

Macrobenthos in anthropogenically influenced zones of a coralline marine protected area in the Gulf of Kachchh, India

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Abstract

The Gulf of Kachchh Marine National Park and Sanctuary (MNPS) has one of the four coral reef systems of India. However, owing to its unique geographical position, this area has been transformed into an industrial hub dominated by oil and gas production, refining and transportation facilities. This study investigates the status of macrobenthos along with associated hydro-sedimentological data at 30 stations, sampled within three industrially active zones of the MNPS. The bottom water and sediment characteristics recorded in the study area fulfill the prescribed criteria for ecosensitive zones of India, despite the various stressors operational in the region. The univariate parameters suggest a healthy macrobenthic community except for a few pockets of stressed environment. However, CCA and correlation analyses indicate that even at low levels, petroleum hydrocarbons, along with sediment texture, were influencing polychaete community structure. As this protected area is denoted a “high oil spill risk area”, polychaete/amphipod ratio was employed to verify the environmental status which revealed that a major part of the study area had a good representation of oil-sensitive amphipods. The current study is the first of its kind to provide valuable baseline data of macrobenthos along with prevailing environmental conditions in this ecosensitive area.

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1. Introduction

Coastal aquatic pollution has been a major concern in various parts of the world (Peso-Aguilar et al., 2000), despite the plethora of national and international regulations in place. Impacts of marine pollution on coastal marine habitats and communities, which have been extensively chronicled (Gesteira and Dauvin, 2000; Kingston, 2002; Islam and Tanaka, 2004), can manifest through physical impacts, habitat alteration, toxicity, modification of biotic community structure and food webs and at times in large scale elimination of sensitive and commercial species (Kennish, 2001). The threat from coastal pollution is more significant in developing countries due to the rapid pace of industrialisation and consequent increase in pollution loads which tend to end up in near shore waters, one way or another (Islam and Tanaka, 2004).

Marine Protected Areas (MPAs) are popular conservation and management measures for protecting vulnerable species in shallow complex habitats like coral reefs (Shears et al., 2006; Russ and Alcala, 2011), preventing habitat exploitation and maintaining biodiversity and ecosystem health (Sobel and Dahlgren, 2004). The Gulf of Kachchh (GoK) is an indentation on the northwest coast of India, oriented in the east–west direction, occupying an area of about 7350 km² and has one of the four major reef systems of the country on its southern shoreline. This area, which extends from Okha (22°30'N, 69°00'E) in the west, to Navlakhi (22°30'N, 70°40'E) in the east, is rich in marine wealth and biodiversity and therefore was designated as a Marine National Park and Sanctuary (MNPS) in 1982 to protect the unique marine ecosystem (Fig. 1). The spectacular biodiversity in this area is attributed to the availability of different types of habitat present in the demarcated area.

Despite the legal protection it enjoys, ironically, the major anthropogenic threat to the MNPS is the rapidly expanding petroleum and petrochemical industries along its coast, largely due to its proximity to the oil exporting countries of the Middle East and its sheltered waters (Biswas, 2006). The GoK, as such, has been designated as an area of very high oil spill risk by a recent status report (<http://www.icmam.gov.in/scma.pdf>). The presence of oil pipelines passing through the marine national park and the occurrence of a major oil spill during 1999, have only amplified the fears of damage to the protected area from oil pollution (Asari and Jani, 2004; Kankara and Subramanian, 2007).

Despite the site-specific studies carried out in the GoK for various industrial projects, a perusal of literature reveals that studies on its marine environment are limited (Desa et al., 2005). A recent review has attempted to give an overview of the status of flora and fauna in the GoK (Nair, 2002).

Limited surveys and biodiversity studies in the MNPS have been carried out by others in the past, most of them concentrating on coral and other faunal diversity (Pillai and Patel, 1988; Thomas et al., 1996; Singh, 2003; Ingole and Goltekar, 2004; Singh et al., 2006). However, given the recent spate of growth of industrialisation and anthropogenic activities in the MNPS, what is unknown is its impact on the benthic life in this biosphere as no previous study in the area has hitherto studied the macrobenthic diversity in relation to the various natural and anthropogenic parameters probably influencing them.

Benthic macrofauna can integrate conditions over a period of time (Dauvin et al., 2010) as they are relatively sedentary and long-lived. Hence, the study of macrobenthos has often been used as a tool in many monitoring studies (Fitch and Crowe, 2010). Among macrobenthos, polychaetes have been proposed as surrogates for marine biodiversity and environmental quality studies (Olsgard et al., 2003) as they are the numerically dominant, ubiquitous, species-rich macrobenthic group with diverse feeding modes and differential response to various types of environmental disturbances (Dean, 2008). Studies have shown that identification of organisms at higher taxonomic levels was cost-effective with little loss of information in marine environmental impact assessment and monitoring programmes (De Biasi et al., 2003; Bevilacqua et al., 2009) and reduction in identification errors (Dauvin and Ruellet, 2007). Also, anthropogenic effects are more discernable at higher taxonomic levels (Ferraro and Cole, 1990; Munari et al., 2009). Investigations have indicated that family-level data is sufficient for cost-effective monitoring of marine protected areas (Vanderklift et al., 1998) and studying pollution effects in marine zones impacted by oil spills (Gesteira et al., 2003; Dauvin et al., 2003). Joydas et al. (2009) have endorsed the application of taxonomic sufficiency for a rapid evaluation of human impact on the ecology of the Arabian Sea where the MNPS is located.

The current study was designed to: 1) evaluate the biodiversity and distribution of the macrobenthos at three select industrialised locations of MNPS (Mithapur-Okha, Vadinar and Sikka), with emphasis on the major macrobenthic group-polychaetes, 2) to elucidate the major hydro-sedimentological parameters influencing the macrobenthic communities, 3) study the impact of various anthropogenic pressures, if any, in the three selected areas of the MNPS through the study of polychaete families. Information on the distribution and abundance of biota gained from survey of these sensitive areas can be used to determine the environmental status vis-à-vis other regional and global scales.

2. Materials and methods

2.1 Study area

The southern flank of the GoK, where the 457.92 km² MNPS is located, has about 42 islands, most of them having fringing coral reefs. Besides these islands, the MNPS includes diverse habitat like algal beds, mangrove swamp forests, reef vegetation, scrub forests, marsh vegetation, vast intertidal rocky and sandy stretches, mudflats and water mass extending up to the 10 fathom depth line. The climate of the MNPS is dry with temperatures ranging from 7.8°C to 44.8°C. Although the rainfall is erratic in nature, the region gets rain from the south-west monsoon. Due to the mixing wrought by the strong tidal currents, uneven topography and lack of freshwater discharges, the water column has a homogenous temperature and salinity profile (Vethamony et al., 2005). The characteristic arid climate, large semi-diurnal tidal amplitudes (3-5 m), negative water balance, swift water currents and sediment input influence the occurrence, abundance and distribution of biota in this region. Besides the natural factors, the marine habitat of the MNPS is influenced by myriad anthropogenic activities.

The three industrialised zones in the MNPS that were selected to study the benthic communities were Mithapur-Okha, Vadinar and Sikka (Fig. 1). The integrated salt works and inorganic chemical complex situated at Mithapur releases its industrial effluents into the Arambhada bay through an open channel in the MNPS. Okha has an all weather port with direct berthing facilities handling coke, coal, wheat, fertilizers, clinker, chemicals and soda ash. Two oil terminals, a refinery, two crude oil tank farms, three Single Point Moorings (SPMs) and numerous salt pans are located in Vadinar. Besides these, industrial effluents of an oil refinery are discharged 6 kms off the Narara reef. Islands with live corals which are part of the MNPS dot the Vadinar coast. Sikka, located adjacent to Vadinar, has a thermal power plant, a cement factory, a jetty, an extensive pipeline network for unloading crude oil and exporting petroleum products, a liquid cargo jetty and another crude oil tank farm located along its coast. India's largest all-weather petroleum terminal is also located at Sikka. There are 6 SPMs located off Sikka. The effluents of a thermal power plant are discharged in the Sikka creek. The western shore of Sikka creek has dense mangroves, while live corals are present along the Sikka coast.

