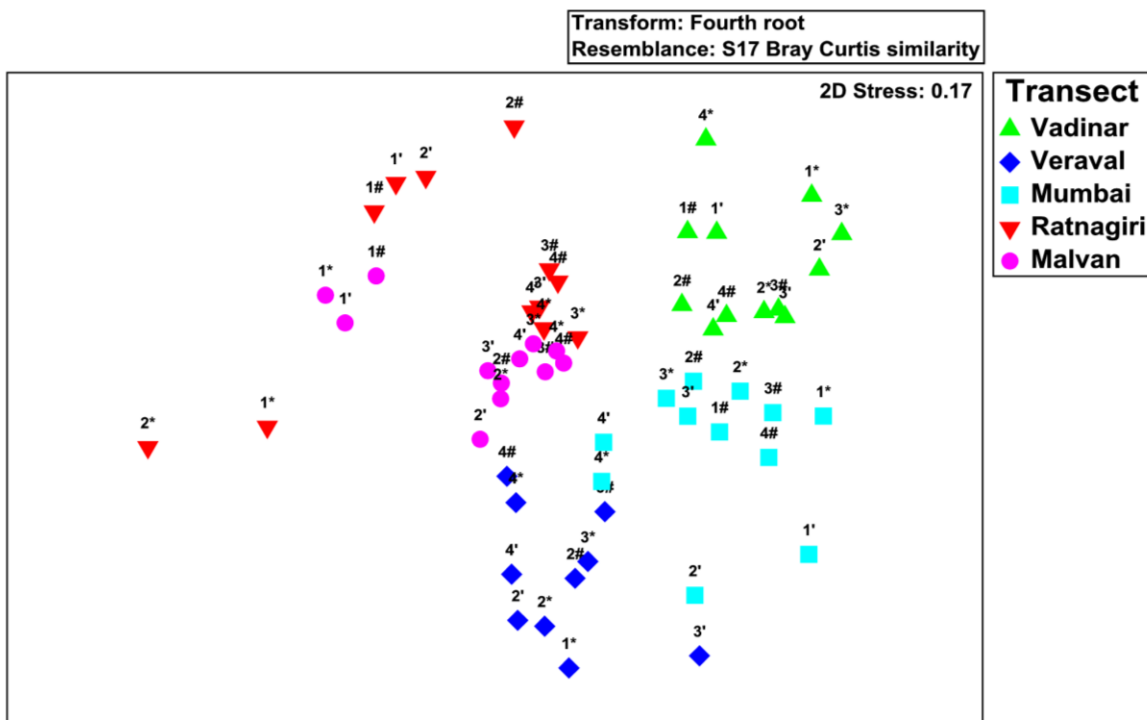


Fig. 6. Multidimensional scaling (n MDS) ordination of fourth-root transformed polychaete species abundances at four stations (1-4) along five studied transects during premonsoon (#), postmonsoon (‘) and monsoon (*) seasons.

	Global test R	R value	Significance level
Transects	0.737		0.0001
VD,V		0.928	0.0001
VD,MY		0.681	0.0001
VD,R		0.799	0.0002
VD,M		0.868	0.0001
V,MY		0.668	0.0001
V,R		0.813	0.0001
V,M		0.717	0.0001
MY,R		0.740	0.0001
MY,M		0.792	0.0001
R,M		0.462	0.0003
Seasons	0.086		0.069
Pre, Post		0.067	0.226
Pre, Mon		0.161	0.001
Post, Mon		0.030	0.315

Table 2. Two-way crossed ANOSIM testing for the differences of polychaete assemblages between five transects: Vadinar (VD), Veraval (V), Mumbai (MY), Ratnagiri (R), Malvan (M); and between seasons: Premonsoon (Pre), Postmonsoon (Post), Monsoon (Mon). Comparisons at a significance level of 0.05 with Bonferroni correction are highlighted in **bold**.

The SIMPER analysis revealed the polychaete species characterizing each transect and those responsible for differences between transects ([Appendix B](#)). The total average dissimilarities between transects ranged from 75.23% (Ratnagiri-Malvan) to 91.33% (Vadinar-Veraval). The most

important taxa those explained majority of the differences between transects were spionids like *Streblospio* sp. and *Paraprionospio patiens*. The distinction between Vadinar-Ratnagiri (avg. dissimilarity=88.94%), Mumbai-Ratnagiri (avg. dissimilarity=87.52%) and Vadinar-Malvan (avg. dissimilarity=85.65%) was mainly due to *Mediomastus* sp. The major contributor for dissimilarity between Vadinar-Mumbai (avg. dissimilarity=79.79%) was *Aphelochaeta filiformis*.

