

Assessment of ecosystem health status using benthic diversity as tools in coastal sediment off the southwest coast, India

DB Arya

University of Kerala

PS Godson

Manonmaniam Sundaranar University

P Selvaraj

Sri Kaliswari College

S Krishnakumar

University of Madras

NS Magesh

Ministry of Earth Sciences

Salom Gnana Thanga Vincent (✉ salom@keralauniversity.ac.in)

University of Kerala

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Abstract

The diversity of macro and meiobenthos was documented in order to assess the ecosystem health of an anthropogenically impacted coastal ecosystem for the first time along the southwest coast of Tamil Nadu. Offshore sediment and water samples (n=63) were collected from 14 sampling stations using the grid sampling method. Water and sediment samples were analysed for environmental variables such as pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), salinity, sulphate, dissolved oxygen (DO), carbohydrate (CHO), protein, lipid, labile organic matter (LOM), total organic carbon (C_{org}), total organic matter (TOM) and sediment texture using standard methods. Benthic macro and meiobenthos were isolated and identified using standard identification keys. A total of 5 phyla of macrobenthos with 29 species and 5 phyla of benthos with 60 species were identified in the study area. Relative abundance analysis showed that the largest numbers of species belonged to polychaeta for macrobenthos and foraminifera for meiobenthos. Redundancy analysis indicated that sediment carbohydrate content was the highest determining factor for explaining variation in the diversity of benthos. AMBI & M-AMBI results revealed that among the 14 stations, 2 were categorized as “poor” and 9 as “bad”. Multiple anthropogenic activities in the coastal environment leading to increased organic matter input, have resulted in a decline in the ecosystem health of this region which warrants for site-specific management to control organic pollution.

Introduction

Marine and coastal systems are highly diverse with respect to genetic, economic, taxonomical, and ecological aspects (Atkins et al. 2011). They are dynamic due to the continuous interaction between land and oceans (Muniz et al. 2011). Coastal ecosystems are the most productive (Poore and Wilson 1993), and globally they are important ecosystems with regard to climate regulation, nutrient balance, and primary productivity (Falkowski et al. 1998). Two-thirds of the global ecosystem services are from the oceans (Costanza et al. 2014). Biologically, oceans are important areas of the biosphere with major roles in the biogeochemical cycling of nutrients (Gattuso et al. 1998). In coastal sediments, organic matter accumulation is one of the significant ecological processes (Kelly and Nixon 1984; Giblin et al. 1997). Increased nutrient concentration as a result of anthropogenic activities such as shipping, fishing, aquaculture, raw sewage disposal (Korpinen et al. 2012; Micheli et al. 2013; Taşkın et al. 2020) lead to high primary production and organic enrichment in the sediment (Villnäs and Norkko 2011).

For the conservation and management of marine habitats, it is very important to evaluate the ecosystem health (Dai et al. 2013; D’Alessandro et al. 2020). It mainly depends upon the structure and function of inhabitant organisms which includes their physiology, metabolism and interactions in the environment (Tett et al. 2013). The bottom sediments of coastal ecosystem are considered as sinks of contaminants that affects the benthic communities (Tamburrino et al. 2019). Due to their ability to resist or adapt against these contaminants, benthic communities can be considered as good indicators of various environmental pressure (Kim et al. 2019). Benthic study is very important and can be used as baseline data for investigating the environmental health of the habitat (Varadharajan et al. 2010). Different types of ecological health tools and methods were developed by following the chapter 40 of Agenda 21 of United Nations Conference on Environment and Development (UNCED) which highlights the importance of sustainable use of coastal ecosystem (Albayrak et al. 2006). The use of multiple tools and methods are well suited for ecosystem health assessment rather than using single indicator (Magni et al. 2000). Benthic indices are very relevant for efficient management owing to their ability to act as site-specific indicators of benthic habitats (Teixeira et al. 2012). Various biotic indices like AMBI (Borja et al. 2000), M-AMBI (Muxika et al. 2007) were validated and calibrated for assessing environmental health (Jayachandran et al. 2022). These indices help to summarize the state of an ecosystem which includes environmental and biological conditions to a numerical term, which can easily be used for decision making (Borja and Tunberg 2011). Having understood the various anthropogenic pressures in the coastal belt along the Southwest (SW) coast of Tamil Nadu (Godson et al. 2018), this study has been done for the first time to evaluate the ecosystem health of southwest coast of India using benthic invertebrates as bioindicators.

Materials And Methods

Study area

The study was done in the Arabian Sea along the SW coast of Tamil Nadu, India (Fig.1), located between latitudes (N) 8°13'33.55" - 8°03'45.78" and longitudes (E) 77°10'14.98" -77°32'55.51" over a distance of about 60km from Thengapattinam to Kanyakumari. The southwest coast is heavily populated (1111/km²) and is influenced by the discharge of a large amount of sewage from AVM (Andaman Victoria Marthandavarman) canal (Anitha and Kumar 2013). Some of the anthropogenic activities visible in the study area are coir retting, tourism, placer mining, shell bleaching by small scale industries, mixing of sewage effluent, anti-biofouling paint spills, spreading of oil spills, etc. (Chandrasekar et al. 2007; Nandakumari et al. 2014). The rivers (Tamirabarani, Pazhayar, and Pannayar) drain into the Arabian Sea, and the study area also comprises three estuaries (Thengapattinam, Manakudi, and Rajakkamangalam).

Sample collection and preparation

Sixty-three offshore bottom sediment and water samples were collected from 14 stations (3-5 replicates per station), approximately 1.5km offshore, using grid sampling pattern from the study area during March 2017. Van Veen grab and Niskin bottom water samplers were used to collect the marine sediment and bottom seawater samples from the study area, respectively. Environmental variables water (pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), salinity, sulphate, dissolved oxygen (DO)) and sediment (pH, temperature, electrical conductivity (EC), sulphate, dissolved oxygen (DO), carbohydrate (CHO), protein, lipid, labile organic matter (LOM), total organic carbon (C_{org}), total organic matter (TOM) and sediment texture) were analysed using standard methods (Lowry et al. 1951; Dubois et al. 1956; Trivedy et al. 1998; Grasshoff et al. 1999; Parsons et al. 1974). For analysis of benthic macro and meiobenthos diversity, rose bengal stain (1g/L) was added to the sediment samples *on site*, and the samples were preserved following a standard protocol (Sommerfield and Warwick 1996). Before identification, the contents previously kept in polythene bags were emptied into sieves of three different mesh sizes (0.5 mm, 230 µm and 63 µm) and directly washed in running tap water until the stain was removed entirely. From the samples, benthic macro and meiobenthos were isolated

and identified by viewing under a stereomicroscope (Thilagavathi et al. 2013) using standard taxonomic identification keys (Fauvel 1953; Day 1968; Platt and Warwick 1988; Giere 2008).

