Tropical Ecology **56**(2): 139-154, 2015
ISSN 0564-3295

www.tropecol.com

Spatial and temporal changes in biofouling community structure at Visakhapatnam harbour, east coast of India

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Abstract: Biofouling on wooden harbour structures and fishing craft causes huge economic losses. The magnitude of biofouling is often high in tropical countries due to the influence of high temperature on early recruitment of multiple species and the high abundance of biofoulers throughout the year. In the disturbed regions such as Visakhapatnam harbour, India, the biofouling community has undergone drastic changes over the past 25 years. Biofouling community structure was studied in the polluted Visakhapatnam harbour at three sites (Slipway Complex, Ore Berth, and Marine Foreman Jetty) from February 2007 to January 2009 using wood test panels. Biofouling community structure was analyzed in relation to temperature, salinity, pH, dissolved oxygen, BOD, nitrite, phosphate, and silicate through canonical correspondence analysis. The structure of the biofouling community was examined separately for short-term (1 month old) and long-term (1 to 12 months old) panels using community indices (species richness, total abundance, diversity, dominance, and evenness). Fouling communities varied spatially and temporally in relation to salinity and pollution (BOD, nitrite, phosphate, and silicate). Species richness, diversity, and evenness were high when salinity was relatively high and low when pollution was high. Three distinct groups of biofoulers *viz.* marine species, opportunistic species, and typical brackish water species were identified in the harbour. Temporal changes in species richness and biofouling composition observed during the past 25 years can significantly affect the control methods used to overcome the biofouling problems, causing an extra economic burden.

Resumen: La bioincrustación en estructuras portuarias de madera y embarcaciones de pesca causa pérdidas económicas enormes. La magnitud de la bioincrustación es a menudo alta en los países tropicales debido a la influencia de la temperatura alta en el reclutamiento temprano de numerosas especies y la gran abundancia de organismos bioincrustantesdurante todo el año. En regiones perturbadas, como el puerto de Visakhapatnam, India, la comunidad bioincrustadaha sufrido cambios drásticos en los últimos 25 años. La estructura de dicha comunidad fue estudiada en tres lugares delcontaminado puerto de Visakhapatnam (Slipway Complex, Ore Berth y Marine Foreman Jatty) desde febrero de 2007 hasta enerode 2009, utilizando paneles de prueba de madera. La estructura de la comunidad bioincrustante fue analizada en relación con la temperatura, salinidad, pH, oxígeno disuelto, DBO, nitrito, fosfato y silicato, por medio de Análisis Canónico de Correspondencias. La estructura de la comunidad bioincrustada fue examinada por separado para paneles de corto (1 mes de edad) y de largo plazo (de 1 a 12 meses de edad), usando índices de comunidad (riqueza de especies, abundancia total, diversidad, dominancia y uniformidad). Las comunidades bioincrustadas variaron espacial y temporalmente en función de la salinidad y la contaminación (DBO, nitrito, fosfato y silicato).

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La riqueza de especies, la diversidad y la uniformidad fueron relativamente altas cuando la salinidad fue alta, y bajas cuando la contaminación fue alta. Se identificaron tres grupos distintos de bioincrustadores en el puerto: especies marinas, especies oportunistas y especies típicas de agua salobre. Los cambios temporales en la riqueza de especies y la composición de la bioincrustación observados durante los últimos 25 años pueden afectar significativamente los métodos de control utilizados para resolver los problemas de la bioincrustación, causando una carga económica adicional.

Resumo: Asbio-incrustações em estruturas portuárias de madeira e embarcações de pesca provocam grandes perdas económicas. A magnitude da incrustação é frequentemente elevada em países tropicais, devido à influência da alta temperatura sobre o recrutamento precoce de várias espécies e alta abundância de bio-incrustantes ao longo do ano. Nas regiões perturbadas, como o porto de Visakhapatnam, na Índia, a comunidade de incrustantes sofreu mudanças drásticas ao longo dos últimos 25 anos. A estrutura da comunidade dos bio-incrustantes foi estudada no porto poluído de Visakhapatnam em três locais (Complexo rampa de arrastamento, Ore Berth, e Marina de Foreman Jetty) de fevereiro de 2007 a janeiro de 2009, utilizando provetesde madeirapara teste. A estrutura da comunidade de bio-incrustantes foi analisada em relação à temperatura, salinidade, pH, oxigénio dissolvido, CBO, nitrito, fosfato e silicato por meio da análise canónica de correspondência. A estrutura da comunidade de incrustantes foi analisada separadamente nos provetes no curto prazo (1 mês de idade) e a longo prazo (1 a 12 meses de idade) usando índices de comunidade (riqueza específica, abundância total, diversidade, dominância e equitabilidade). As comunidades incrustantes variaram espacial e temporalmente em relação à salinidade e poluição (CBO, nitrito, fosfato e silicato). A riqueza específica, a diversidade e a equitabilidade eram altas quando a salinidade era relativamente alta, e baixa quando a poluição era alta. Três grupos distintos de bio-incrustantes, como sejam espécies marinhas, espécies oportunistas e espécies típicas de água salobra, foram identificados no porto. Mudanças temporais na riqueza de espécies e composição de incrustantes observadas durante os últimos 25 anos podem afetar, significativamente, os métodos de controlo utilizados para superar os problemas de bio-incrustação, causadores de um ónus económico adicional.