To identify the potentially important drivers responsible for polychaete species structure in the study area, CCA was performed. The first 2 axes of CCA explained 51.5% of the variance of species-environment relationship. The first axis separated the stations and species mainly based on the textural (silt, sand, PHc) and hydrological descriptors (DO, SS). The second axis was determined largely by salinity (Table 3).

Environmental variables	Axis 1	Axis 2	Axis 3	Axis 4
Sand	-0.79	-0.41	0.31	0.04
Silt	0.81	0.39	-0.29	-0.04
Clay	0.23	0.45	-0.31	-0.06
C _{org}	0.45	0.23	-0.58	-0.24
PHc	0.75	-0.49	0.15	0.02
Depth	-0.52	0.46	-0.38	0.08
WT	-0.01	-0.39	0.04	0.02
SS	0.63	-0.19	-0.02	0.19
Salinity	-0.21	0.52	0.32	-0.0003
DO	-0.66	0.27	0.37	-0.01
Nitrate	0.48	-0.04	-0.24	0.38
Ammonia	0.56	-0.36	0.06	-0.005
Eigenvalues	0.897	0.732	0.440	0.327
Species-environment correlations	0.986	0.967	0.896	0.802
Cumulative percentage variance				
of species data	11.8	21.4	27.2	31.5
of species-environment relation	28.4	51.5	65.4	75.7

Table 3. Summary of the results of CCA analysis.

The relationship between the environmental variables, major polychaete species and the stations during three sampling seasons are represented in the biplots (Fig. 7). The polychaete species that were mostly associated with the sand dominated stations of Ratnagiri and Malvan during the study period were *Jasmineira elegans*, *Scoloplos uniramus*, *Cirratulus* sp., *Mediomastus* sp., *Isolda pulchella* and *Paraprionospio patiens*. During monsoon season, the outer stations of Malvan, Ratnagiri and Veraval were mainly characterized by *Paraprionospio* sp 1., *P patiens* and *Cossura coasta*, *P cristata* respectively. *Streblospio* sp. dominated in the inner harbour segment of Veraval having low bottom water DO, high concentration of ammonia, SS and sediment PHc. The majority of remaining transects and the species were mainly influenced by silt, salinity and DO. The significance of the first canonical axis ($F=6.14$, $p=0.002$) and for all axes ($F=2.97$, $p=0.002$) was confirmed by Monte Carlo test.