Diversity indices

Various biodiversity indices (Shannon-Weiner diversity, Margalef's species richness, Pielou's evenness and Simpson dominance index) were used to analyze biodiversity of benthic organism along the southwest coast of Tamil Nadu.

Shannon- weiner diversity, $H = \pi * \ln(\pi)$

Where, \ln =Natural log ; π =The proportion of the entire community made up of species i

Margalef's species richness, $d = (S-1)/\text{Log}(N)$

Where, N = total number of individuals; S = total number of species.

Pielou's evenness index, $J' = H'/\text{Log}(S)$.

Where, H' =Shannon-Wiener Diversity Index; $\text{Log } S$ =maximum possible value of Shannon index.

Simpson dominance index, $D = \sum ni(ni-1)/N(N-1)$

Where, ni = The number of organisms that belong to species i; N = The total number of organisms

Environmental health analysis

The BIOENV and Biotic indices (AZTI's Marine Biotic Index (AMBI), Multivariate- AMBI (M-AMBI) were used in this study to measure the ecosystem health assessment (Table 1 &2).

Statistical analysis

The spatial variation of environmental variables among stations was analyzed by ANOVA. Redundancy Analysis (RDA) was done to examine the relationship between environmental parameters and benthic diversity. The above-mentioned univariate and multivariate analyses were performed using software packages such as PRIMER software (Plymouth Routines In Multivariate Ecological Research Ver. 6), SPSS 20.0, and RStudio (Clarke et al. 2001; Campelo et al. 2018). Spatial map was prepared using Arc GIS software

Results

Changes in environmental variables of sediment

The sediment temperature values remained homogenous throughout the study area (Table 3) and the spatial difference was statistically insignificant (Table S1). Electrical conductivity of sediment samples varied from 2085.50 to 5246.40 μs . Slightly alkaline pH was observed along the study area and the spatial variation was statistically significant. Sulphate concentration ranged from 7.05 to 24.09 mg/g. C_{org} and TOM were in the range of 0.28 to 2.29% and 0.48 to 3.95%, respectively. The labile part of organic matter ranged from 0.06 to 0.12% and comprised of CHO (1.12 – 2.87mg/g), protein (2.13 – 6.76mg/g) and lipid (1.98 – 5.3mg/g). The environmental variables such as pH, sulphate, EC, CHO, protein, lipid, LOM, C_{org} , TOM, LOM (% of TOM), sand, silt and clay showed a significant spatial variation ($p < 0.001$) (Table S1). The granulometric analysis of the sediment samples revealed the predominance of sand (Fig. 2).

Changes in environmental variables of overlying water

Similar to sediment temperature, the seawater temperature also remained homogeneous and spatial variation were insignificant (Table 4). pH values ranged from 7.35 to 9.42, salinity from 25.43 to 28 PSU and EC values ranged between 39390- 43196 $\mu\text{s}/\text{cm}$. TDS ranged from 25.09 to 28.06ppm. Along the study area, DO ranged from 1.22mg/L to 6.12mg/L (Fig. 3). The environmental variables such as EC, salinity, sulphate and water depth showed significant spatial variations ($p < 0.001$) (Table S2).

Faunal composition and diversity indices of macro and meiobenthic communities

A total of 319 macrobenthic organisms were isolated, which belonged to 27 species of 5 phyla, including polychaeta, oligochaeta, amphipoda, decapoda, and gastropoda in the offshore sediments of the study area, along the SW coast of Tamil Nadu (Table S3). The relative abundance of macrobenthos (Fig. 4) was represented by polychaeta (76.41%) as dominant taxa followed by gastropoda (21.69%). In the case of polychaeta, *Pisionidens sp.* was abundant, followed by *Polygordius sp.* and *Arabella sp.* *Pyramidellidea sp.* was the predominant taxa in Gastropoda followed by *Physidea*, *Turritellidae*, and *Cerithideae*. Most of the diversity indices showed significant correlation with TOM and C_{org} content. The maximum Shannon-Weiner diversity index value was 0.8 (S23-Manavalakurichi-MK), whereas species richness, species evenness index and Simpson index were 1.44, 1.0 and 0.67 respectively (Table S4).

A total of 2525 benthic meiobenthos were isolated which belonged to 60 species and 5 phyla including foraminifera, polychaeta, nematoda and amphipoda (Table S5). Relative abundance of meiobenthos (Fig.4) showed foraminifera (86.85%) as dominating taxa followed by polychaeta (11.08%). In polychaeta, dominant species was *Polygordius sp.* followed by *Pisionidens sp.* In nematoda, predominant species was *Daptonema sp.* In the phylum foraminifera, the

most abundant was *Elphidium sp.* followed by *Quinqueloculina sp.* and *Ammonia sp.* The Shannon-Weiner diversity index was 0.94 (S25-Kadiapattinam-KP), whereas, species richness, species evenness index and Simpson index were 0.87, 1.0 and 0.58 respectively (Table S6).

Effect of environmental variables on benthic diversity

Redundancy analysis (Fig. 4) showed that CHO, a part of the TOM, was the highest determining factor for explaining most variation in the composition of the macrobenthos of all the 63 sampling sites, followed by temperature and protein concentration. The relative abundance of gastropods and amphipods increased with CHO concentration, whereas that of polychaetes increased with the increase of LOM (% of TOM), which indicates the affinity of polychaetes to LOM. Decapoda and oligochaeta showed an increasing trend with increasing protein concentration. Similar to macrobenthos, RDA showed that CHO, a part of the TOM followed by salinity was the highest determining factor for explaining most variation in the composition of the meiobenthos of the 63 sampling sites (Fig. 5). The relative abundance of polychaeta and foraminifera increased with CHO concentration.

Ecological health analysis

BIOENV Analysis

A total of 22 environmental variables were used as the input parameters for BIOENV analysis (Table 5). The results clearly shows that the combination of five variables such as pH, LOM (%), TOM (%), clay% (sediment) and EC (water) explained the best match ($\rho = 0.899$) influencing the benthic distribution in the study area.