Key words: Community structure, diversity, fouling, India, pollution, temporal change, Visakhapatnam harbour.

Introduction

Humans have been launching and installing numerous structures made of a variety of material into the marine environment since time immemorial. Almost all these structures provide additional space in the form of substrata to a wide array of organisms (Bacchiocchi & Airoldi 2003) and as a result the materials are subjected to deterioration in many ways. Biofouling is one of the deterioration processes that affect all stationary and moving engineered structures irrespective of the nature and type of material employed. Biofouling comprises several benthic life forms, which attach themselves to various artificial substrata (Eguia & Trueba 2007). This process is a technical obstruction and economical hindrance leading to an increase in frictional resistance/fuel consumption, loss of propeller efficiency/speed, dubious depth recording by acoustic systems in boats and ships, and interference with the fluid flow in industrial conduits (Yan & Yan 2003). Though several materials are used in marine construction, wood is the only natural and renewable material with unceasing potential especially in the light of growing environmental safety concerns (Cragg 1996).

The success in controlling fouling depends upon the generation of basic information on species composition, growth, biomass build up, diversity, seasonality, succession, and distribution of the organisms concerned in order to estimate the fouling potential of a given area (Satheesh 2006). Fouling is characterized by continuous changes in species composition in relation to different biotic

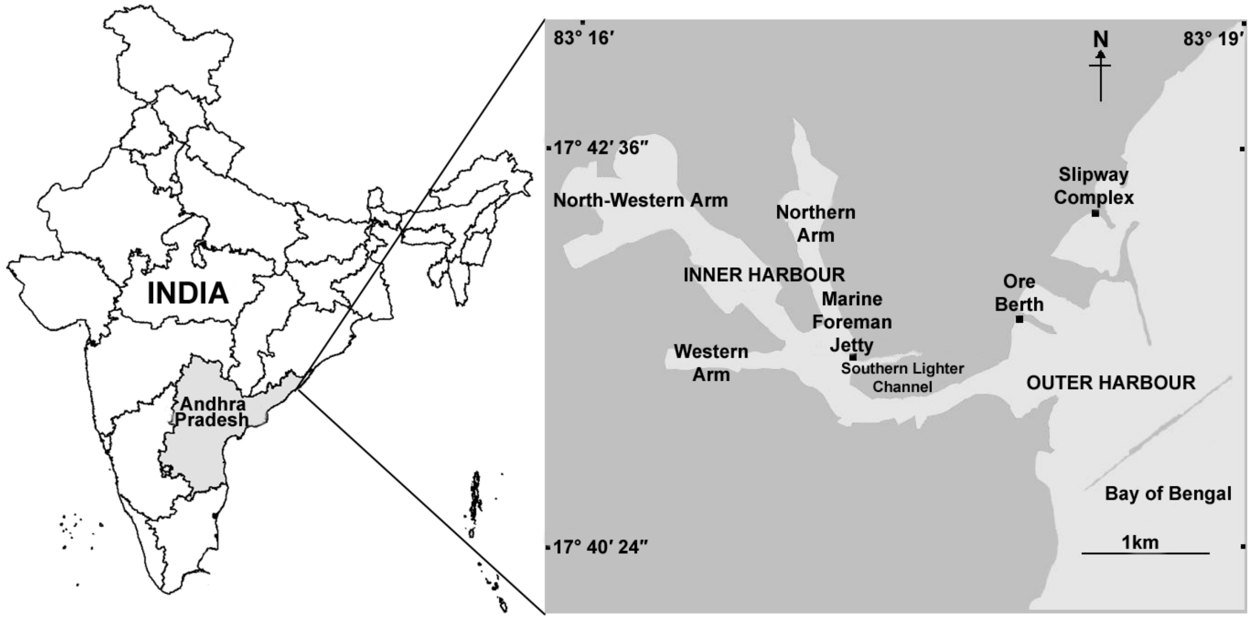

Fig. 1. Map of Visakhapatnam harbour.

and abiotic factors over a time period, which is referred to as fouling community development (Greene & Schoener 1982). Fouling composition varies temporally as well as spatially (Brown & Swearingen 1998). "Therefore, understanding the formation of biofouling communities specific to a region and their development through time is an essential prerequisite for economic design and construction of marine structures and establishing appropriate cleaning programs" (Yan *et al.* 1999). At the same time, knowledge on taxonomic diversity at species level is also a prerequisite to understand the functioning of a community because each species is characterized by an independent ecological role (Maggiore & Keppel 2007). Benthic organisms attached to artificial substratum act as a link to marine environment in energy transfer (Krohling *et al.* 2006). Studies on recruitment of biofoulers on artificial substratum are useful to understand the recruitment process of corresponding sedentary organisms on natural substratum (Perkol-Finkel & Benayahu 2007). Biofouling studies on hard substratum are considered to be an important tool in environmental impact assessment (Balaji & Satyanarayana Rao 2004).