2.2 Field sampling and analyses

Thirty stations in total were sampled in all three study areas for macrobenthic, water and sediment analyses during April-May 2010 (summer), which was considered the most stressful quarter of the year due to high air temperatures. Seven, eleven and thirteen stations were sampled at Mithapur-Okha, Sikka and Vadinar respectively (Fig. 1). The number of stations selected was based on the

different anthropogenic activities in the respective zones. Nomenclature, area description and water depth of sampled stations are given in Table 1. Sediment samples for macrobenthic analyses were collected in quadruplicate using a van Veen grab of 0.04 m² bite area. Hence altogether 120 grab samples were analysed for the study. The animals retained after sieving the sediment samples through a 0.5 mm mesh sieve were fixed in 5% formalin mixed with Rose Bengal. Benthic organisms were sorted to major taxa (phylum, order or class), enumerated and expressed as ind.m⁻². The dominant taxa, polychaetes, were then identified up to family level (Day, 1967; Fauchald, 1977) and their feeding guilds were ascertained as per Fauchald and Jumars (1979). Considering that not only biology and ecology but also the taxonomic knowledge of the benthic fauna in the region is limited, the above procedure minimized the time taken to sort them out (Hatje et al., 2006).

Sediment samples were also analysed for sediment texture, organic carbon (C_{org}), and petroleum hydrocarbons (PHc-sediment). At each station, bottom water samples were collected using Niskin samplers for analyzing temperature, pH, suspended solids (SS), salinity, dissolved oxygen (DO), nitrate-nitrogen (NO₃⁻-N), ammonia (NH₄⁺-N) and petroleum hydrocarbons (PHc-water). Temperature was recorded using a mercury thermometer with an accuracy of ±0.1°C. pH was measured on a Cyber Scan (Model pH 510) pH meter. Salinity, SS, DO, and nutrients were analyzed using standard methods (Grasshoff et al., 1999). PHc in sediment and water was measured with a fluorescence spectrophotometer (LS 3B Perkin Elmer) (IOC-UNESCO, 1982; 1984). C_{org} was analyzed by titration method (Walkey and Black, 1934) and sediment texture by combined sieving and pipette method (Buchanan, 1984).

2.3. Data analysis

Univariate and multivariate analyses of polychaete family abundance data were carried out using the statistical software, PRIMER v6. The univariate techniques employed were Shannon-Wiener diversity index, H' (log₂); Margalef's index, d ; and Pielou's evenness index, J' . Multivariate analyses included the ordination of fourth root transformed polychaete family data using Bray-Curtis similarities by non-metric Multi-Dimensional Scaling (MDS). One-way ANOVA was used on abiotic and biotic parameters to detect significant differences between the three sites. Pearson correlation coefficient (r) was estimated between macrobenthic taxa, polychaete feeding groups, diversity indices and environmental parameters, using the software Statistica 7. Polychaete family data was initially analysed by Detrended Correspondence Analysis (DCA) (Hill and Gauch, 1980) to determine whether to use a linear or unimodal model of numerical techniques. As the gradient length was more than 2SD, Canonical Correspondence Analysis (CCA) was selected as the unimodal response model (ter Braak

and Prentice, 1988; Hasse and Nolte, 2008; Hårnström et al., 2009) to explore the relationships between polychaete families, and suite of environmental variables using CANOCO version 4.5 (ter Braak and Smilauer, 2002). Analysis included 17 significantly contributing families having over 1% of relative abundance and 10 selected environmental variables. Monte Carlo Permutation test (with 499 unrestricted permutations) was incorporated to test the significance of the ordination axes.

In this paper polychaete/amphipod ratio has been employed in order to study the potential impact of oil industrialisation taking place along this part of the southern GoK. Polychaete/amphipod ratio will increase when environmental condition degrades as amphipods are less tolerant to contaminants than polychaetes (Nikitik and Robinson, 2003). Thus this ratio has been proved to be a useful, effective environmental indicator to evaluate ecological change caused by petroleum activities (Gesteira and Dauvin, 2000; Andrade and Renaud, 2011). The ratio was obtained by dividing the total number of polychaetes by amphipods for individual stations. Only at station M1 where the number of amphipods was zero, a value of 1 was considered in order to avoid division errors (Dauvin and Ruellet, 2007). The relationship of the polychaete/amphipod ratio with all chemical and biological variables was examined using Pearson correlation.

3. Results

3.1. Bottom water characteristics

The depth of the stations varied from 1.5 m (S1) to 41 m (V8) (Table 1). Water temperatures were generally lower in Mithapur-Okha as compared to Vadinar and Sikka (Fig. 2a, Table 2), possibly due to the proximity of the former to the Arabian Sea leading to better circulation of water in the area. The observed water temperatures were expectedly high (min-max 24-31.9 °C) as the sampling was undertaken during summer (April 2010). However, aberrant values of water temperature in the stations near the industrial effluent release points (M1, V5 and S5) were not observed (Fig 2a). The consistent pH (min-max 7.8-8.0; mean±SD 7.8±0.07) (Fig 2b) and DO (min-max 5.0-7.8 mg l⁻¹; mean±SD 6.5±0.5 mg l⁻¹) were as expected in natural waters (Fig 2c). SS were generally low (<50 mg l⁻¹), though sporadic higher values were observed in areas of high silt i.e. V1 (84 mg l⁻¹), V4 (82 mg l⁻¹), S1 (71 mg l⁻¹) and S6 (85 mg l⁻¹) (Fig 2d). Water salinities were markedly higher (min-max 35.6-39.2 ‰) than typical seawater which is characteristic of the GoK where the evaporation exceeds precipitation (Fig 2e). Salinity in the Vadinar zone was comparatively higher than Mithapur-Okha and Sikka probably due to the presence of salt pans along its coast (Table 2). In the Mithapur-Okha zone, higher salinity (38.2 ‰) was observed at M1 (Mithapur effluent release point) (Fig 2e).

The nutrients (NO_3^- -N, NH_4^+ -N) were generally low in all three segments (Fig 2f; Table 2). PHc in water was $<10 \mu\text{g l}^{-1}$ in most of the stations (73%). However, elevated values were observed near the effluent discharge point at Mithapur (M1; $16.4 \mu\text{g l}^{-1}$), oil terminal at Vadinar (V2; $17.8 \mu\text{g l}^{-1}$), landfall point of the SPM pipeline at Narara (S1; $30.6 \mu\text{g l}^{-1}$), Singach creek (S2; $28.1 \mu\text{g l}^{-1}$), fertilizer jetty (S3; $22.1 \mu\text{g l}^{-1}$) and nearby area (S4; $42.2 \mu\text{g l}^{-1}$) (Fig 2g).

3.2. Sediment characteristics

Sediments in Mithapur-Okha were mostly sandy (min-max 48.4-95.8 %) with lower silt fraction (min-max 2.4-44.4 %). Vadinar sediments had variable combinations of sand (min-max 9.5-94.2 %) and silt (min-max 10-83.7 %); while at Sikka, sediments were predominantly silty (min-max 11.6-93.4 %) with smaller proportions of sand (Fig 2h). In general, it was observed that sandy texture had a decreasing trend from outer (Mithapur-Okha) to inner GoK (Sikka), while in the case of silt/clay fractions it was vice-versa (Table 2). The C_{org} (min-max 0.2-1.2 %) values were indicative of an area free from organic pollution (Fig 2i). Though low PHc levels ($\leq 1.7 \mu\text{g g}^{-1}$) in sediments were observed in a majority of stations, relatively higher values ($>1.7 \mu\text{g g}^{-1}$) were recorded at M1, M5, M6 and S1 (Fig 2j). Considering the substantial anthropogenic activities in the bay, the present levels of PHc (min-max $0.02 - 3.9 \mu\text{g g}^{-1}$) in subtidal sediments of the study area indicate that the PHc released does not settle, but probably gets advected and distributed over a large area due to tidal movements.

3.3. Macrobenthic composition and density

Collectively, thirty three macrobenthic groups were identified from all three locations (Appendix 1), Sikka having higher group diversity than Mithapur-Okha and Vadinar (Table 2). Macrobenthic density ranged from 225 ind m^{-2} to 14745 ind m^{-2} (Fig 2k) with insignificant variations among the three zones (Table 2). Overall, Polychaeta (37%) was the most dominant group followed by Amphipoda (26%), Bivalvia (13.5%) and Decapod larvae (8.2%). Twenty nine other smaller groups ($\leq 2\%$) comprised the remaining 15.3%. Polychaeta was the only macrobenthic group present in all 30 stations and comprised as high as 93 % (M1) of macrobenthic abundances to a low of 5% at M2. Amphipods contributed from 3.5% (S1) to 64.9% (M2) to the macrobenthic densities and were absent at M1. The other major group, bivalves, were most dominant at S8 (62.3%) but absent at V10. It was also observed that polychaetes and amphipods together accounted for $>50\%$ of the macrobenthic abundances in a majority of stations, except for V1, V4, S1, S8 and S12, where other groups like decapod larvae and bivalves were present in substantial numbers. The polychaete abundances (%)

revealed a significant inverse relationship with amphipod ($r=-0.60$, $p<.0001$) and pelecypod ($r=-0.40$, $p<.027$) percentage densities.