AZTI Marine Biotic Index (AMBI) and Multivariate-AZTI Marine Biotic Index (M-AMBI)

Percentage composition of various ecological groups (EG) of polychaete species were recorded at various stations in the study (Table 6). A total of 14 polychaete species were identified in all the sampling stations. Among the 14 polychaete species, 2 species (20%) were assigned in EG-I, 3 species (30%) in EG-II, 4 species (40%) in EG-III, and only one species (10%) in EG-V. The remaining 3 species were not assigned in any ecological groups available in the AMBI classification. Moreover, there were no polychaete species under the group of EG-IV (Fig. 7). The AMBI index values of the stations TP, IN, MI, MU, PT, RT, ST, PA and KK showed very high (7) value, which highlights the anthropogenic disturbances in this area. Pollution tolerant polychaete species (EG-III) *Myrianida sp.*, *Eunice sp.* and *Syllids sp.* and EG-II species (species unaffected by pollution) such as *Polygordius sp.* and *Pisione sp.* were observed in the study area (Fig. 8).

The low value of M-AMBI index (0.015) indicates that the stations TP, IN, MI, MU, PT, RT, ST, PA and KK had a “bad” ecological status revealing the anthropogenic disturbance. The M-AMBI values (0.35-0.366) of the stations (MA and KO) clearly illustrated the poor ecological status with slightly increased diversity value (0.211-0.337) and richness value (0.2). The station CO had the M-AMBI value of 0.447 which shows the “moderate” ecological status with the diversity value of 0.961. The “good” M-AMBI values (0.876-0.931) recorded in the stations MK and KA indicates the “high” ecological status with increased diversity (2.56 to 2.82) and richness (0.7-0.8). The AMBI index value (1.05-1.89) of the stations MK and KA indicates the undisturbed and slightly disturbed environmental condition which also shows the presence of pollution-sensitive species (*Polygordius sp.* and *Pisione sp.*) and other ecological groups of species (Fig. 9). The AMBI value of other three stations CO, MA and KO was “0” which demonstrates the undisturbed condition and the presence of pollution sensitive species in this area.

Discussion

Southwest coast of Tamil Nadu is critically subjected to various anthropogenic pressures and the ecosystem-based management requires the combined use of multiple tools which includes physicochemical parameters, biological parameters and biotic indices (Mangano et al. 2017). The DO concentration was observed to be low particularly, towards the southern part of the study area. In most of the cases oxygen depletion is directly influenced by anthropogenic activities (Diaz and Rosenberg 1995) specifically, due to non-point sources like untreated sewage and agricultural runoff as well as point sources like mixing of coir retting liquor (Nandan 1997), shipping and oil discharge (Chatzinikolaou et al. 2018) in the study area. The study area also comprises a shipping harbour Muttom (MU) and the busiest beach tourist destination Kanyakumari (KK) in India, responsible for increased anthropogenic pressures in coastal environment. The hypoxic condition in the sediment can induce a stress on the benthic organisms (Tyson and Pearson 1991), which may affect their abundance and diversity. Except temperature, most of the environmental variables showed spatial variation among stations ($p < .001$).

The maximum biodiversity index was 1.44 for macrobenthos and 1.17 for meiobenthos in the study area. Kumar and Khan (2013) earlier reported that the benthic diversity ranged from 1.80 to 2.83 in Pondichery mangrove. Similarly, Reizopoulou and Nicolaidou (2004) reported a benthic diversity that ranged from 0.8 to 3.0 in Rodia lagoon, Greece. Various anthropogenic activities like coir retting, raw sewage disposal, placer mining wastes, anti-biofouling paint spills, harbour effluent mixing, agricultural runoff, shell bleaching by small scale industries and tourism activities have previously been reported along the SW coast of Tamil Nadu (Godson et al. 2018). Such activities have led to high organic matter pollution, thus developing hypoxic conditions even in the shallow sediments, which may be anthropogenically induced (Diaz and Rosenberg 1995; Levin 2003). For example, a large amount of organic matter accumulation occurs in the coastal sediments as a result of coir retting (Nandan and Azis 1995) that results in oxygen depletion. Meiobenthos showed high diversity than macrobenthos, which is attributed to the presence of more tolerant groups of meiobenthos than macrobenthos (Giere 1993). Benthic communities show high abundance than diversity, which is attributed to their preference for high organic matter content in the sediments (Levin and Gage 1998). However, the diversity of benthic invertebrate increases with the increase of organic input to a moderate level and then shows a decreasing trend with a large amount of organic input (Rosenzweig and Abramsky 1993; Rosenzweig 1995).

In south west coast of Tamil Nadu, polychaetes were dominant among macrobenthic assemblages. Previous studies by Yucel-Gier et al., (2007) (Yucel-Gier et al. 2007) also suggested polychaetes as dominant phyla in Eastern Aegean, Turkey. In both marine and estuarine sediments of the South Tamil Nadu coast, polychaetes were the dominant phyla among macrobenthos (Prabakaran et al. 2019). Polychaetes are opportunistic species in polluted areas (Pearson

1978) and are more tolerant to low oxygen and organic enrichment than molluscs and crustaceans (Levin and Gage 1998), which explains the prevalence of polychaetes in the study area. Nandan 1991 has observed polychaetes as the dominant organism in the coconut husk retting zones of Cochin backwaters, where the oxygen level reduces due to high organic matter content released during retting of coconut husk. However, Latha and Vincent 2010 have reported a higher incidence of gastropoda and insects in the retting zone of Kadinamkulam lake in South Kerala.

Organic matter retaining capacity of sandy sediment is less (Jeshma et al. 2017) and can influence the abundance of benthos (Yucel-Gier et al. 2007). The C_{org} content may depend on the sediment particle size (Milliman 1994; Arya et al. 2022). In the study area, the sediment was predominantly sandy in most of the stations (Fig. 2). The sand percentage varied between 53.08% and 87.82% and the maximum value was in S63 (Kanyakumari); whereas, silt and clay percentages varied between 0.63 and 19.56% and 1.09 and 41.38%, respectively. Previous researches have suggested that sediment grain size can influence the spatial distribution of benthos (Galope-Bacaltos 2002; Kim et al. 2020). Most of the organisms may be present in sandy sediment than muddy sediment due to the interstitial space (Coull 1999). C_{org} and TOM content of sandy sediment were low which may be due to the low retaining capacity of sandy sediment (Ansari et al. 2012).