Marine fouling communities formed on different substrata and various harbour structures, coastal installations, hydrotechnical constructions, and allied facilities have been extensively studied over the past four decades (Boyd 1972; Emara & Belal 2004; Field 1982; Kashin *et al.* 2003; Nelson 2009; Perkol-Finkel *et al.* 2008; Rico & López Gappa 2006; Sutherland & Karlson 1977; Wilhelmsson & Malm 2008; Yan *et al.* 2006; Zvyagintsev *et al.* 1993). Similar studies were also conducted in India (Ismail & Azariah 1978; Satyanarayana Rao & Balaji 1994; Swami & Udhayakumar 2004). No comprehensive study on fouling and related topics in Visakhapatnam harbour has been carried out since that of Balaji (1988). Several physical, chemical, and biological changes have occurred in Visakhapatnam harbour during the past couple of decades due to anthropogenic pressures around the city and within the harbour. Hence, the present study was undertaken with an aim to understand how the diversity and abundance of biofoulers has altered since the environmental parameters changed in Visakhapatnam harbour.

Material and methods

Visakhapatnam harbour (17° 40′ N and 83° 16′ E) (Fig. 1) has two distinct areas, namely, outer harbour and inner harbour, interconnected by a narrow entrance channel. One of the city's main drainage systems the 'southern lighter channel' and a freshwater polluted stream from the monsoon-fed reservoir the 'Mehadrigedda' empties into the inner harbour. A pollution gradient exists in the region from inner harbour to the outer harbour (Balaji 1988; Raman & Ganapati 1983; Tripathy *et* *al*. 2005). The present study was carried out at three sites, namely, Slipway Complex, Ore Berth, and Marine Foreman Jetty. Slipway Complex (5 m water depth) is located in the relatively pollution-free outer harbour area, which is partially separated by break waters from the Bay. Marine Foreman Jetty (10 m water depth) is situated close to Southern Lighter Channel in the inner harbour area, which is affected by pollution due to industrial effluents, oil contamination and domestic sewage. Ore Berth (15 m water depth) is located in the outer harbour area in between the former two sites and has moderate pollution levels.

Wooden test panels (150 × 80 × 20 mm) were fastened with a 3 mm nylon rope into vertical ladders. For short-term fouling studies, each ladder containing 6 panels (of the 'soft wood' species *Bombax ceiba* Linnaeus, 1753 to facilitate early recruitment) arranged so that the uppermost panel was in the intertidal zone and the rest were well below the lowest low water mark with a gap of 100 mm in between each of them. One each of the vertical ladders was subjected to marine exposure with the aid of a suitable weight for 30 days at each of the three sites for the entire sampling period. Vertical ladders were retrieved monthly for two years; the timeframe for the first year was February 2007 to January 2008 and for the second year was February 2008 to January 2009. For long-term fouling studies, a total of 12 ladders (arranged in a similar fashion like that of short-term ladders but containing panels of a relatively durable timber species *Pinus roxburghii* Sargent, 1897) were immersed at the beginning of each year and retrieved single ladder-wise from each site at the end of each month consecutively until rescue of the last ladder. After retrieval of ladders, both the short-term and long-term panels were separated from the rope, gently washed with seawater to remove any adhering mud and silt while taking care not to lose any animals and brought to laboratory in individual seawater containers.

Environmental parameters particularly salinity and pollution are known to affect the structure and composition of biofouling community (Ramadan *et al*. 2006; Sahu *et al*. 2011; Swami & Udhayakumar 2008). Thus, one surface seawater sample was collected from each of the three sites during the monthly retrieval of test panels and analyzed for temperature, pH, salinity, dissolved oxygen (DO), biological oxygen demand (BOD) and nutrients (nitrite, phosphate and silicate) following standard procedures (Grasshoft *et al*. 1999; Parsons *et al*. 1984).

At the laboratory, all fouling species were enumerated through a random sampling method employing 4 cm^2 grids. Exactly 10 random grids per panel (from all sides) were sampled thus making a total of 60 grids from the 6 replicates. Subsequently, the accumulated fouling community on each panel was carefully removed, segregated into individual species, narcotized and preserved in glycerin modified 70 % ethyl alcohol for qualitative and quantitative analyses. Identifications of fouling species were done following standard literature (Antony Fernando 2006; Çinar 2006; Dev Roy & Bhadra 2005; Dey & Ramakrishna 2007; Fauvel 1953; Kott 1985; Krishna Pillai 1961; Lakshmana Rao 1969; Mammen 1963, 1965; Menon & Menon 2006; Satyanarayana Rao 1975; Subba Rao 2003). Individual animals were enumerated by species in each grid and the average of all the 60 grids was considered as abundance of a species for that month/period. As per normal convention, colonial forms such as hydrozoans, entoprocts, ectoprocts, and compound ascidians were regarded as individuals by colony count. Whole group or species that come under Primary Fouling Assemblages (PFA: foulers directly attached to the substratum) were given in bold font in Table 1 to distinguish them from those under Secondary Fouling Assemblages (SFA: foulers freely living on or among the attached organisms). In the case of animals distinguished as belonging to SFA, species count could not be resorted through random grid sampling due to their motility and instead average direct numeric count of a species from all replications was taken as their abundance.