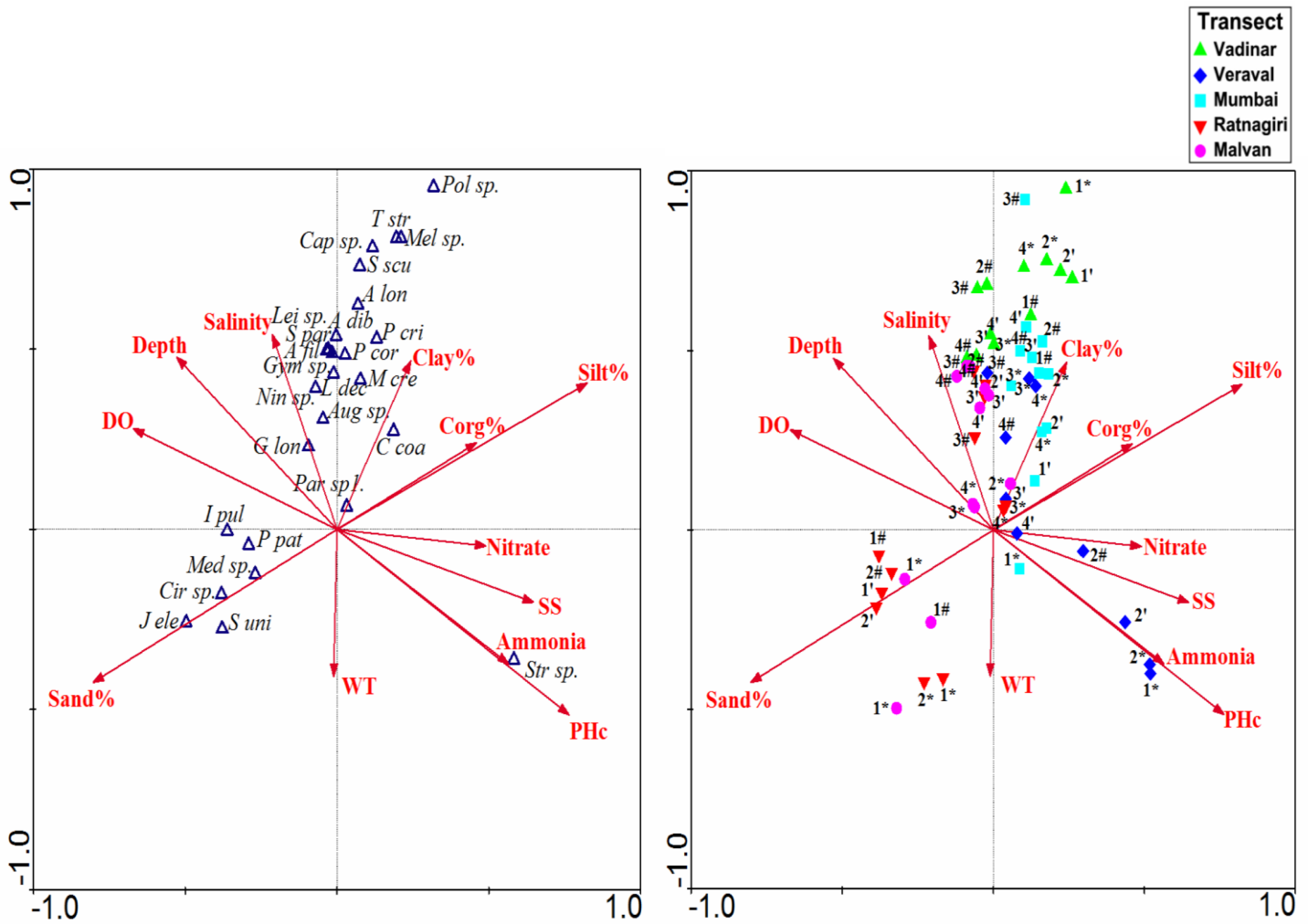


Fig. 7. Canonical correspondence analyses biplot of 27 most abundant polychaete species and 12 explanatory variables at four stations (1-4) along five studied transects during premonsoon (#), postmonsoon (') and monsoon (*) seasons. →:environmental variables; Sand; Silt; Clay; C_{org}; PHc; Salinity; DO; WT; SS; Ammonia; Nitrate and Depth. Δ: Polychaete species; *G lon*: *Glycera longipinnis*; *A dib*: *Aglaophamus dibranhis*; *Gym sp.*: *Gymnonereis sp.*; *L dec*: *Leonnates decipiens*; *S par*: *Sigambra parva*; *Aug sp.*: *Augeneria sp.*; *Nin sp 1*: *Ninoe sp 1.*; *S uni*: *Scoloplos uniramus*; *A lon* : *Aricidea longobranchiata*; *C coa*: *Cossura coasta*; *Par sp 1.*: *Paraprionospio sp 1.*; *P cor*: *Paraprionospio cordifolia*; *P cri*: *Paraprionospio cristata*; *P pat*: *Paraprionospio patiens*; *Str sp.*: *Streblospio sp.*; *M cre*: *Magelona crenulifrons*; *S scu*: *Sternaspis scutata*; *Cap sp.*: *Capitella sp.*; *Med sp.*: *Mediomastus sp.*; *Lei sp.*: *Leiochone sp.*; *A fil*: *Aphelochaeta filiformis*; *Cir sp.*: *Cirratulus sp.*; *I pul*: *Isolda pulchella*; *Mel sp.*: *Melinna sp.*; *Pol sp.*: *Polycirrus sp.*; *T str*: *Terebellides stroemii*; *J ele*: *Jasmineira elegans*.

The results of CCA thus identified the major sediment and hydrological variables that were responsible for the distribution patterns of polychaete species along the northwest Indian inner shelf.

3.4 Functional Trait Analysis

The functional composition of polychaete community of northwest Indian inner shelf was analysed by Fuzzy Correspondence Analyses (FCA). The results of the FCA are shown in two-dimensional plots where the first plot displayed the distribution of transects during three sampling events based on the weighted abundance of polychaete community along the gradient of first two axes (Fig.8). The distribution of different modalities of every studied trait was indicated in the second plot in relation to the same axes (Fig. 9).