The abundance of benthic organisms is directly related to the amount of food available in the sediment (Sibuet et al. 1984; Rodil et al. 2008). The flow of food for benthic organisms can be reduced due to organic matter degradation (Portnova and Polukhin 2018) and may lead to oxygen depletion (Kon et al. 2015); this may affect benthic diversity. Organic matter can influence the structure and function of benthic communities (Rex et al. 1997; Bianchelli et al. 2020) and act as an important parameter for determining polychaete diversity (Levin and Gage 1998). The varying content of organic matter can influence the abundance and diversity of benthos (Gooday and Turley 1990; Snelgrove and Butman 1995). Moreover, benthic foraminifera can also dominate in low oxygen conditions, which support less diversity with high abundance, because the respiratory oxygen demand of benthic foraminifera is less. This explains their ability to survive in such conditions (Gupta and Machain-Castillo 1993) and also adapt to marine salinity levels (Kasilingam et al. 2019)

Application of site-specific multi-indices helps to best describe the ecological status of coastal ecosystems based on the pollution load as well as the benthic diversity (Ryu et al. 2016). The AMBI and M-AMBI indices developed by European Water Framework Directive (WFD) provided insights in the ecological health status (Selvaraj et al. 2019) of the 14 sampling stations in the southwest coast of Tamil Nadu. Based on these indices, the stations were clustered into various ecological groups (EG I to EGV) revealing their ecological status. Such classification also corroborated with the presence of pollution tolerant species of macro/meio benthos in the stations showing poor ecological health (EG IV& V) and pollution sensitive species in the stations with moderate to good ecological health (EG I to EGIII). Among the 14 stations, 2 were classified as "poor" and 9 as "bad". This is due to the fact that these stations were subject to multiple anthropogenic pressures such as input of coir retting effluent, tourism, placer mining deposits, disposal of sewage effluent and the prevalence of fishing harbours leading to hydrocarbon contamination along the study area (Godson et al. 2018). The predominant among these are coir retting effluents and untreated sewage rich in organic matter entering the coastal environment through streams and channels in addition to small rivers (Thamirabharani River, Pazhayar River and Pannaiyar River) that enters the coastal ecosystem through estuaries (Thengapattinam, Rajakkamangalam and Manakudi). As the decline in ecosystem health is a threat to coastal fisheries, management measures to control organic pollution input in the coastal environment should be given top priority in this region.

Conclusions

Increased input of organic matter due to anthropogenic activities like raw sewage disposal, fishing activity, tourism and coir retting in the coastal environment of Arabian Sea in Tamil Nadu have caused oxygen depletion in the sediments. This, consequently, has caused spatial changes in the structure and function of benthic organisms. Among macrobenthos, opportunistic taxa like polychaetes which are tolerant to low oxygen concentration were the dominant group. The ecosystem health analysis based on AMBI and M-AMBI indices classified the sampling stations into different ecological groups, obviously due to the presence of pollution tolerant and sensitive species in the study area. The study highlights the importance of using macro and meio benthic fauna for monitoring ecosystem health in coastal environment, which further impacts coastal productivity. Nevertheless, the results also reveal the spatial variations in benthic community assemblages under the influence of anthropogenic pressures, particularly organic pollution from coir retting and untreated sewage, which warrants site-specific management solutions to reduce organic pollution in this region.

Declarations

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Conflict of Interest : The authors have declare no conflict of interest

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Tables

Table 1 Ecological group status according to biotic indices with pollution effect (Chainho et al. 2007)

Ecological Group	Classifications
Ecological Group 1 (EG I)	Pollution sensitive species (High)
Ecological Group 2 (EG II)	Species unaffected by pollution (Good)
Ecological Group 3 (EG III)	Pollution tolerant species (Moderate)
Ecological Group 4 (EG IV)	Second-order opportunistic species (Poor)
Ecological Group 5 (EG V)	First-order opportunistic species (Bad)

Table 2 AMBI, M- AMBI scale with different pollution classification

ECOLOGICAL GROUP	AMBI	M-AMBI
Unpolluted	$0 < \text{AMBI} \leq 1.2$	$0.82 < \text{M-AMBI} \leq 1.00$
Slightly polluted	$1.2 < \text{AMBI} \leq 3.3$	$0.61 < \text{M-AMBI} \leq 0.82$
Moderately polluted	$3.3 < \text{AMBI} \leq 4.3$	$0.40 < \text{M-AMBI} \leq 0.61$
Heavily Polluted	$4.3 < \text{AMBI} \leq 5.5$	$0.20 < \text{M-AMBI} \leq 0.40$
Extremely polluted	$5.5 < \text{AMBI} \leq 6.0$	$0 < \text{M-AMBI} \leq 0.20$

Table 3. Environmental variables of sediment samples in the study area

Stations	Temp. (°C)	pH	EC (µs)	SO ₄ ²⁻ (mg/g)	Carbohydrate (mg/g)	Protein (mg/g)	Lipid (mg/g)	LOM (%)	C _{org} (%)	TOM (%)
TP	29.86±0.37	7.32±0.38	2085.50±237.96	8.06±1.31	1.12±0.82	3.74±2.81	2.21±1.43	0.07±0.03	2.29±0.64	3.95±1.1
IN	29.78±0.23	8.21±0.29	2153.00±54.16	8.28±1.04	1.82±0.75	2.13±0.96	1.98±1.24	0.06±0.02	0.36±0.23	0.62±0.3
MI	29.86±0.57	8.10±0.11	2511.00±183.49	9.49±3.28	1.81±0.96	2.46±1.77	5.32±4.07	0.10±0.04	1.72±0.87	2.97±1.4
CO	29.89±0.57	7.90±0.52	2181.00±315	7.24±0.37	2.38±0.66	2.45±0.94	3.61±1.23	0.08±0.02	1.04±0.38	1.79±0.6
MK	29.47±0.37	8.19±0.77	2445.00±700.91	7.05±1	2.67±1.24	6.76±4.92	2.68±0.83	0.12±0.06	1.40±0.97	2.42±1.6
KA	29.07±0.51	7.46±0.67	5246.40±6934	9.43±2.11	2.87±0.54	2.64±0.59	2.92±2.62	0.08±0.03	1.38±0.96	2.37±1.6
MU	29.21±0.48	8.75±0.39	2223.00±459.71	8.43±1.19	2.02±0.97	3.67±1.64	4.69±2.40	0.10±0.02	0.66±0.21	1.14±0.3
PT	29.12±0.30	8.20±0.88	2589.67±527.86	9.19±1.07	2.28±0.69	5.10±3.05	3.02±2.16	0.10±0.02	0.70±0.12	1.21±0.2
RT	30.11±1.31	8.82±0.36	3473.00±1046.92	9.16±2.17	1.94±1.19	2.69±1.34	2.36±2.41	0.07±0.01	1.11±1.34	1.91±2.3
SA	29.20±0.40	9.28±0.30	3058.00±241.73	11.87±4.23	1.83±0.62	3.93±2.19	2.99±0.48	0.09±0.02	0.67±0.20	1.15±0.3
PA	29.01±0.11	9.19±0.60	3018.00±290.80	24.09±22.55	1.84±0.64	3.99±1.89	3.86±1.65	0.10±0.02	0.66±0.25	1.14±0.4
MA	29.79±0.63	8.98±0.41	3079.00±339.31	19.85±16.85	2.53±0.59	4.45±3.86	2.60±2.03	0.10±0.03	0.56±0.25	0.97±0.4
KO	29.88±0.50	9.39±0.07	2999.67±213.62	14.52±6.28	2.98±1.68	4.48±1.09	2.33±2.20	0.10±0.01	0.28±0.15	0.48±0.2
KK	29.61±0.26	9.07±0.07	2677.50±204.71	16.06±8.20	2.81±1.27	4.05±0.59	2.89±1.98	0.10±0.01	0.47±0.22	0.80±0.3