Community structure of the fouling organisms on short-term and long-term panels was analyzed separately using species richness (S), Shannon's diversity index (H´), Simpson's dominance index (C), and Shannon's evenness index (J´) as per Magurran (1988) with the aid of software PAST version 1.96 (Hammer *et al*. 2001) and a multivariate method of ordination, *viz*., non-metric multi-dimensional scaling on the abundance of all fouling species from the three sites for monthly observations during the two years employing PRIMER 6.1 (Clarke & Gorley 2006). The relationship between all the environmental parameters and fouling community parameters (species richness, total abundance, diversity, dominance and evenness) for each month were analyzed with Canonical Correspondence Analysis (CCA) using PAST.

Results

Environmental parameters and biofouling community structure

A relationship between environmental parameters (temperature, salinity, pH, DO, BOD, and nutrients) and fouling community parameters (species richness, total abundance, diversity, dominance, and evenness) was revealed through CCA (Fig. 2). Species richness, diversity, and evenness were high when salinity was relatively high and low when BOD, nitrite, phosphate, and silicate were high. Thus, salinity, BOD and nutrients (nitrite, phosphate and silicate) were the important parameters influencing biofouling community at Visakhapatnam harbour.

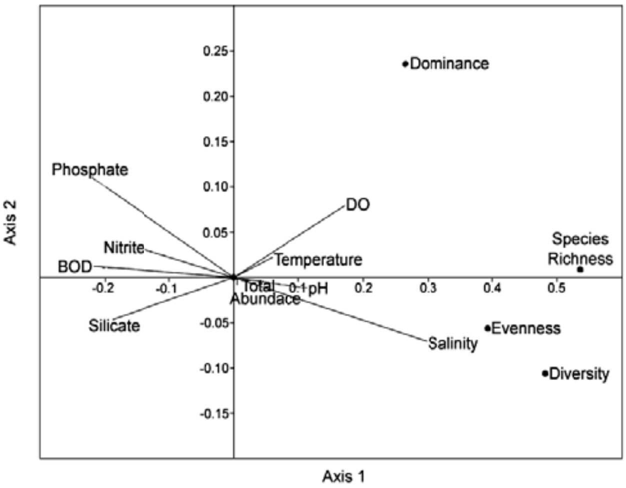

Fig. 2. Canonical Correspondence Analysis showing the relationship between environmental and fouling community parameters.

The mean values of salinity, nitrite, phosphate, and silicate were higher during first year than the second year at the three sites with exceptions at Ore Berth for nitrite and phosphate (Fig. 3). The magnitude of variations in salinity, phosphate, and silicate were relatively high during the second year compared to the first year at each site except Slipway Complex for silicate, and Marine Foreman Jetty for phosphate (Fig. 3). On the other hand, variation in nitrite was relatively high during the first year compared to the second year (Fig. 3). Spatially, moving from Slipway Complex to Ore Berth to Marine Foreman Jetty salinity exhibited a decreasing trend whereas BOD, nitrite, phosphate, and silicate values showed an increasing trend (Fig. 3).

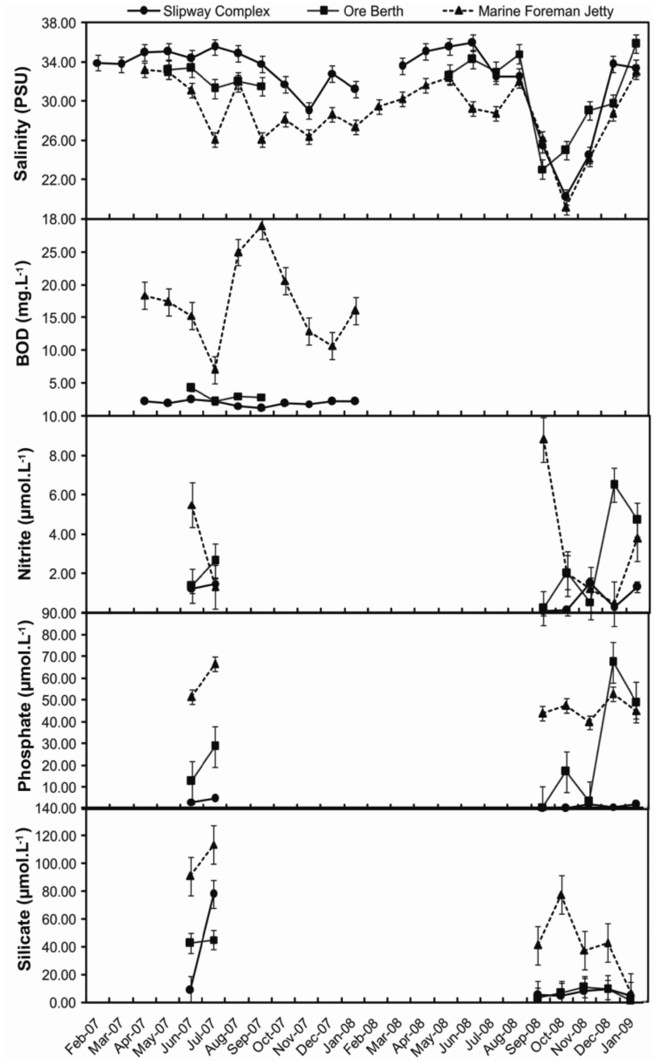

Fig. 3. Monthly variations of important environmental parameters (salinity, BOD, nutrients) in Visakhapatnam harbour over two years.