3.4. Polychaete assemblages and feeding guild

Polychaete abundances varied from 50 ind m⁻² to 2331 ind m⁻² (Fig 2k). Twenty nine polychaete families were identified from the study area. Highest number of polychaete families were identified from Sikka (27 families), as compared to Vadinar (25 families) and Mithapur-Okha (21 families) (Appendix 1). The most widespread polychaete families in the study area were Lumbrinereidae, Spionidae (25 stations each), Syllidae, Terebellidae, Cirratulidae (21 stations each) and Orbiniidae (20 stations). The most dominant polychaete families in terms of their relative abundances were Capitellidae (12.5%), Syllidae (10.8%), Cirratulidae (9.7%), Nereidae (9.4%), Spionidae (7.7%) and Terebellidae (7.3%) which together accounted for 57.4% of the total polychaete density. With the exception of 10 families viz. Ampharetidae, Flabelligeridae, Magelonidae, Sternaspidae (absent in Mithapur-Okha zone), Arbellidae, Polynoidae (absent in Vadinar zone), Serpulidae, Hesionidae (absent in Mithapur-Okha and Sikka zones), Onuphidae and Sigalonidae (absent in Mithapur-Okha and Vadinar zones), the remaining 19 families were observed in all three zones. The rare polychaete families present in the study area were Hesionidae (1 station), Sigalonidae, Sternaspidae (2 stations each) and Ampharetidae (3 stations).

Polychaete families could be categorized into five groups based on the feeding guilds viz deposit feeders (12 families), carnivores (8 families), omnivores (5 families), deposit feeding omnivores (2 families) and filter feeders (2 families). It was observed that deposit feeders were present in higher numbers at Sikka while carnivores, omnivores and filter feeders were more prevalent in outer GoK (Mithapur-Okha). However, zonal differences in the relative abundances of these feeding guilds were not significant (Table 2).

3.5. Univariate and Multivariate analyses

Shannon-Wiener H' (\log_2) values for the entire study area ranged from 0.7 (S1) to 3.6 (S7), whereas the Margalef's richness index d varied from 0.3 (S1) to 2.9 (S7) and the Pielou's evenness index, J' varied between 0.4 (S1) and 1.0 (V4) (Fig 2l). The univariate indices did not show highly significant inter-zonal differences (Table 2). Generally, H' values were ≥ 2.4 in all stations across all three zones except for S1 ($H'=0.7$), M1 and M2 (both $H'=1.9$). Apart from S1, all stations also had high evenness values ($J'>0.7$). The station that stood apart from all other stations in terms of very low diversity indices was S1, the landfall point of the SPM pipeline. At this station only 3 polychaete

families were present and the polychaete assemblages were dominated by nereids (86.7%). Station M1 ($H'=1.9$), which was near an industrial effluent release point was dominated by spionids (40%).

The MDS plot (Fig. 3) indicated 3 distinct groups among the stations. The main group (group 1) comprised of a majority of stations excluding M1, M2, M3 (group 2) and S1 (group 3). Stress values >0.2 may yield plots that are difficult to interpret (Clarke, 1993). However as stress values increase with the number of data points in the MDS (Clarke, 1993), stress values greater than, but close to 0.2 remain meaningful where many data points are included (Hobday et al., 1999). Group 1 had average similarity of 49% contributed majorly by Spionidae, Lumbrineridae, Terebellidae and Cirratulidae. Group 2 similarity (58%) was due to the presence of Nephtyidae, Lumbrinereidae, Orbiniidae and Syllidae. Abundances of six most dominant families i.e. Nereidae, Capitellidae, Cirratulidae, Spionidae, Syllidae and Terebellidae were superimposed as bubbles on the polychaete family abundance MDS plot (Fig. 3).

Significant Pearson's correlations ($p \leq 0.05$) between the environmental variables and biotic parameters are presented in Table 3. Sabellids and syllids had a positive correlation with sand (and therefore a negative correlation with silt and clay) while cossurids, onuphids, pilargids and terebellids correlated positively with silt and/or clay (with a corresponding negative correlation with sand). Amphipods, filter-feeders and omnivores among polychaete assemblages also indicated a positive correlation with sand while deposit-feeding polychaetes had a significant affinity for clay dominated sediments. Cossurids, pilargids and deposit-feeders showed a positive correlation with C_{org} . However, amphipods, syllids and omnivores indicated a negative correlation with C_{org} . PHc-sediment had a positive influence on the abundance of nereids and omnivores, while PHc-water positively correlated with capitellids and polychaete group density. However, abundance of amphipods and carnivores among polychaetes were negatively impacted by PHc-water. Among the polychaete diversity indices, H' and J were negatively correlated with PHc-water and d was negatively correlated by PHc-sediment. J was positively influenced by salinity.

CCA was performed on selected polychaete families and environmental parameters as depicted in Fig. 4. The arrows representing the environmental variables indicate the direction of maximum change of that variable across the diagram and the length of the arrow is proportional to the rate of change. Thus PHc-sediment, silt and sand were the principal environmental parameters influencing polychaete assemblages in the study area. Four axes on canonical ordination plots together explained 76.8% of variation in species abundance data. Axis 1 of CCA analysis displayed 25.7% of the total variance and was strongly influenced by sediment PHc-sediment ($r=-0.65$) and to a lesser extent by

clay ($r=0.54$), C_{org} ($r=0.53$), NH_4^+-N ($r=0.43$), sand ($r=-0.42$) and silt ($r=0.40$). The second axis (variance=22.2%) divided all stations based on the sediment texture i.e. silty versus sandy, as silt was positively correlated ($r=0.73$) and sand was negatively correlated ($r=-0.71$) with that axis. Other parameters that were weakly linked with Axis 2 were SS ($r=0.45$) and DO ($r = 0.38$). Axis 3 was mainly characterized by PHc-water ($r=-0.65$) and axis 4 by salinity ($r=-0.50$) (Table 4). The CCA plot indicated that Terebellidae, Pilargidae, Cossuridae, Nephtyidae, Lumbrineridae and Cirratulidae were partial to silty-clayey substratum with high organic content while Eunicidae, Orbiniidae, Phyllodocidae, Syllidae, Dorvellidae, Sabellidae, Aphroditidae, Maldanidae and Spionidae preferred sandy substratum having low organic content. Nereidae was mainly influenced by PHc-sediment whereas Capitellidae by PHc-water (Fig. 4). The validity of significance of both the first canonical axis ($F=3.43$, $p=0.02$) and for all axes ($F=2.797$, $p=0.002$) was proved by Monte Carlo test. Thus CCA analysis revealed that not only natural factors but anthropogenic variables also influenced the polychaete community structure.

3.6. Polychaete/amphipod ratio

Ratio levels calculated for the entire study region ranged from 0.1 to 500, both from Mithapur-Okha region (Fig. 5). At Vadinar and Sikka the ratio was (min-max) 0.2-6.3 and (min-max) 0.4-13.5 respectively. Station M1, which was the nearest station to an industrial discharge point, had the highest polychaete/amphipod ratio (ratio=500) in the Mithapur-Okha zone. Likewise V2 (ratio=6.3) and S1-S4 (min-max 10.5-13.5) exhibited higher ratios in Vadinar and Sikka respectively. It was also observed that these stations had relatively higher PHc-water levels than other stations in their respective zones. The polychaete/amphipod ratio significantly correlated positively with PHc-water ($r=0.7$, $p<.0001$).

4. Discussion

The primary water quality criteria set by the Central Pollution Control Board (CPCB) of India prescribes DO levels $\geq 5.0 \text{ mg l}^{-1}$, pH range of 6.5-8.5 and PHc levels $\leq 0.1 \text{ mg l}^{-1}$ for designated best use of coastal seawater as ecologically sensitive zone (SWI waters) (Anon, 1993). Water quality values of the current study (Figs. 2b, 2c and 2g) fulfil the criteria of CPCB for ecosensitive zones despite the various stressors operational in the region. The present DO values were also comparable with historical data (Desa et al., 2005) suggesting consistent DO levels that were not influenced by the industrial activities. Relatively higher PHc-water values ($16.4\text{-}42.2 \text{ } \mu\text{g l}^{-1}$) observed in stations impacted by various anthropogenic activities were lower than the limits prescribed by the CPCB ($100 \text{ } \mu\text{g l}^{-1}$) for marine protected areas.