Thengapattinam-TP, Inayam-IN, Midalam-MI, Colachal-CO, Manavalakurichi-MK, Kadiapattinam-KP, Muttom-MU, Pillaitopu-PT,

Rajakkamangalam Thurai-RT, Sanguthurai-ST, Pallom-PA, Manakudi-MK, Kovalam-KO, Kanyakumari-KK

Table 4. Environmental variables of underlying water in the study area

Stations	Temp. (°C)	pH	EC (µs)	TDS (ppm)	Salinity (PSU)	DO (mg/l)	SO ₄ ²⁻ (mg/l)	Depth
TP	29.90±0.37	7.35±0.38	42202.50±237.96	27.05±0.09	25.43±3.18	4.18±1.79	24.78±1.21	4.33±0.54
IN	29.82±0.23	8.24±0.29	42270±54.16	27.08±0.06	27.06±0.12	6.12±0.87	28.92±5.40	3.75±0.88
MI	29.90±0.57	8.13±0.11	42628±183.49	27.30±0.1	27.29±0.09	5.80±0.89	29.73±4.90	7.40±3.58
CO	29.93±0.57	7.93±0.52	42298±315.86	27.09±0.16	25.77±2.86	4.76±1.17	28.69±2.16	28±4.95
MK	29.51±0.37	8.22±0.77	42562±700.91	27.14±0.17	25.93±2.95	5.62±1.2	30.73±3.83	22.8±8.04
KA	29.11±0.51	7.49±0.67	39390±6409.15	25.09±4.6	25.75±2.85	4.66±0.63	34.69±6.05	12.4±2.7
MU	29.26±0.47	8.78±0.39	42340±459.71	27.33±0.36	27.16±0.25	5.91±0.90	33.76±2.97	4.67±1.78
PT	29.16±0.3	8.23±0.88	42706.67±527.86	27.43±0.23	27.45±0.22	3.72±2.3	44.52±18.35	12.33±2.08
RT	30.15±1.31	8.85±0.36	43590±1046.92	28.06±0.41	28±0.29	2.69±1.67	31.07±5.13	21.8±9.98
ST	29.24±0.4	9.31±0.3	43175±241.73	27.67±0.15	27.72±0.16	1.22±0.06	39.97±4.97	12.75±6.6
PA	29.05±0.11	9.22±0.6	43135±290.8	27.64±0.2	27.69±0.31	1.24±0.03	37.14±3.32	19±4.16
MA	29.83±0.63	9.01±0.41	43196±339.31	27.67±0.21	27.59±0.25	1.31±0.16	36.8±2.44	5.2±1.35
KO	29.92±0.5	9.42±0.07	43116.67±213.62	27.63±0.13	27.68±0.19	1.39±0.39	35.26±5.98	10.67±2.08
KK	29.65±0.26	9.10±0.07	42794.5±204.71	27.43±0.12	27.4±0.14	1.47±0.17	38.64±1.4	29±11.83

Table 5 Bio-Env analysis of meiofauna along the study area with respective seasons

No. of Variables	Parameters	Spearman correlation
5	Sediment pH, Sedi. LOM (%), Sediment TOM(%), Clay%, Water EC	0.899
5	Sediment LOM (%), Sediment TOM(%), Clay%, Water pH, Water EC	0.899
5	Sediment pH, Sediment LOM (%), Sediment TOC(%), Clay%, Water EC	0.899
5	Sediment LOM (%), Sediment TOC(%), Clay%, Water pH, Water EC	0.899
5	Sediment pH, Sediment LOM (%), Sediment TOC(%), Clay%, Water TDS	0.897
5	Sediment LOM (%), Sediment TOC(%), Clay%, Water pH, Water TDS	0.897
5	Sediment pH, Sediment LOM (%), Sediment TOM(%), Clay%, Water TDS	0.897
5	Sediment LOM (%), Sediment TOM(%), Clay%, Water pH, Water TDS	0.897
5	Sediment pH, Sediment LOM (%), Sediment TOC(%), Water pH, Water EC	0.896
5	Sediment pH, Sediment LOM (%), Sediment TOM(%), Water pH, Water EC	0.896

Table 6. AMBI site disturbance classification and M-AMBI values in the various stations of the study area

Stations	AMBI	Diversity	Richness	X	Y	Z	M-AMBI	Status
TP	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
IN	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
MI	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
CO	0	0.961	2	0.716	1.37	0.041	0.447	Moderate
MK	1.05	2.56	7	3.64	2.26	0.013	0.876	High
KA	1.89	2.82	8	4.10	2.23	0.002	0.931	High
MU	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
PT	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
RT	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
ST	7	0	1	-1.21	-1.08	-0.012	0.015	Bad
PA	7	0	0	-1.54	-1.21	0.022	-0.036	Bad
MA	0	0.337	2	0.184	1.16	-0.014	0.365	Poor
KO	0	0.210	2	0.076	1.12	-0.026	0.348	Poor
KK	7	0	0	-1.54	-1.21	0.022	-0.036	Bad