Spatial and temporal variations in fouling community structure

In all, as many as 100 fouling species belonging to 24 faunal groups were observed on both short-term and long-term panels at the three sites (Table 1). Among these, 68 taxa (43 PFA and 25 SFA) were represented from Slipway Complex and 57 species (35 PFA and 22 SFA) from Ore Berth, but only 18 taxa (9 PFA and 9 SFA) from Marine Foreman Jetty. While 31 species were common to Slipway Complex and Ore Berth, 11 taxa each were common to Slipway Complex-Marine Foreman Jetty and Ore Berth-Marine Foreman Jetty.

As few as 8 fouling species, namely, *Metridium* sp., Polyclad-1, *Polydora* sp., *Branchiomma cingu-*

Table 1. Spatial distribution of biofouling species in Visakhapatnam harbour (SWC: Slipway Complex; OB: Ore Berth; MFJ: Marine Foreman Jetty; *: Present; -: Absent). Primary Fouling Assemblages are in bold font.

Group	Fouling Species	SWC	OB	MFJ
Porifera	1. Sponge-1 (Unidentified)	*	*	-
	2. *Bimeria vestita* Wright,1859	*	-	-
Hydrozoa	3. *Clytia gracilis* (Sars, 1850)	*	*	-
	4. *Clytia hendersoni* Torrey, 1904	*	*	-
	5. *Clytia linearis* (Thorneley, 1900)	-	*	-
	6. *Clytia noliformis* (McCrady, 1859)	-	*	-
	7. *Obelia bidentata* Clark, 1875	-	*	-
	8. *Obelia dichotoma* (Linnaeus, 1758)	*	-	-
	9. *Halecium* sp.	*	-	-
	10. Hydrozoan-1 (Unidentified)	*	-	-
	11. Hydrozoan-2 (Unidentified)	*	-	-
Actiniaria	12. *Anthopleura* sp.	*	-	-
	13. *Aiptasia* sp.	*	-	-
	14. *Diadumene* sp.	-	-	*
	15. *Metridium* sp.	*	*	*
Turbellaria	16. Polyclad-1 (Unidentified)	*	*	*
Entoprocta	17. *Pedicellina cernua* (Pallas, 1774)	*	-	-
Ectoprocta	18. *Bugula neritina* (Linnaeus, 1758)	*	*	-
	19. *Hippoporina americana* (Verrill, 1875)	*	*	-
	20. *Hippopodina feegeensis* (Busk, 1884)	-	*	-
	21. *Jellyella tuberculata* (Bosc, 1802)	*	-	-
	22. *Membranipora* sp.	-	*	-
	23. *Thalamoporella gothica indica* (Hincks, 1880)	*	-	-
	24. Bryozoan-1 (Unidentified)	*	*	-
	25. Bryozoan-2 (Unidentified)	-	*	-
	26. *Bowerbankia gracilis* Leidy, 1855	*	*	-
	27. *Zoobotryon verticillatum* (Delle Chiaje, 1828)	*	-	-
Spionidae	28. *Polydora* sp.	*	*	*
Sabellidae	29. *Branchiomma cingulata* (Grube, 1870)	*	*	*
	30. Sabellid-1 (Unidentified)	*	-	-
	31. Sabellid-2 (Unidentified)	-	*	*
Isopoda	51. *Cirolana fluviatilis* Stebbing, 1902	-	-	*
	52. *Cirolana* sp.	-	*	-
	53. *Sphaeroma walkeri* Stebbing, 1905	*	-	-
	54. *Paracerceis* sp.	*	-	-
Other Crustaceans	55. *Sinelobus stanfordi* (Richardson, 1901)	-	*	-
	56. *Calappa* sp.-2	*	-	-
	57. *Doclea* sp.	-	*	-
	58. *Platylambrus prensor* (Herbst, 1903)	-	*	-
	59. *Scylla* sp.-1	*	-	-
	60. *Portunus* (*Portunus*) *pelagicus* (Linnaeus, 1758)	*	-	-
	61. *Charybdis* (*Charybdis*) *helleri* (A. Milne Edwards, 1867)	*	-	-
	62. *Charybdis* sp.	*	-	-
	63. *Thalamita crenata* Rüppell, 1830	*	-	-
	64. *Macromedaeus crassimanus* (A. Milne Edwards, 1867)	-	*	-
	65. *Myomenippe hardwickii* (Gray, 1831)	-	*	-
	66. Pinnotherid-1 (Unidentified)	-	*	-
	67. Crab-1 (Unidentified)	*	*	-
	68. Crab-3 (Unidentified)	-	*	-
	69. *Synalpheus brevicarpus* (Herrick, 1891)	*	*	*
	70. *Pycnogonum* sp.	*	-	-
Aplacophora	71. Nudibranch-1 (Unidentified)	*	-	-
Gastropoda	72. *Littoraria scabra* (Linnaeus, 1758)	*	-	-
	73. *Assiminea* sp.	-	*	-
	74. *Mauritia arabica* (Linnaeus, 1758)	*	-	-
	75. **Vermetid-1 (Unidentified)**	*	-	-
	76. *Anachis terpsichore* (G.B. Sowerby II, 1822)	*	-	-
	77. *Drupella rugosa* (Born, 1778)	-	*	-
	78. *Nassarius* sp.	-	-	*
	79. Gastropod-1 (Unidentified)	-	-	*
	80. Gastropod-2 (Unidentified)	*	*	-
Bivalvia	81. ***Perna viridis* (Linnaeus, 1758)**	-	*	-

Contd...