The present results also indicate that the study area did not receive much anthropogenic discharge of nutrients and the land runoff was negligible. Although the effluents discharged off Vadinar (V5) and Sikka (S7) had higher salinities, the receiving water exhibited normal salinities suggesting effective dispersal of the effluent after release. The effluent dispersal was not as effective at Mithapur, as evidenced by higher salinity and PHc-water levels measured near the discharge point (M1) compared to other stations in the zone. As the C_{org} values were low despite the presence of extensive mangroves near some stations, it appears that the organic matter, both natural and anthropogenic, entering the system, was effectively dispersed by the currents. Similarly, the swift current speeds and high tidal displacements discourage the settlement of fine SS as well as the weathered residue of PHc, on the bed and disperse the anthropogenic contaminants over a wide area thereby diminishing their influence. An analysis of 27 years of data indicated that in GoK sediments, the average PHc concentration was $0.7 \mu\text{g g}^{-1}$ (Vethamony et al., 2007) which is in agreement with the current average value ($0.8 \mu\text{g g}^{-1}$). The role of the good flushing system of the GoK, which is attributed to the strong tidal currents, in dispersing PHc contaminants has been observed by Vethamony et al. (2007). It is apparent from the results (Fig. 2j) that the sediment in a major part of the study area, except for a few elevated values of PHc, was not impacted by the ongoing multiple anthropogenic activities.

The overall average macrobenthic density (av. 1796 ind.m^{-2}) was comparable with values reported from the Lakshadweep coral islands, west coast of India (av. 2418 ind.m^{-2} ; Ansari et al., 1991) and higher than that of the Andaman Sea, east coast of India (av. 406 ind.m^{-2} ; Parulekar and Ansari, 1981). Higher macrobenthic densities than the current study were reported in the Tahiti lagoon, French Polynesia (av. 9229 ind.m^{-2} ; Frouin and Hutchings, 2001), coral reef sediments of the Great Barrier Reef (range $3115\text{-}43690 \text{ ind.m}^{-2}$; Riddle, 1988) and Gray's Reef National Marine Sanctuary, USA (range $423\text{-}50258 \text{ ind.m}^{-2}$; Hyland et al., 2006).

The Shannon-Wiener diversity range for polychaete families in the present study (0.7-3.6) was higher than polychaete family diversity values (1.7-2.8) reported by Joydas et al. (2009) for the Indian west coast shelf. In a healthy environment, Shannon-Wiener species diversity is in the range of 2.5-3.5 (Khan et al., 2004). Apart from 3 stations, all stations had healthy Shannon family diversity ($H'=2.8\pm 0.5$) and evenness values ($J'=0.8\pm 0.1$). Considering that family-level diversity values are generally lower than species- and genus-level diversity (Gesteira et al., 2003), the current H' values indicated a quality marine environment. Similarly, high values of evenness in a large part of the study area (except S1) were indicative of balanced benthic assemblages (Díaz-Castaneda and Harris, 2004).

However, low univariate indices at station S1 indicated that this landfall point of a SPM had a disturbed ecology. S1 had a silty substratum with dense mangrove cover and an abundant presence of nereids which are known to dominate mangrove areas affected by anthropogenic activities (Pagliosa, 2005). The positive correlation of nereids with PHc-sediment indicated its resistance to this pollutant. Similarly M1, which also had low species richness and diversity, was dominated by spionids. Abundances of nereids and spionids are known to increase in areas impacted by hydrocarbon pollution (Jewett et al., 1999). Significant negative correlation of H' and J' with PHc-water and d with PHc-sediment (Table 3) indicated that even at present low levels, petroleum hydrocarbons impacted polychaete diversity and evenness.

Members of Maldanidae (Belan, 2003), Syllidae (Giangrande et al., 2005) and Terebellidae (Olsgard et al., 2003) have been used as negative indicators of poor benthic conditions, that is their presence in the community is an indication of good environmental conditions. In our study area, the above families contributed effectively to the total polychaete abundance, signifying healthy environmental conditions. Syllids and terebellids were present in 70% of stations and were the second and sixth most dominant family respectively in terms of relative abundance indicating that the area was conducive to their proliferation and therefore largely free from pollutants.

It was observed that, although lumbrinereids were categorized as pollution-sensitive by others (Belan, 2003; Hobbs et al., 1990), they were the second dominant group after spionids at M1 which receives industrial waste water. Thus it was probable that lumbrinereids in the southern Gulf were probably resistant to low levels of pollution and therefore may not serve as negative indicators of pollution here. Lumbrinereids have been observed to be a major group in an area impacted by sewage outfall by Del-Pilar-Ruso et al. (2009). It appears that each geographic region has its own positive and negative indicators which are specific to it and these indicators may respond differently in other zones (Dean, 2008).

Amphipods have been used in benthic indices (Dauvin and Ruellet, 2007; Andrade and Renaud, 2011) as they are known to be particularly sensitive to organic and hydrocarbon pollution (Gesteira and Dauvin, 2000; de-la-Ossa-Carretero et al., 2012). The substantial presence of the second major group, amphipoda (0-65%) in a majority of the stations implies that the area for most part was not severely impacted by oil pollution and other industrial effluents (Joydas et al., 2012). However, the absence of amphipods at M1 and lower percentage abundance at V2, S1-S4 indicated that these areas were not conducive to the proliferation of this sensitive faunal group. Incidentally these stations had relatively higher values of PHc-water and C_{org} . The negative impact on amphipod densities due to

the rising levels of PHc-water and C_{org} is validated by the significant negative correlation between these parameters (Table 3). The decline in amphipod density with increasing polychaete abundance at higher PHc values observed in this study has also been reported by others (Jewett et al., 1999; Nikitik and Robinson, 2003). As observed by Gesteira and Dauvin (2000), the correlation values (Table 3) in this investigation indicated the tolerance of polychaetes (opportunists) to higher levels of PHc-water.

The low polychaete/amphipod ratios (<5.5) in a majority of the stations (80%) suggest that for the most part, the study area was not impacted by the ongoing industrial and oil related activities. However, relatively higher ratios at M1, V2 and S1-S4 indicate that these specific areas were disturbed to various extents by anthropogenic activity. While the PHc-water values in these stations were higher than those in other stations, they were still lower than prescribed limits as elaborated earlier. It was also observed that though the PHc-water levels were comparatively low at M1, amphipods were absent. A probable reason could be that the amphipods must have been exposed to a short period of much higher concentrations of hydrocarbons than measured (Jewett et al., 1999) with enough exposure to reduce or eliminate amphipod population (Kingston et al., 1995). The existing PHc concentrations may not have allowed the re-colonisation of amphipods at M1 as juveniles are more oil-sensitive. The threshold effects concentration for various species and different hydrocarbons and their mixtures in water are reported to be as low as a few $\mu\text{g l}^{-1}$ (GESAMP, 1993). The persistent exposure of macrobenthos to continuous and frequent chronic sub-lethal inputs of oil in a natural environment may have resulted in a progressive decrease in amphipod abundance. Since the study area is a “high oil spill risk area”, the current assessment with polychaete/amphipod ratio provides a baseline study.

According to Snelgrove and Butman (1994), except in extreme habitats, the benthic community in the coastal zone is not controlled by one but a combination of interacting parameters as observed during our studies. CCA results revealed that sediment texture along with PHc-sediment mainly influenced the distribution of polychaete families. PHc-sediment was significantly negatively correlated with species richness just as PHc-water had an inverse relationship with species diversity and evenness. Experimental studies involving contamination of defaunated sediments with petroleum hydrocarbons have resulted in lower species numbers (Berge, 1990). Petroleum hydrocarbons derived from anthropogenic activities are toxic to benthos due to their persistence in sediments and can produce perturbations in an ecosystem by changing its abiotic conditions and affecting its biota (Rudling, 1976).

Deposit feeders in the study area were strongly associated with finer sediment and therefore higher levels of organic matter (Table 3). Omnivores displayed an affinity for sandy sediment (Table

3) as sandy substrata are known to provide a wide range of interstitial spaces that provide space for the search and capture of potential prey for omnivore families such as Syllidae and Eunicidae (Del-Pilar-Ruso et al., 2009). Omnivores were the second dominant group after the deposit feeders at Vadinar and Sikka stations. Pagliosa (2005) proposed that omnivorous species had a much wider range of feeding opportunities compared to filter feeders and surface deposit feeders and were better able to respond to changes in their environment. This probably explains their widespread distribution in the area. Filter-feeders were inclined towards sandy substrata (Table 3) as has been observed by others (Maurer and Vargas, 1984; Mair et al., 2009). Thus it is apparent that the sediment composition had a major role in determining the polychaete community composition in these protected coastal waters of southern GoK. The role of sediment in shaping macrobenthic community composition has been emphasized in many studies (Chou et al., 2004; Díaz-Castaneda and Harris, 2004; Pagliosa, 2005; Ganesh and Raman, 2007). Mair et al. (2009) consider assessing sediment nature and associated communities integral to formulating management plans of a MPA intended to protect all habitat/community categories, other than reef habitats. The presence of thirty-three major taxonomic groups and twenty-nine polychaete families (Appendix 1) in the three zones of the MNPS highlights the existing macrobenthic diversity in the area, which is a resultant of the myriad micro-habitats generated by heterogeneous sediments.