Figures

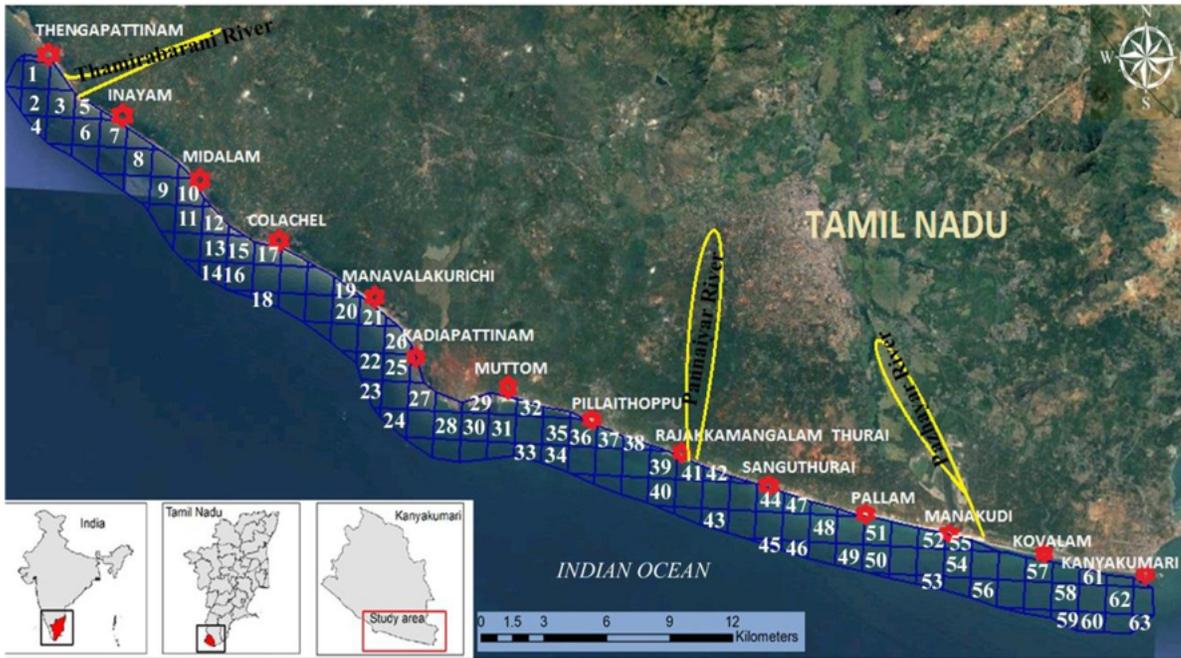


Figure 1
Location map of the study area

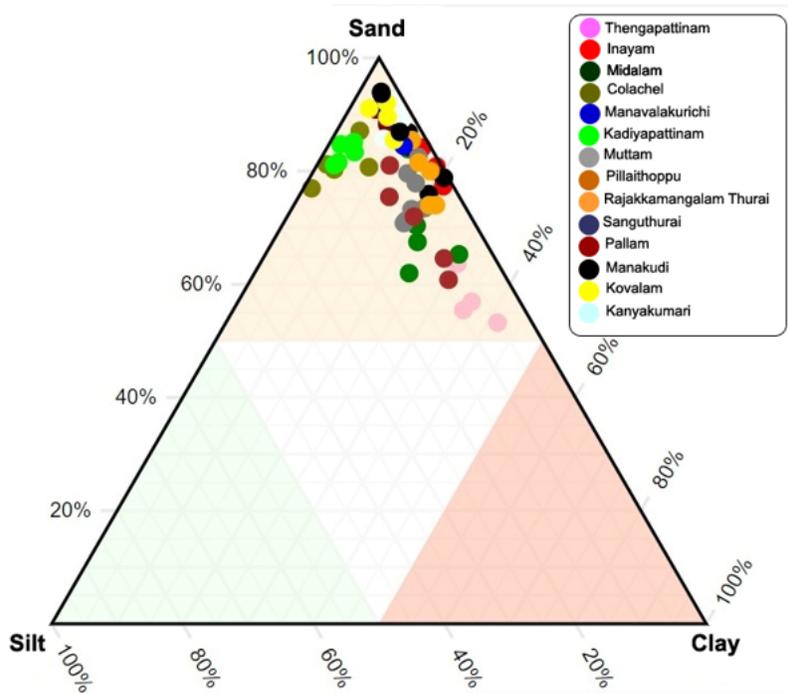


Figure 2
Ternary diagram illustrating the nature of sand, silt and clay content in the study area

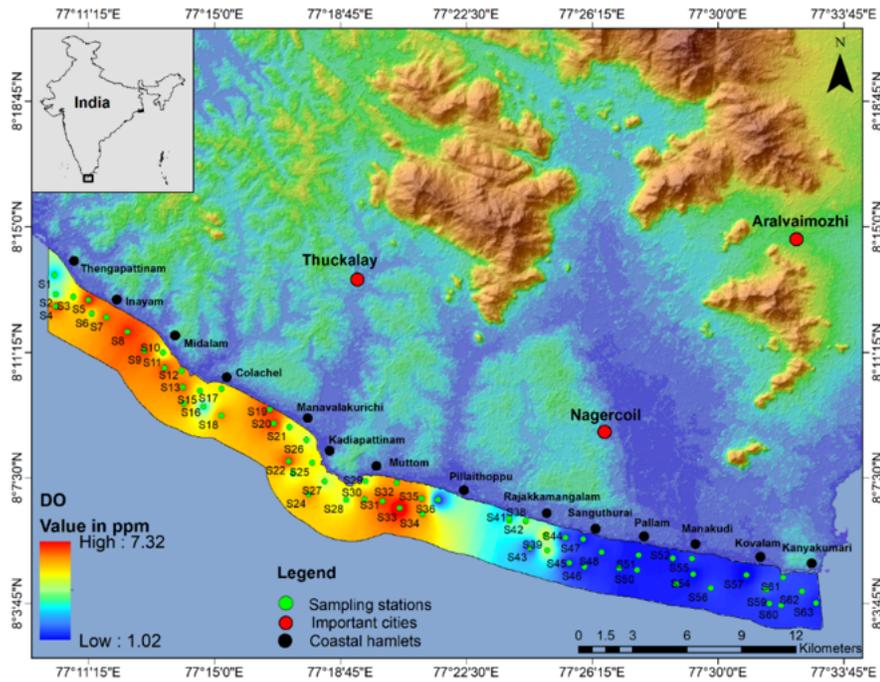


Figure 3
Spatial distribution map of DO in underlying water samples in the study area.