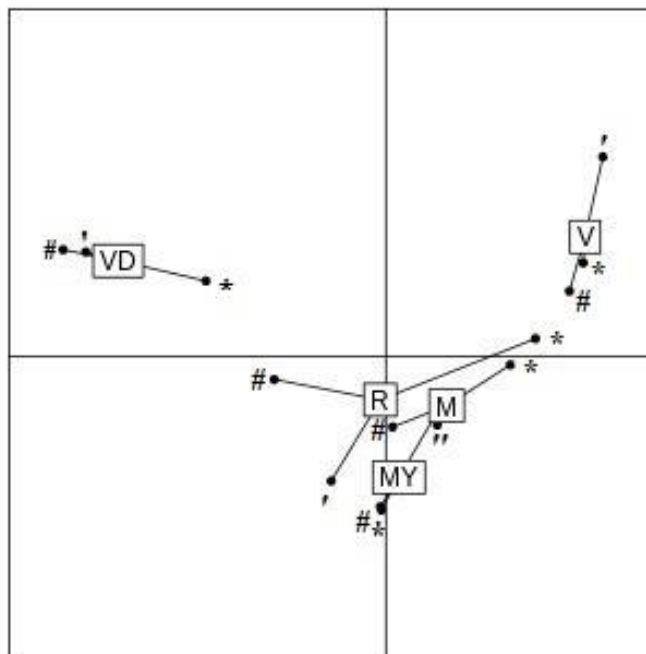


Fig. 8. Result of Fuzzy Correspondence Analysis (FCA). Ordination of samples based on trait-modalities weighted by polychaete species abundances at Vadinar (VD), Veraval (V), Mumbai (MY), Ratnagiri (R) and Malvan (M) during premonsoon (#), postmonsoon (') and monsoon (*) seasons.

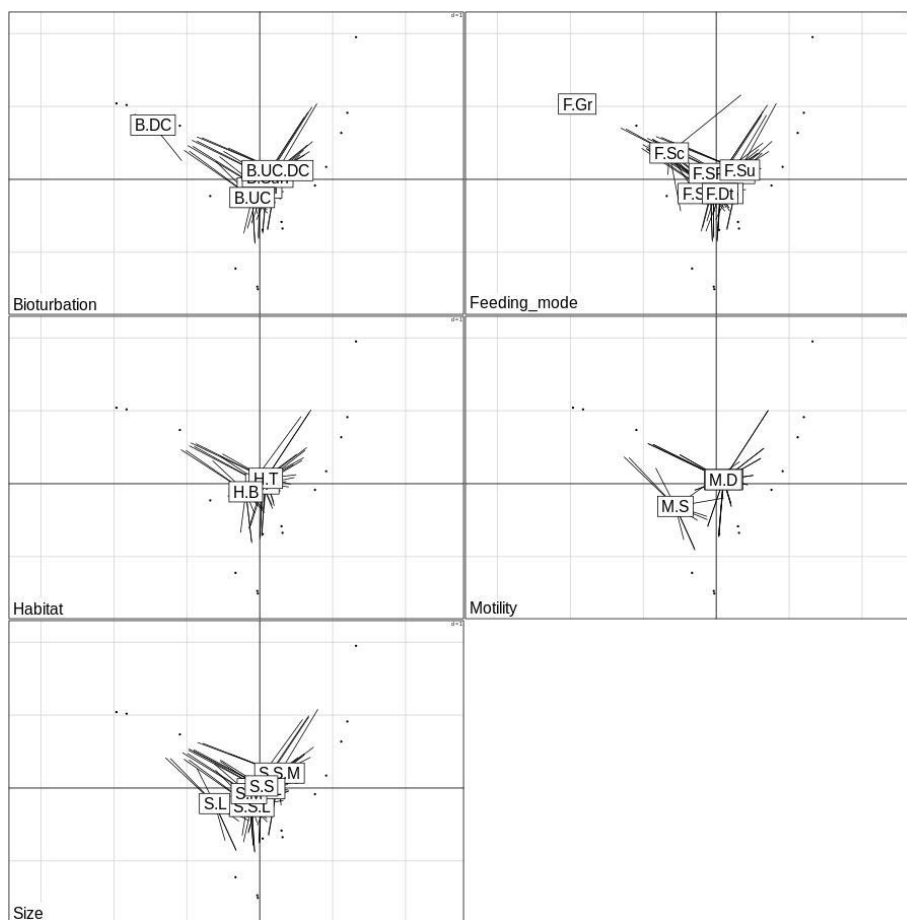


Fig. 9. Ordination plots of the functional traits with corresponding modalities based on Fuzzy Correspondence Analysis (FCA) of the abundance-weighted polychaete assemblage traits. The labels of the modalities within each trait category are provided in [Table 1](#).