5. Conclusion

The present investigation provides evidence that although pockets of higher stress to benthic fauna can occasionally occur, the impact of industrial activity on macrobenthic communities in this diverse but sensitive ecosystem in the protected waters of the coralline southern GoK is probably low. A study of this scale and level of detail is rare for this biogeographic region and provides a valuable, comprehensive appreciation of the resident benthos. Management measures for MPAs require integration of invaluable baseline biodiversity data with contemporary ecological conditions to facilitate managers in creating effective tools capable of predicting changes and impacts on particular communities as well as conserving natural habitats. Thus it is expected that the information provided by this study would help in site-specific conservation and management plans of the MNPS. The danger due to oil spills from the multiple oil production and transport installations to the MNPS is a possibility. Therefore the results obtained provide a quality background data for environmental assessment in the event of any major anthropogenic disturbance, given the rapid pace of industrialisation in this sensitive zone.

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Table 1 Details of sampling locations in the study area

Study area	Station	Description	Depth (m)
Mithapur Okha	M1	Discharge point of industrial effluent	4
	M2	2 km from discharge point	5
	M3	Mithapur bay	12.5
	M4	6 km from discharge point	4
	M5	Fisheries jetty	3
	M6	Between Bet Dwarka jetty and Mithapur jetty	7
	M7	2.5 km from Okha port	13
Vadinar	V1	Jetty	11
	V2	Oil terminal	27
	V3	Ship traffic route between Narara and Kalubhar reef	17
	V4	Narara reef	16
	V5	Discharge point of industrial effluent	27
	V6	Single Point Mooring (SPM)	16.5
	V7	Single Point Mooring (SPM)	30.5
	V8	Single Point Mooring (SPM)	41
	V9	Gulf	35
	V10	West of Kalubhar reef	22
	V11	South of Kalubhar reef	14.5
Sikka	S1	Landfall point of SPM pipeline	1.5
	S2	Singach creek	14.5
	S3	Fertilizer jetty	10
	S4	Between Goose and Sikka reef	6.5
	S5	Ro-Ro Jetty	12
	S6	Oil terminal near Sikka reef	33
	S7	Discharge point of industrial effluent	18
	S8	Between Goose and Narara reef	15
	S9	Pipeline route	14
	S10	Pipeline route	15
	S11	Single Point Mooring (SPM)	19
	S12	Single Point Mooring (SPM)	33

Table 2 Comparison of abiotic and biotic variables (mean±SD) between three sites. Parameters significantly different as per ANOVA are indicated with asterisk.

Parameter	Mithapur-Okha	Vadinar	Sikka
Temperature (°C)***	27.5±1.6	29.8±0.4	30.3±0.7
pH***	7.9±0.1	7.8±0.04	7.8±0.1
SS (mg l ⁻¹)	29.1±11.0	43.0±22.3	32.4±21.9
Salinity (‰)***	36.9±0.7	38.1±0.6	36.9±0.8
DO (mg l ⁻¹)*	6.6±0.3	6.3±0.4	6.8±0.4
NO ₃ ⁻ -N (μmol l ⁻¹)*	0.7±0.5	4.5±4.7	1.4±0.5
NH ₄ ⁺ -N (μmol l ⁻¹)***	0.3±0.2	1.0±0.3	0.8±0.3
PHc-water (μg l ⁻¹)	8.5±3.6	9.4±3.6	12.6±14.2
Sand (%)*	79.6±19.3	49.8±33.7	33.1±34.0
Silt (%)*	16.3±17.5	44.0±32.7	59.1±34.0
Clay (%)*	4.3±1.9	6.4±1.9	7.8±1.0
C _{org} (%)	0.6±0.2	0.8±0.3	0.7±0.3
PHc (μg g ⁻¹)*	1.6±1.5	0.7±0.5	0.4±0.5
Depth***	6.9±4.2	23.4±9.5	16±9.3
Macrobenthic groups*	11±4	9±3	13±2
Macrobenthic abundance (ind.m ⁻²)	2103±1526	1813±1916	1604±947
H' (log ₂)	2.7±0.6	2.9±0.4	2.6±0.7
J' *	0.9±0.1	0.9±0.1	0.8±0.1
D	1.4±0.5	1.7±0.4	1.8±0.6
Carnivores	114±133	53±32	54±37
Deposit feeders	269±242	345±413	404±524
Deposit feeders & Omnivores	67±49	66±77	34±20
Omnivores	301±360	119±154	154±199
Filter feeders	26±29	18±31	6±11

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3 Pairwise Pearson correlation between polychaete families (%), macrobenthic groups (%), feeding guilds (%), univariate indices and environmental variables. N=30

	Sand	Silt	Clay	C _{org}	PHc-sed	Temp	pH	SS	Sal	DO	NO ₃ ⁻ -N	NH ₄ ⁺ -N	PHc-wat	Depth
Arabellidae			-.43*			-4.6**	.47**							
Capitellidae													.43*	
Cossuridae	-.48**	.48**		.40*				.54**						
Dorvilleidae										-.62***	.54**			
Magelonidae				-.40*										
Nereidae					.40*									
Onuphidae	-.39*	.38*												
Orbiniidae												-.38*		
Phyllodocidae												.43*		.41*
Pilargidae	-.63***	.63***	.42*	.41*										
Polynoidae						-.41*								
Sabellidae	.37*	-.36*	-.41*											
Sigalionidae						-.37*		.38*						
Spionidae									.40*					
Syllidae	.72***	-.72***	-.52**	-.73***								-.36*		
Terebellidae	-.53**	.52**	.49**											
Polychaetes													.40*	
Amphipods	.49**	-.5**		-.62***									-.52**	
Filter feeders	.37*	-.36*	-.41*											
Deposit feeders			.58***	.47**										
Carnivores													-.49**	
Omnivores	.42**	-.40*	-.40*	-.50**	.44**									
Deposit feeders & omnivores										-.36*				
J'									.54**				-.61***	
H'													-.36*	
d					-.36*									

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Table 4 Summary of the results of CCA analysis

Environmental variables	Axis 1	Axis 2	Axis 3	Axis 4
Sand	-0.42*	-0.71***	0.26	0.01
Silt	0.40*	0.73***	-0.25	0.01
Clay	0.54**	0.21	-0.19	-0.31
C _{org}	0.53**	0.30	-0.31	-0.14
PHc sediment	-0.65***	0.07	-0.10	-0.31
SS	-0.10	0.45*	-0.07	-0.04
Salinity	-0.05	0.08	0.45*	-0.50**
DO	-0.02	0.38*	0.17	-0.27
NH ₄ ⁺ -N	0.43*	0.12	-0.08	0.17
PHc water	0.20	-0.22	-0.65***	0.15
Eigenvalues	0.30	0.25	0.19	0.14
Species-environment correlations	0.88	0.94	0.90	0.92
Cumulative percentage variance				
of species data	15.3	28.5	38.3	45.7
of species-environment relation	25.7	47.9	64.3	76.8