Table 1. Continued.

Group	Fouling Species	SWC	OB	MFJ	Group	Fouling Species	SWC	OB	MFJ
Serpulidae	32. *Serpula vermicularis* Linnaeus, 1767	*	*	-	Bivalvia	82. ***Modiolus philippinarum* (Hanley, 1843)**	*	-	-
	33. *Hydroides brachyacanthus* Rioja, 1941	*	*	-		83. ***Brachidontes striatulus* (Hanley, 1843)**	-	*	-
	34. *Hydroides diramphus* Mörch, 1863	*	-	-		84. ***Pinctada imbricata fucata* (Gould, 1850)**	*	-	-
	35. *Hydroides elegans* (Haswell, 1883)	*	*	*		85. ***Pinna* sp.**	-	*	-
	36. *Hydroides operculatus* (Treadwell, 1929)	*	-	-		86. ***Crassostrea cuttackensis* (Newton & Smith, 1912)**	*	*	-
	37. *Hydroides vizagensis* Lakshamana Rao, 1969	*	-	-		87. ***Saccostrea cucullata* (Born, 1778)**	*	*	-
	38. *Hydroides* sp.-1	*	-	-		88. ***Anomia achaeus* Gray, 1850**	-	*	-
	39. *Hydroides* sp.-2	*	-	-		89. ***Anomia* sp.**	-	*	-
	40. *Ficopomatus enigmaticus* (Fauvel, 1923)	*	*	-		90. ***Mytilopsis sallei* (Récluz, 1849)**	*	*	*
Other Polychaetes	41. Nereid-1 (Unidentified)	*	*	-		91.*Neotrapezium sublae-vigatum* (Lamarck, 1819)	*	-	-
	42. *Eunice afra* Peters, 1855	-	-	*		92. *Trapezium* sp.	-	*	-
	43. *Eunice laticeps* Ehlers, 1868	*	*	*		93. *Laternula* sp.	-	*	-
	44. *Cirratulus* sp.	*	-	-	Echinodermata	94. Ophiurid-1 (Unidentified)	-	*	-
	45. Cirratulid-1 (Unidentified)	*	-	-	**Ascidiacea**	95. *Ascidia gemmata* Sluiter, 1895	*	*	-
Cirripedia	46. *Amphibalanus amphitrite amphitrite* (Darwin, 1854)	*	*	*		96. *Styela canopus* (Savigny, 1816)	*	*	-
	47. *Amphibalanus variegatus* (Darwin, 1854)	*	-	*		97. *Symplegma oceania* Tokioka, 1961	*	*	-
Amphipoda	48. *Americorophium triaenonyx* (Stebbing, 1904)	*	*	*		98. Ascidian-1 (Unidentified)	*	*	-
Isopoda	49. *Cirolana* (*Anopsilana*) *willeyi* (Stebbing, 1904)	-	*	-	Pisces	99. Gobiid-1 (Unidentified)	*	-	-
	50. *Cirolana bovina* Barnard, 1940	*	*	-		100. Gobiid-2 (Unidentified)	-	-	*

Table 2. Temporal distribution of foulers in Visakhapatnam harbour.

	Study Period	Number of species recruited		
		Slipway Complex	Ore Berth	Marine Foreman Jetty
Short-term panels	First year	25	19	11
	Second year	18	19	5
Long-term panels	First year	49	38	15
	Second year	33	28	6

lata (Grube, 1870), *Amphibalanus amphitrite amphitrite* (Darwin, 1854), *Americorophium triaenonyx* (Stebbing, 1904), *Synalpheus brevicarpus* (Herrick, 1891), and *Mytilopsis sallei* (Récluz, 1849) occurred in common at the three sites in Visakhapatnam harbour (Table 1). In contrast, as many as 36 taxa of biofoulers were exclusively observed at Slipway Complex. Similarly, 25 species of fouling organisms were unique to Ore Berth whereas only 6 fouling species were unique to Marine Foreman Jetty.

A total of 25 species of fouling organisms recruited during the first year on short-term panels at Slipway Complex in contrast to 18 taxa during second year (Table 2). On the contrary, an equal number of biofoulers (19) recruited to panels during both the years at Ore Berth. Still differing from the above two sites, 11 and 5 fouling forms recruited to panels at Marine Foreman Jetty during first and second years, respectively.

Depicting a trend similar to that observed on short-term panels, recruitment of fouling organisms on long-term panels accounted for 49 and 33 species at Slipway Complex, 38 and 28 taxa at Ore Berth and 15 and 6 species at Marine Foreman Jetty, during first and second years, respectively (Table 2).

In general, species richness (S) of foulers on short-term and long-term panels was relatively higher during the first year than the second year (Figs. 4 & 5), and highest at Slipway Complex followed by Ore Berth and Marine Foreman Jetty.