Major proportion of variability (70.0%) was explained by the first two axes (51.1% and 18.9% in FC1 and FC2 respectively) ([Table 4](#)). The first axis separated the trait-modalities mainly based on bioturbation, feeding modes, motility and size. The biological trait ‘habitat’, however, provided a weaker contribution to the variability.

	FC 1	FC 2
Functional Traits	(51.1%)	(18.9%)
Bioturbation	0.13	0.05
Feeding mode	0.10	0.04
Size	0.06	0.02
Motility	0.06	0.02
Habitat	0.01	0.01

Table 4. Correlation matrix between the first two axes of the FCA and the functional traits studied. Figures in brackets indicate the variation explained by the corresponding axis. Higher contributions are highlighted in **bold**.

Factorial map of traits per station matrix showed a clear spatial segregation of transects in the study area (Fig. 8). Veraval was populated by polychaetes that were small, small-medium sized, UC/DC conveyors, tubiculus habitat residing, suspension and surface deposit feeding types. Similar trait-modalities were also observed at Ratnagiri and Malvan during the monsoon season. The small-large body sized, sessile forms were related to Ratnagiri during premonsoon and postmonsoon seasons. Vadinar was characterized by large body sized downward conveyors with grazing and scavenging feeding modes. Polychaetes observed at Malvan during premonsoon and postmonsoon seasons were mainly surface and subsurface feeding upward conveyors and surface modifiers. A combination of modalities of bioturbation (diffusers, UC/DC and upward conveyors) and feeding traits (surface and subsurface deposit feeding) predominated at Mumbai. Motile and discretely motile polychaete fauna was well represented throughout the study area (Fig. 9). The maximum value of FD index was noted at Vadinar (4.5 ± 0.6) while the minimum was at Veraval (2.2 ± 0.1). Mumbai (3.1 ± 0.2), Ratnagiri (3.1 ± 0.2) and Malvan (2.8 ± 0.1) had comparable FD values.

4. Discussion

Nearshore waters form the more fertile and productive parts of the marine environment with highly complex and variable ecological conditions. Contrary to the open sea, the variations in coastal

waters are much greater, owing to the various perturbations impacting this fragile zone. Prioritizing the coastal regions effectively according to their ecological vulnerability is indispensable for planning and management of “marine hotspots” (Zacharias and Gregr, 2005). In order to specify the “designated best use” of the coastal segments, the Central Pollution Control Board (CPCB) of India has set the primary water quality criteria at DO levels of 5.0 mg. l⁻¹ and ≥3.0 mg. l⁻¹ for ecologically sensitive zones and harbours, respectively. The present average DO values at ecosensitive zones of Vadinar, Malvan, as well as the harbours of Mumbai and Ratnagiri met the above conditions, signifying appropriate environmental quality despite the stressors present within each transect. Veraval possessed the only transect that did not fulfill the stated primary water quality conditions. Anoxic water conditions at Veraval harbour, as observed in the present study, have been reported in the past as well (COMAPS, 2012; Majithiya *et al.*, 2018). Higher salinity at Vadinar is characteristic of the GoK, because the evaporation exceeds precipitation in this area (Vethamony *et al.*, 2007). The baseline concentration of sediment PHc along the north-west coast of India is reported to be around 1.5 µg g⁻¹ (wet wt) (Ram and Kadam, 1991). PHc-sediment concentrations higher than the prescribed baseline value were found at the inner stations of some transects (i.e., Veraval, Mumbai and Malvan), the values being more pronounced at the Veraval harbour. The observed organic carbon at the GoK (<1%), Mumbai (1-2%) and Ratnagiri and Malvan (2-4%) were similar to that reported by Paropkari *et al.* (1992) who had extensively studied the organic content of sediments of the inner west Indian shelf. High organic carbon values in the outer silty stations of Ratnagiri and Malvan can be attributed to the naturally high organic content in these areas (Paropkari *et al.*, 1992).

Broad-scale macrobenthic studies along the west Indian shelf in deeper waters have been carried out by others (Harkantra *et al.*, 1980; Jayaraj *et al.* 2007, 2008; Joydas and Damodaran, 2009). Despite the above studies being located in deeper waters, similar dominance patterns among the major constituents of macrobenthos like Polychaeta, Crustacea and Mollusca were observed in the shallow depths of our study area as well. In the depth range of 30-200 m, Jayaraj *et al.* (2007) reported 39 polychaete families with 133 species along the northwest shelf. In the present study, a total of 140 species of polychaetes belonging to 42 families were recorded from the same region but in shallower depths (5-30m). Joydas and Damodaran (2009) recorded 33 families and 165 species from the entire west Indian shelf. While studying polychaete assemblage of coastal waters of the South-eastern Arabian Sea, Rengaiyan *et al.* (2017) reported occurrence of only 16 families and 71 species. Comparatively, more number of polychaete families and species recorded in the present study could be, in part, due to the usage of the updated classification keys that have revised and categorized some of the ‘sub-families’ into ‘new families’. A previously unreported polychaete

family (i.e., Longosomatidae) with new species of *H indica* (Parapar *et al.*, 2016) was reported in this investigation.