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$

Fig.1

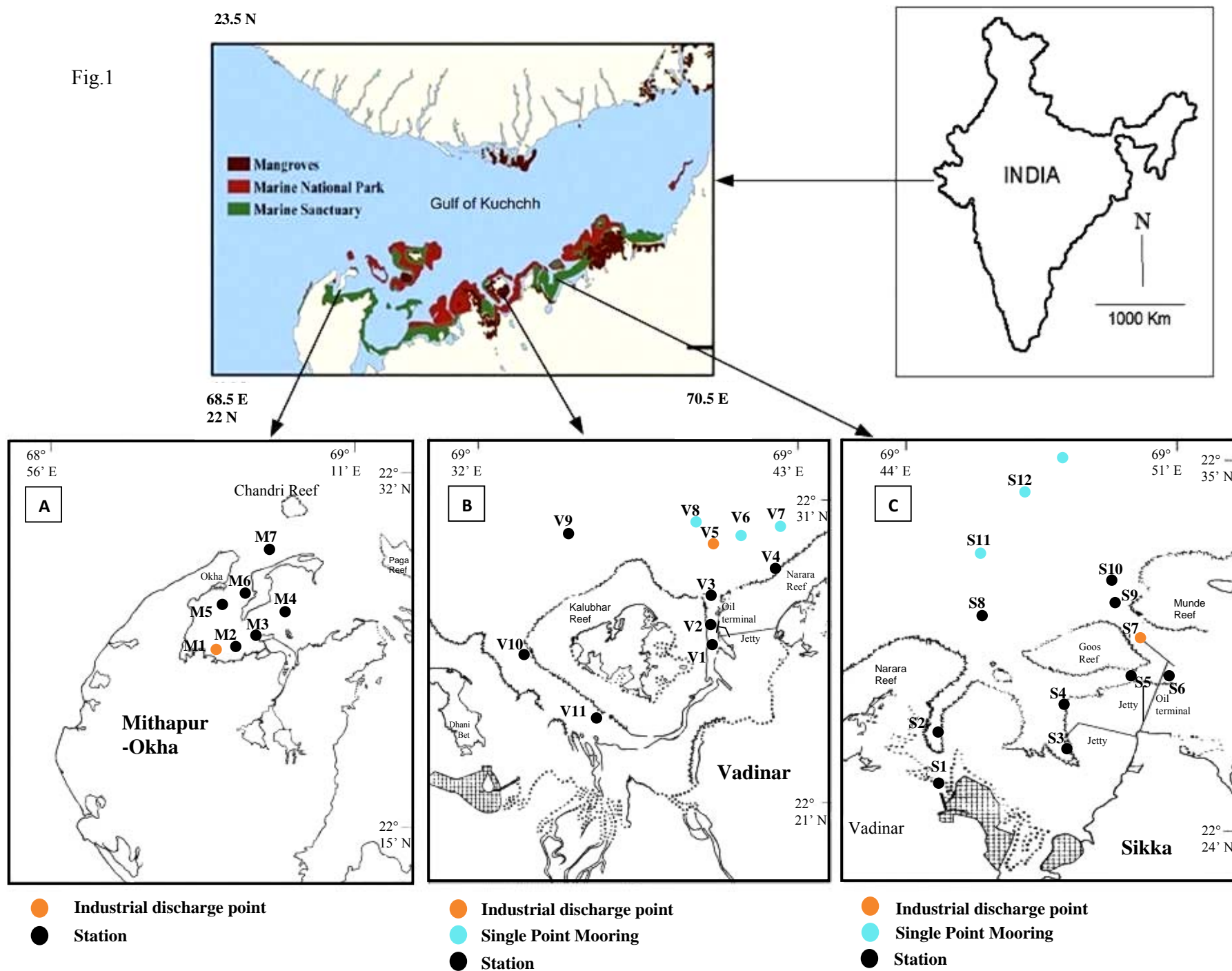
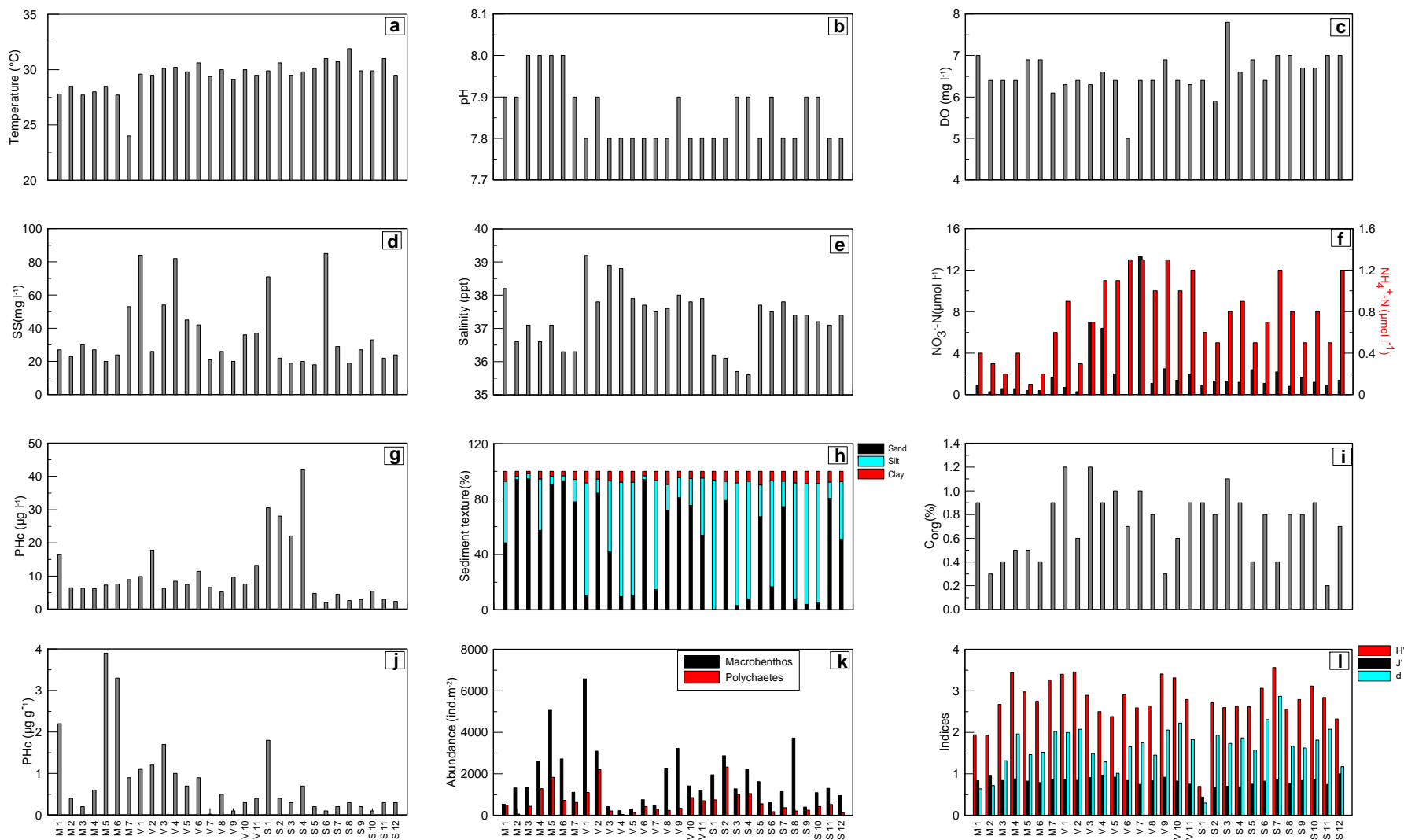