Total abundance (N, individuals m^{-2}) of foulers at each site was usually high during all time periods when the species richness was low on both the type of panels (Figs. 4 & 5). On both the types of panels at Slipway Complex, the most abundant species were *B. cingulata* and *Polydora* sp. during the first year and the second year, respectively. *Amphibalanus amphitrite amphitrite* was the most abundant species on both the types of panels during both the years at Ore Berth. At Marine Foreman Jetty, *M. sallei* was the most abundant species on short-term panels during both the years. On the long-term panels at Marine Foreman Jetty, *M. sallei* was the most abundant species during the first year whereas *M. sallei* along with *Polydora* sp. were the highest contributors to abundance during the second year.

Diversity (H´) and evenness (J´) of biofoulers on short-term and long-term panels were normally highest at Slipway Complex followed by Ore Berth and Marine Foreman Jetty whereas dominance index (C) was in reverse order (Figs. 4 & 5). The diversity and evenness of the fouling communities generally increased with exposure period of long-term panels during the first year only at all the sites expect Marine Foreman Jetty (Fig. 5). At Slipway Complex, while the forms, namely, *Polydora* sp., *B. cingulata*, *Serpula vermicularis* Linnaeus, 1767, *Hydroides elegans* (Haswell, 1883) and *A. amphitrite amphitrite* were dominant on the short-term panels, *Metridium* sp., *Bugula neritina* (Linnaeus, 1758), *Zoobotryon verticillatum* (Delle Chiaje, 1828), *H. elegans*, *Amphibalanus variegatus* (Darwin, 1854), *Ascidia gemmata* Sluiter, 1895 and *Styela canopus* (Savigny, 1816) were additional dominant foulers on long-term panels almost throughout the duration of the study. The dominant species found at Slipway Complex on short-term panels were also found to be major foulers in the case of Ore Berth. But on long-term panels at the latter site, additional dominating forms were *Clytia hendersoni* Torrey, 1904, *B. neritina*, *Crassostrea cuttackensis* (Newton & Smith 1912) and *Saccostrea cucullata* (Born, 1778). Throughout most of the study period on both the types of panels, dominant foulers at Marine Foreman Jetty were *Metridium* sp., *Polydora* sp., *A. amphitrite amphitrite*, *A. variegatus* and *M. sallei*.

Faunal composition of the assemblages during certain months resembled one another either temporally or spatially or both. Fouling compositions at Slipway Complex and Ore Berth showed similarity (38 %) during all the months in the first year barring that at the former site during June. But, the composition at Marine Foreman Jetty was notably different from the other two sites during most of the months except March, June, and December (Fig. 6). During the second year, biofouling compositions at the three sites were more distinct from one another than during the first year (Fig. 7) except for some similarity in species compositions between Slipway Complex and Ore Berth during November, December, and January. However, the species compositions at Slipway Complex and Ore Berth showed 37 % similarity and remained distinct from Marine Foreman Jetty.

Discussion

Environmental parameters

Salinity ranges observed in Visakhapatnam harbour during this study (19.1 to 35.5) are similar to historic ranges of the last three decades (12.50 to 34.00; Balaji 1988) suggesting that salinity has remained fairly stable. Reduction in BOD values [deciphered by the decline of upper limit of BOD from 42.5 mg l^{-1} (Balaji 1988) to 29 mg l^{-1} (present study)] over three decades indicates the curtailing of pollution (APPCB 2010) through treatment of effluent/sewage discharge into harbour waters. Reduced waste inputs from fertilizer industries followed by discontinued sewage discharge through the city's main drainage system 'Southern Lighter Channel' are the probable contributors to the reduction in eutrophication [interpreted from the decline of upper limit of nitrite from 109 µmol.l^{-1} (Raman 1995) to 8.81 µmol. l^{-1} (present study) and phosphate from 170 µmol.l^{-1} (Ratna Bharati *et al.* 2001) to 66.51 µmol.l^{-1} (present study)] over the years in the inner harbour. Despite the fact that environmental parameters in Visakhapatnam har-

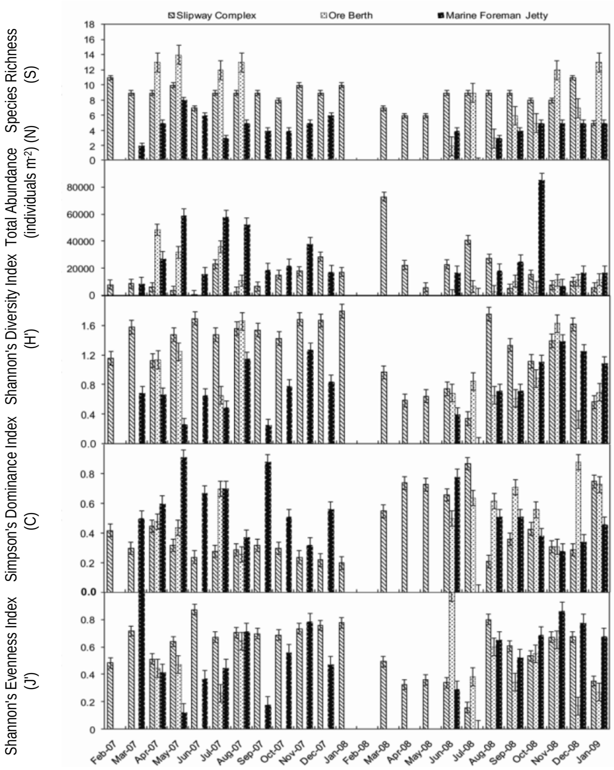

Fig. 4. Monthly variations of biofouling community parameters in Visakhapatnam harbour on short-term panels over two years.