In the present study, the seasonal and spatial trends in polychaete distribution closely mirrored the macrofaunal distribution patterns. This observation thus justified the using of polychaetes as a representative taxon for environmental monitoring studies along the northwest Indian coast. The dominant polychaete species (that constituted >10% of the zone-wise polychaete abundances) were: *A longobranchiata* at Vadinar; *Streblospio* sp. and *C coasta* at Veraval; *Capitella* sp., *S scutata* and *Leiochone* sp. at Mumbai; *J elegans* at Ratnagiri; *P patiens*, *Mediomastus* sp. and *C coasta* at Malvan. Thus the dominant polychaete species were different at each transect in terms of types and relative abundances. Furthermore, the well distributed species were present in variable proportions at different transects. For example, *C coasta* constituted 25.9% at Veraval whereas at other transects it varied from 2.3-12.4% (Appendix A). The significant spatial variations in the polychaete community structure of all transects were confirmed by *n*MDS and ANOSIM as well.

Localized studies on macrobenthic polychaete diversity in subtidal locations of Vadinar (Sukumaran *et al.*, 2013), Mumbai (Sukumaran and Saraladevi, 2009; Mandal and Harkantra, 2013), Ratnagiri (Ingole *et al.*, 2009; Sukumaran *et al.*, 2011) and Malvan (Sukumaran *et al.*, 2016) have been carried out in the past. Comparatively higher diversity was indicated in the present study along the respective transects with the exception of Malvan (51 species). The majority of the above studies did not include monsoonal surveys resulting in data lacunae during this crucial season. The west coast of India is subjected to coastal upwelling phenomenon during the southwest monsoon (Rao *et al.*, 2005). During September, when upwelling peaks, the entire Indian shelf is reported to be inundated by upwelled waters having very low DO levels (Naqvi *et al.*, 2000). Considering that the monsoonal sampling of this study was conducted in September, the significantly low DO values of the bottom water at all transects except Vadinar was most likely resultant of the natural seasonal upwelling processes. Upwelling related hypoxia phenomenon has been previously reported by De Sousa *et al.* (1996) at Ratnagiri and Malvan during the southwest monsoon. Vadinar stations did not indicate seasonal hypoxia probably because this transect was situated in the inner Gulf. Thus, with the exception of the well oxygenated transect of Vadinar, the signature of seasonal hypoxia was observed along the entire northwest inner shelf during monsoon.

The monsoon season (September), characterized by low-oxygenated bottom water, coincided with an increased representation of opportunistic polychaete species in the macrobenthic assemblages. The outermost station of Mumbai was dominated by a maldanid, *Leichone* sp.

Similarly, spionid worms belonging to the genus *Paraprionospio* proliferated in the outer stations of Veraval (*P. cristata*), Ratnagiri (*Paraprionospio* sp.1) and Malvan (*P. patiens*) during the monsoon. The outer stations of Veraval transect (V3 and V4) also had high abundance of *C. coasta* during this period. A study by [Rakocinski and Menke, 2016](#) along the Mississippi Bight confirmed the impact of seasonal hypoxia on the structure and function of soft-bottom macrobenthos where the survivor polychaetes were mainly maldanids, *Cossura delta* and *Paraprionospio pinnata*. While studying the response of macrobenthos to coastal hypoxia off southeastern Arabian Sea, [Ingole et al., 2016](#) reported *Paraprionospio cordifolia* as hypoxia tolerant species. Seasonally recurring hypoxic zone in the Louisiana continental shelf, Mexico lead to the proliferation of *P. pinnata* and *Cossura soyeri* at the affected sites ([Briggs et al., 2017](#); [Shivarudrappa and Briggs, 2017](#)). A cossurid worm, *Cossura chilensis* was dominant in the upwelling ecosystem of central Chile ([Soto et al., 2017](#)). The species belonging to the genera *Paraprionospio* and *Cossura* are capable of persisting in oxygen-deficient environments through morphological and physiological adaptations for augmented oxygen uptake ([Lamont and Gage, 2000](#); [Levin, 2003](#)). Similarly, maldanid worms, congeneric spionidae and cossuridae proliferated in the present study area, as a response to coastal hypoxia. Thus, significant seasonal differences were detected by the pairwise ANOSIM between premonsoon and monsoon seasons. These observations suggested that the seasonal hypoxia during the monsoon had an impact on the polychaete community structure. Although the hypoxic events alter the benthic community structure, [Rosenberg, 2001](#); [Rosenberg et al., 2002](#) observed resiliency of benthic communities following the cessation of hypoxia, as recovery was noticed due to improved oxygen conditions. Though seasonal hypoxia was observed in the present study, evidence of mass mortalities was not detected ([Pacheco et al., 2010](#)).