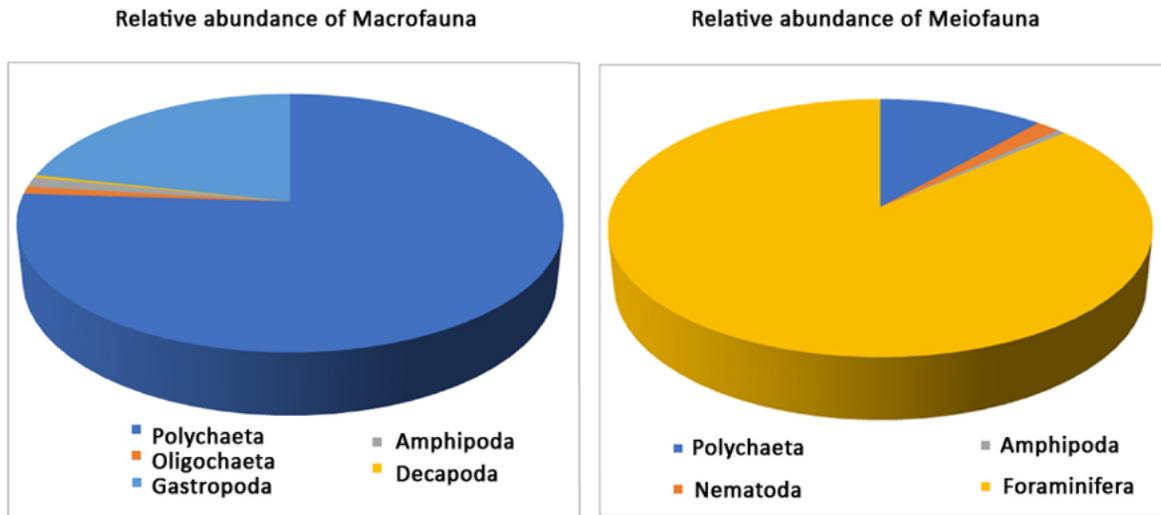


Figure 4
Relative abundance of macrofauna and meiofauna in the study area

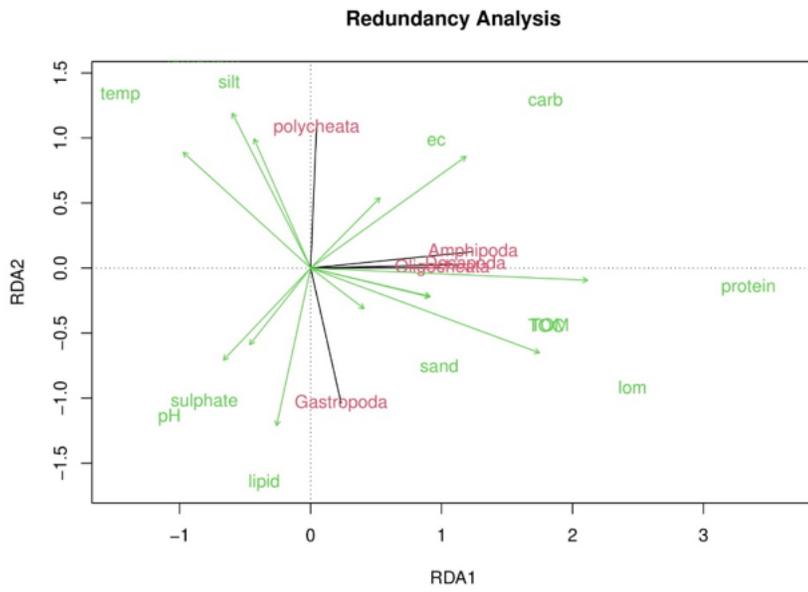


Figure 5
Redundancy analysis plot of macrofauna and other related parameters in the study area

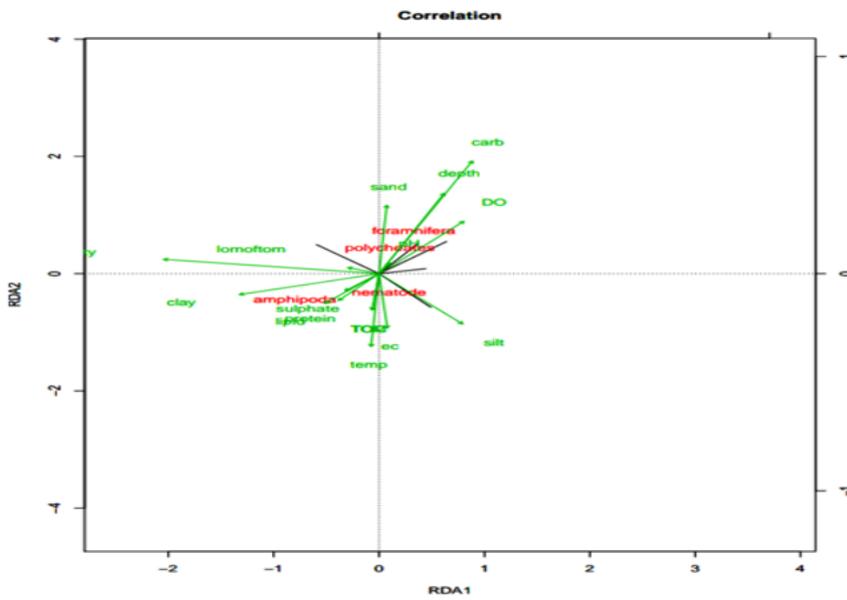


Figure 6
Redundancy analysis plot of meiofauna and other related parameters in the study area