Fig.2



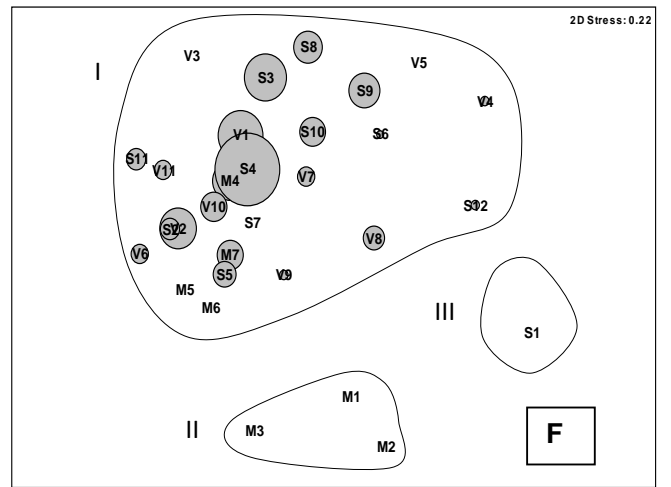
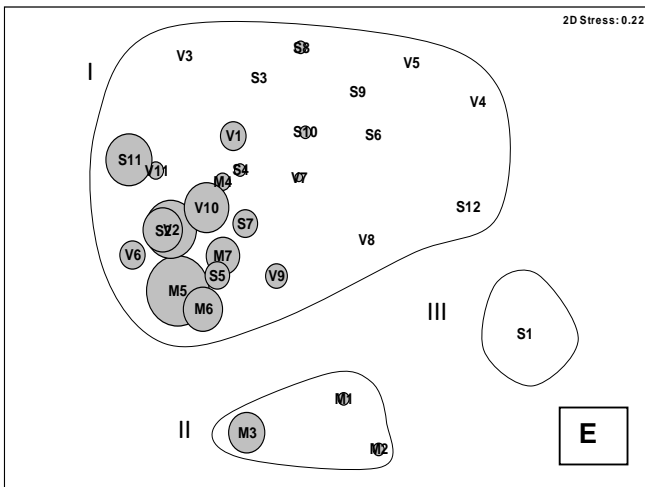
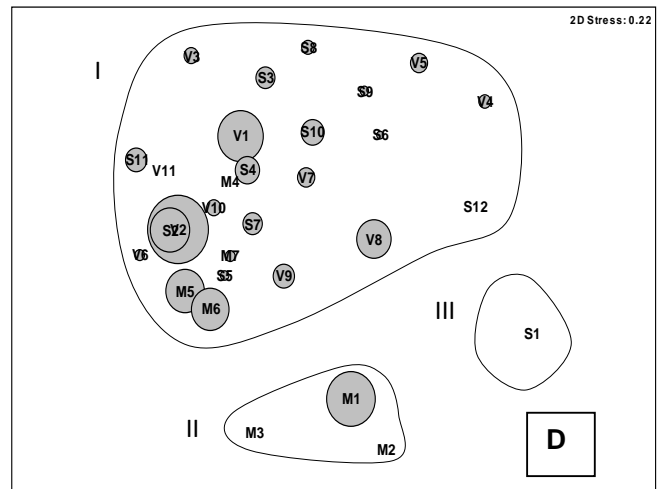
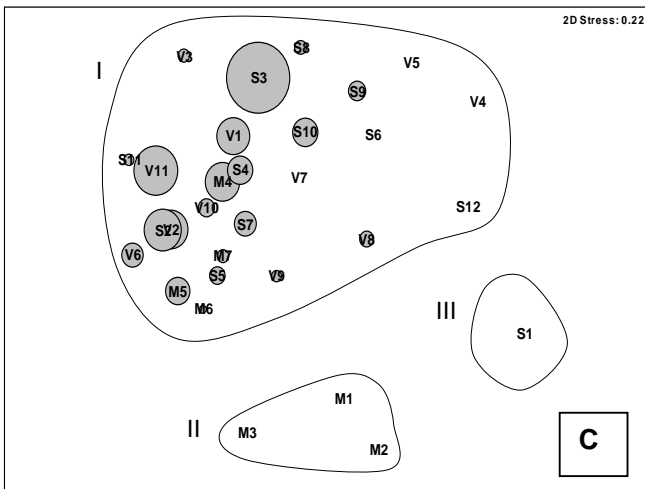
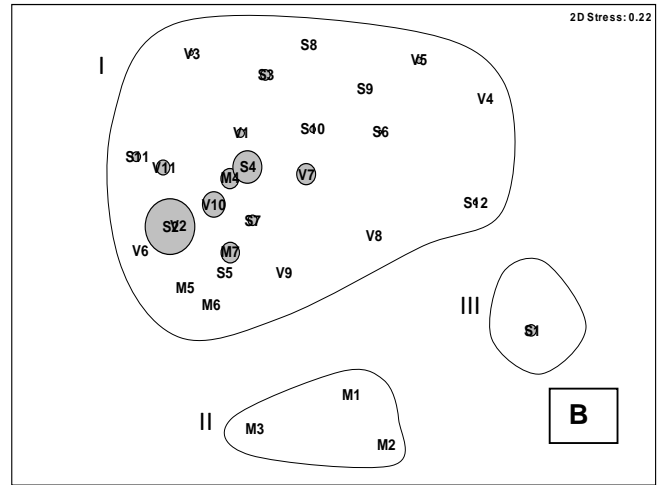
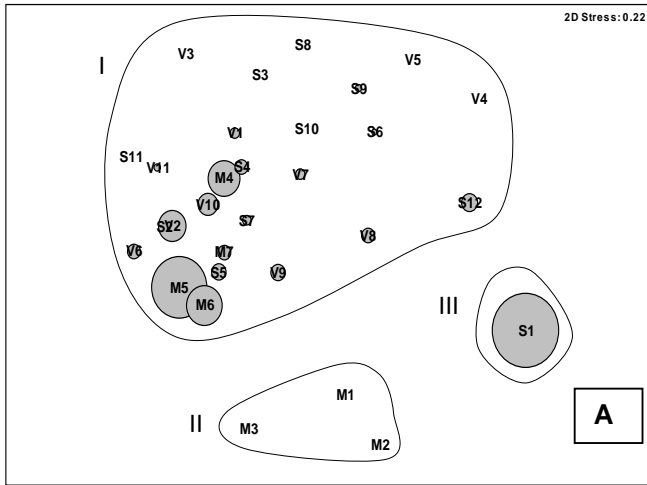