Among the three harbours studied, Veraval was the most polluted as this zone was characterized by low oxygen (sometimes anoxic conditions) and high concentrations of nutrients and sediment PHc, signifying highly eutrophic conditions during all three seasons. Eutrophic conditions in Veraval harbor waters have been reported earlier ([Mandal et al., 2015](#)). The detrimental conditions at the Veraval harbour were magnified during the premonsoon and postmonsoon, leading to the complete depletion of macrobenthos within the harbour. At the station located at the harbor mouth, the macrobenthos was mainly comprised of the opportunistic spionid, *Streblospio* sp. that proliferated in low-oxygen conditions. Members of the genus *Streblospio* are known to tolerate high levels of pollution and low oxygen ([Levin et al., 1996](#); [Borja et al., 2006](#)). Impoverishment of resident fauna, especially in harbours with low-water column DO and elevated pollutant

concentrations, as observed in the Veraval harbour, have been reported elsewhere (Estacio *et al.*, 1997; Guerra-García and García-Gómez, 2005).

The variations in polychaete assemblages patterns are often complex, resulting from multiple ecological interactions that may not be explained by a single environmental variable (Martinez-Garcia *et al.*, 2013). CCA indicated that a suite of sedimentological (texture, PHc) as well as hydrological variables (DO, SS, salinity) were the key determinants of polychaete species distribution pattern along the northwest coastal fringe. These results agree with Jayaraj *et al.*, 2007 who indicated salinity, DO and sediment characteristics are the major influencing factors of macrobenthic composition along deeper northwest Indian shelf. The role of both sedimentary and hydrodynamic parameters in determining the diversity and distribution of polychaete community structure has also been well established in other studies (Sukumaran *et al.*, 2013; El Asri *et al.*, 2018).

The combination of the routine taxonomic approach with broad-scale functional trait analysis of the benthic community can efficiently aid in ecological assessment (Cochrane *et al.*, 2012). The importance of evaluating functional traits like feeding, motility, body size and bioturbation in ecological studies has been highlighted by many authors (eg., Papageorgiou *et al.*, 2009; Wouters *et al.*, 2018). Trophic diversity of polychaetes is extensively utilized in ecological impact assessment studies and can serve as a vital descriptor of environmental conditions (Pagliosa, 2005). Trophic diversity is higher in healthy environment owing to the presence of higher species diversity whereas it decreases in disturbed environment due to the dominance of opportunistic species (Gamito and Furtado, 2009). The opportunistic polychaete species face low inter-specific competition (Dean, 2008) as they proliferate by exploiting the available resources (Pagliosa, 2005) of the other counterparts possessing different trophic structures. Ecosensitive protected zones of Vadinar and Malvan, along with Ratnagiri that had a relatively higher proportion of the sandy fraction, sustained highly diverse feeding types. Sandy sediments support heterogeneous feeding types (Otegui *et al.*, 2016) as they provide interstitial spaces with diverse habitats that support variety of food resources (Muniz and Pires, 1999). Low trophic diversity observed at Veraval was due to the overwhelming dominance of opportunistic species belonging to family Spionidae. Spionid species also dominated the hypoxic and near-hypoxic coastal zones of Ratnagiri and Malvan during the monsoon. Spionidae possess a characteristic feature of switching the feeding mode between suspension and deposit feeding (Jumars *et al.*, 2015), depending on the environmental conditions. This adaptive mechanism probably facilitated their survival and proliferation in naturally disturbed environments of Ratnagiri, Malvan and anthropogenically stressed Veraval. Reduced trophic diversity was evident as a response

to natural (Sukumaran *et al.*, 2016) as well as anthropogenic (Rehitha *et al.*, 2017) disturbances along west coast of India.