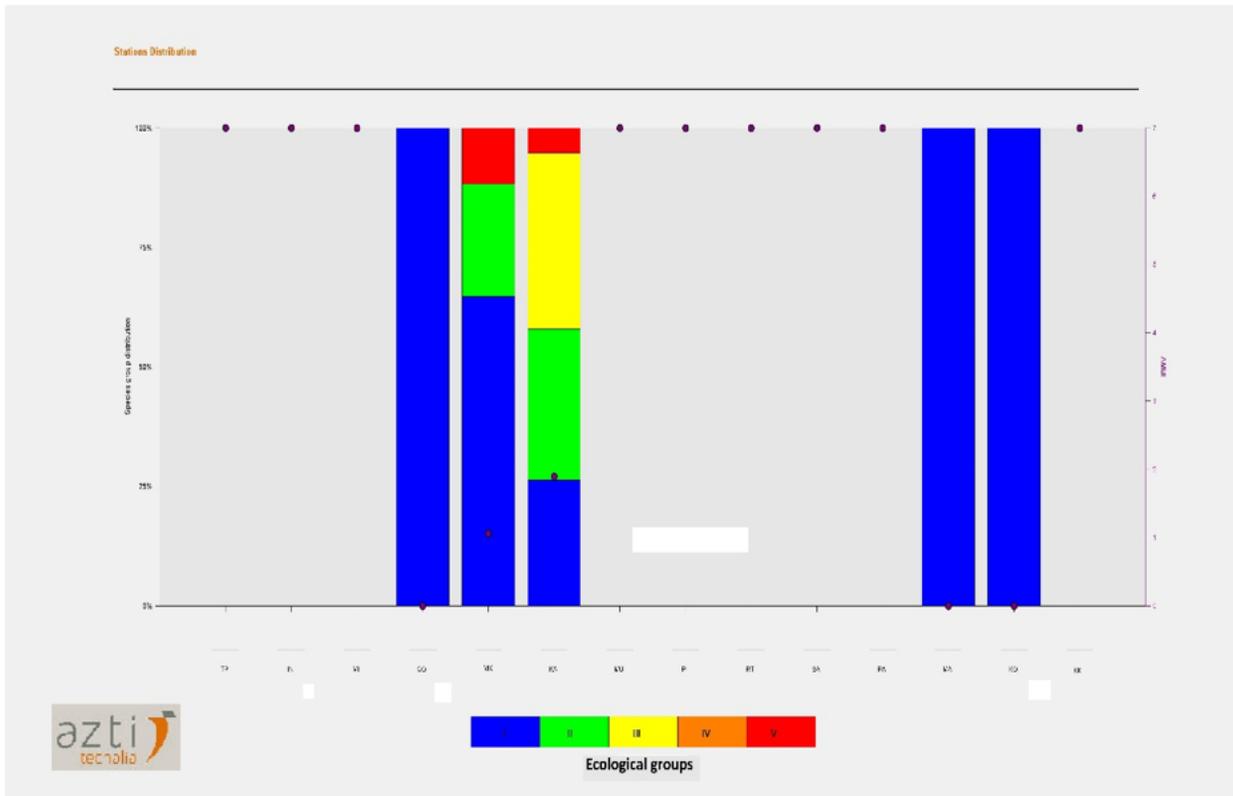


Figure 7
Percentage compositions of various ecological groups recorded at various stations in the study area

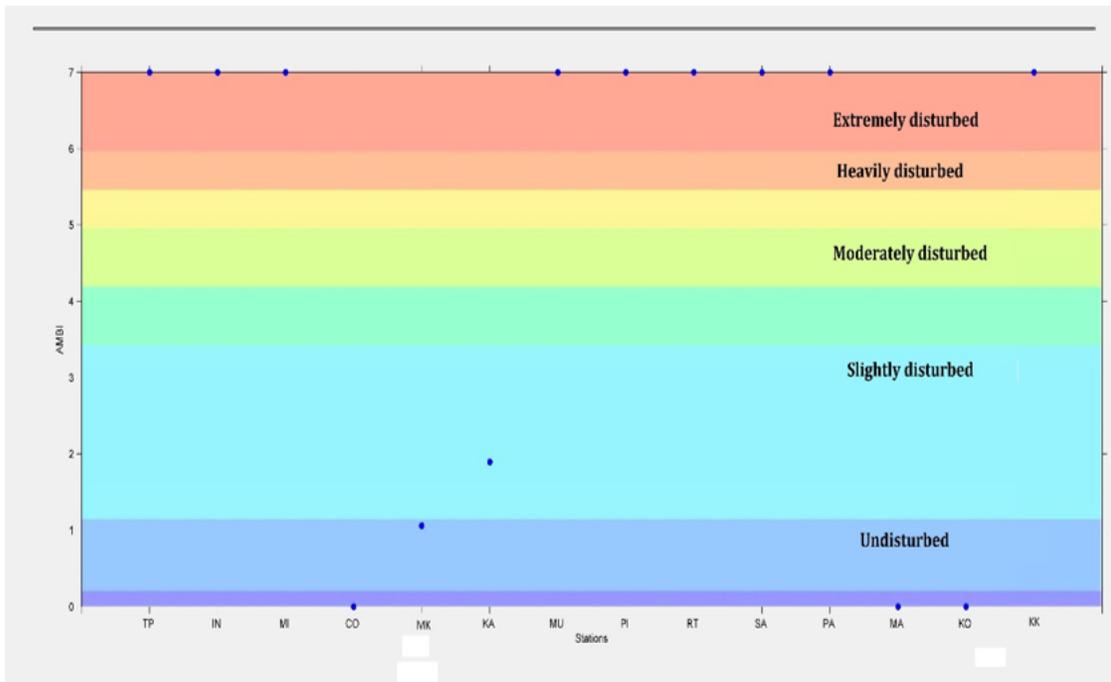


Figure 8
AMBI disturbance classification values for various stations of the study area.

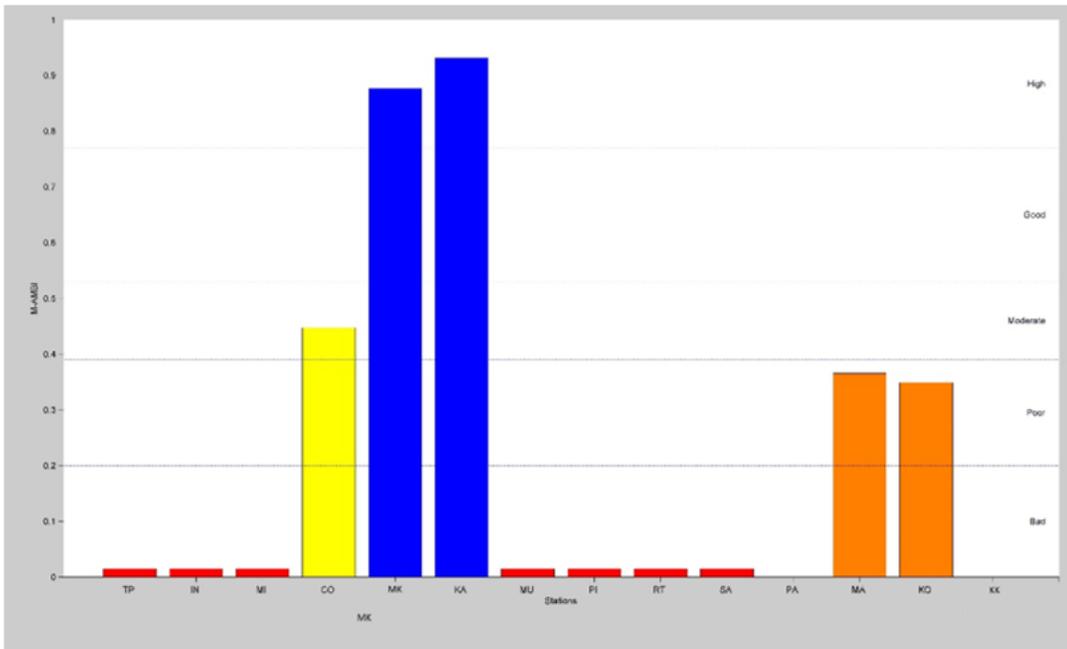


Figure 9

M-AMBI values indicating the ecological status for the stations in the study area.

Supplementary Files

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