Fig.3

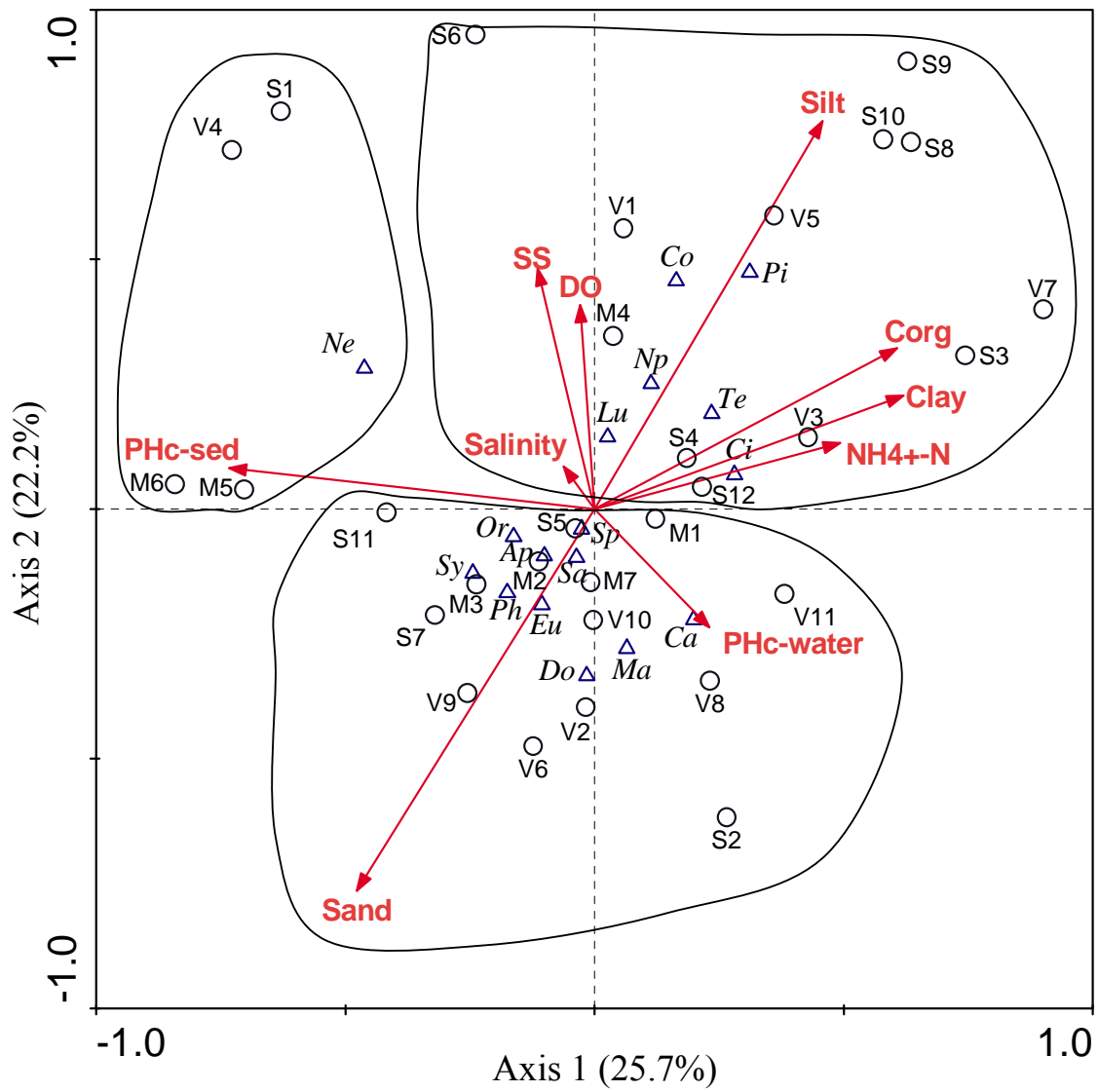


Fig.4

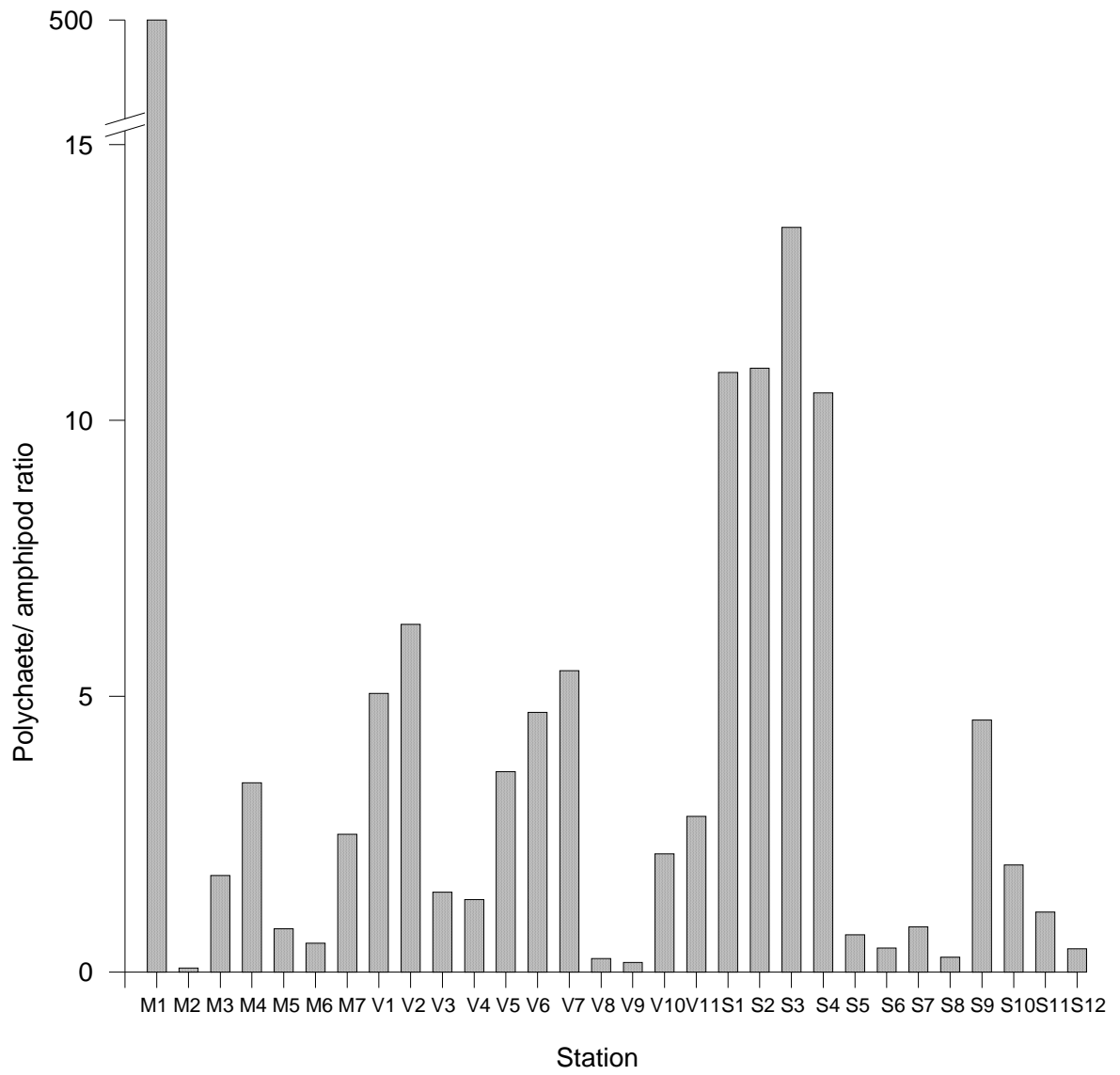


Fig.5

Figure Legends

Fig 1 Sampling stations at three locations (A) Mithapur-Okha, (B) Vadinar (C) Sikka in the Gulf of Kachchh.

Fig 2 Hydro-sedimentological and benthic parameters at Mithapur-Okha, Vadinar and Sikka during April 2010. Water temperature (a), pH (b), DO (c), SS (d), salinity (e), NO_3^- -N and NH_4^+ -N (f), PHc-water (g), sediment texture (h), C_{org} (i), PHc-sediment (j), macrobenthic and polychaete abundances (k) and diversity statistics (l).

Fig 3 Non-metric multidimensional scaling ordination of fourth root transformed polychaete data using Bray-Curtis similarities of Mithapur-Okha (M1-M7), Vadinar (V1-V11) and Sikka (S1-S12) with abundances of Nereidae (A), Capitellidae (B), Cirratulidae (C), Spionidae (D), Syllidae (E) and Terebellidae (F) superimposed as bubbles.

Fig 4 Canonical correspondence analysis (CCA) ordination plots of 17 polychaete families, 30 stations and 10 environmental variables. Δ : Polychaete families; o: stations; \rightarrow : environmental variables; Ap: Aphroditidae; Ca: Capitellidae; Ci: Cirratulidae; Co: Cossuridae; Do: Dorvilleidae; Eu: Eunicidae; Lu: Lumbrineridae; Ma: Maldanidae; Np: Nephtyidae; Ne: Nereidae; Or: Orbiniidae; Ph: Phyllodocidae; Pi: Pilargidae; Sa: Sabellidae; Sp: Spionidae; Sy: Syllidae; Te: Terebellidae.

Fig 5 Polychaete/amphipod ratio for the study area.

<i>Sigalionidae</i>	0	0	0	0	0	0	0	0	4±10	4±9	0	0	0	0	0
<i>Spionidae</i>	38±43	17±29	0	0	131±155	31±24	50±71	6±13	4±10	32±54	13±14	6±13	44±24	38±32	0
<i>Sternaspidae</i>	0	0	0	0	0	0	0	0	0	0	0	6±13	0	0	0
<i>Syllidae</i>	50±84	209±236	25±35	0	163±123	0	13±25	63±109	0	64±124	13±14	0	13±25	225±123	0
<i>Terebellidae</i>	6±13	58±101	25±24	0	31±38	150±117	356±370	44±59	4±10	0	69±38	81±75	56±66	31±13	6±13
Oligochaeta	0	0	0	281±563	0	0	0	13±25	0	19±38	13±25	0	0	13±25	0
Sipuncula	0	0	6±13	6±13	6±13	6±13	31±38	0	0	0	0	0	0	0	0
Echiura	0	0	0	0	0	0	6±13	0	0	0	0	0	0	0	0
Pycnogonida	0	0	0	0	6±13	0	13±25	0	0	0	13±14	0	0	6±13	6±13
Insecta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decapod larvae	0	25±0	13±25	0	0	38±60	6±13	0	6±13	69±107	6±13	0	44±88	0	0
Ostracoda	63±60	17±29	0	0	13±14	0	13±25	19±24	0	13±14	13±25	0	0	0	6±13
Copepoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cumacea	0	0	0	0	13±14	6±13	19±38	0	0	19±24	13±25	6±13	19±24	6±13	6±13
Tanaidacea	0	0	25±29	256±480	0	0	25±20	19±24	69±85	16±19	100±106	13±25	13±25	0	13±14
Isopoda	0	0	0	6±13	19±24	6±13	0	0	88±142	13±14	0	0	6±13	0	0
Amphipoda	1950±2144	400±434	250±170	69±55	213±103	75±54	100±137	838±723	132±72	457±399	806±625	56±32	219±126	481±313	281±207
Mysidacea	0	0	0	0	0	0	0	0	0	13±25	0	0	0	0	0
Sergestidae	0	0	0	0	0	0	0	0	0	0	0	6±13	19±38	0	0
Penaeidae	0	0	0	0	31±38	25±50	0	88±142	13±14	16±19	6±13	6±13	6±13	13±25	0
Brachyura	19±38	42±72	0	431±165	31±24	6±13	0	25±35	0	13±14	6±13	0	6±13	13±14	0
Anomura	0	0	0	0	6±13	0	0	0	0	0	0	0	0	0	0
Crinoidea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Holothuroidea	0	8	0	0	0	0	19±38	6±13	0	0	0	0	0	0	0
Asteroidea	0	0	0	0	0	0	0	0	0	6±13	0	0	0	0	0
Ophiuroidea	69±121	42±72	6±13	0	38±43	0	13±25	6±13	0	13±14	6±13	0	0	25±35	6±13
Invertebrate egg mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ascidacea	0	0	0	0	0	0	0	0	0	0	0	0	0	156±280	0
Fish Larvae	0	0	6±13	0	0	0	0	6±13	0	0	0	0	6±13	0	0