Body size forms one of the important functional traits that effectively reflect the status of the ecosystem (Munari, 2011). The habitats with low stress conditions are known to sustain large sized organisms (Olsgard *et al.*, 2008), as was observed in Vadinar, the only zone that retained the bigger forms substantially during all seasons. In disturbed environs, small-sized organisms prevail replacing the vulnerable large-sized individuals (Norkko *et al.*, 2013). Small-sized opportunistic fauna are known to survive in hypoxic environments (Zhang *et al.*, 2010, Fleddum *et al.*, 2011). This was evidenced in the inner stations of Veraval and in the monsoonal stations at Ratnagiri and Malvan, respectively, where very low DO levels were present. van der Linden *et al.* (2012) also observed dominance of small sized fauna as a response to environmental stress (both natural and human induced) in Mondego estuary and referred this trait as 'opportunistic'. Another response to anthropogenic disturbances and hypoxia was the proliferation of worms residing in tubicolous habitat at Veraval and Ratnagiri- Malvan (monsoon). As tube dwelling organisms are protected inside tubes and they have a pumping mechanism for improved oxygenation, they may increase after the disturbance (Reise, 2002).

Hinchey *et al.* (2006) observed greater adaptability of motile organisms to disturbance events than sessile ones, due to their locomotory ability in the sediment (Gambi *et al.*, 2016). In the current study, presence of sessile forms was either absent (Veraval) or reduced (Ratnagiri, Malvan during monsoon) during the low-oxygen conditions. Bioturbation, also known to have an ecosystem engineering function (Kristensen *et al.*, 2012) is closely associated with an organism's motility (Pearson, 2001) and feeding modes that cause movement of sediment particles within the residential habitat (Dauwe *et al.*, 1998). Diverse reworking strategies of benthic community create a dynamic sediment environment that changes over spatial and temporal scales (Kristensen *et al.*, 2012). Aschenbroich *et al.* (2017) observed dominance of conveyors (both upward and downward) in stressed environmental conditions around the mangrove habitats with reduced functional diversity. Likewise, the conveyors were found to proliferate in the eutrophic conditions at Veraval and also in the naturally stressed, poorly oxygenated environments of Ratnagiri and Malvan during the monsoon.

Functional diversity trends suggested that Vadinar had the most diverse functional traits, whereas Veraval had a poor functional diversity. In general, a lower number of functional categories for each trait were observed at Ratnagiri and Malvan during the monsoonal low-oxygen

conditions. Conversely, [Wouters *et al.*, \(2018\)](#) noted an increased variability of polychaete functional traits in upwelled regions of the Brazilian coast due to increased primary productivity. Thus, it is possible that the response of macrobenthic functional groups to environmental changes can vary depending on the geographical region. These results also indicated that the spatial and seasonal patterns in polychaete diversity were reflected in its key functional traits. The data on the functional modes provided in the present study can serve as a baseline for further research on functional trait analyses of polychaete communities along the vast Indian coastline.

Conclusion

It is difficult to develop effective ecological conservation plans without sufficient information on existing taxonomic and functional diversity. The success of management measures in natural and managed ecosystems depends on understanding the responsible factors shaping complex biotic communities. This study is the first to provide the preliminary information on the spatio-temporal patterns of polychaete functional traits in Indian waters. The distribution trends of polychaete species corresponded with the macrobenthic distribution patterns in the NW Indian inner shelf. Spatial variability in polychaete community structure between the transects was prominent due to differences in species affiliations and relative abundances. Species and functional diversity were maximum at Vadinar and minimal at Veraval. The monsoonal low-DO conditions in the study area triggered a response in terms of altered taxonomic and functional composition of polychaete assemblages, mainly at Ratnagiri-Malvan. Both natural (texture, DO, salinity) and anthropogenic (PHc, SS, ammonia) variables were observed to have influenced the polychaete community structure of the northwest Indian inner shelf. Absence/poor presence of benthic fauna at Veraval with reduced diversity and functional complexity signified the eutrophication-driven stressed environment in the inner harbour segment. Remedial actions are urgently warranted at this segment to avoid further ecological deterioration. The structural and functional approaches integrated in the present study can aid in developing appropriate management and conservation plans to restore and protect the ecosystem integrity. The suitably reliable, broad-scale and temporally synchronous data generated from this benthic environment assessment can serve as a suitable template against which future studies can be compared for the ecologically and economically significant “marine hotspots”.

Supplementary material

Appendix A

Appendix B

Acknowledgments

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