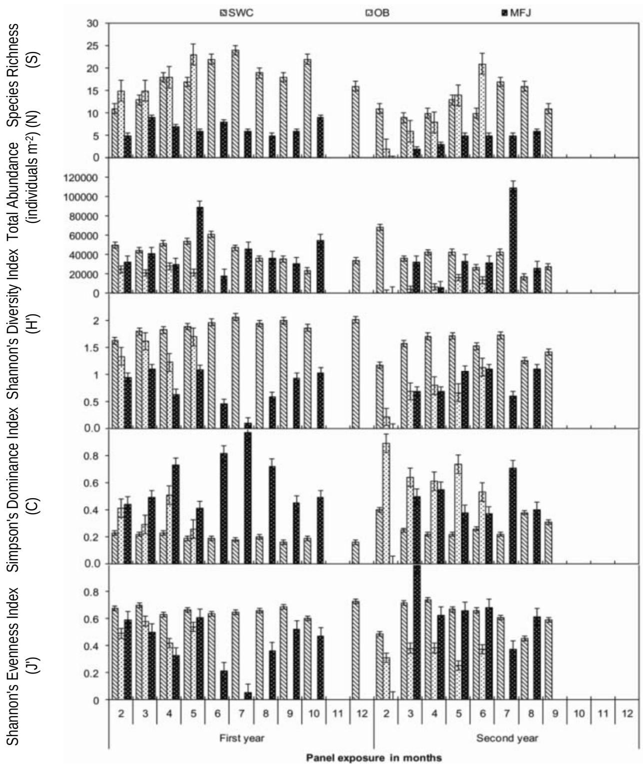

Fig. 5. Monthly variations of biofouling community parameters in Visakhapatnam harbour on long-term panels over two years.

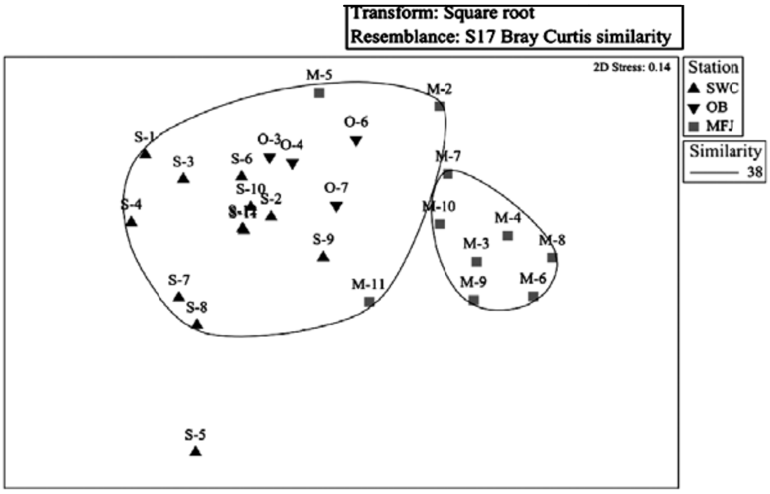

Fig. 6. Non-metric multi-dimensional scaling illustrating the similarities of fouling species composition on short-term panels among sites in Visakhapatnam harbour (S for Slipway Complex; O for Ore Berth; M for Marine Foreman Jetty) during the first year (numbers 1 to 12 represent the months February to January).

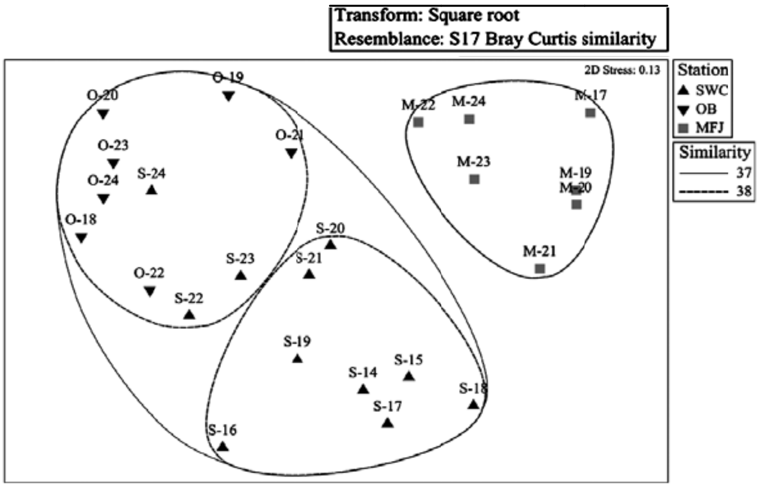

Fig. 7. Non-metric multi-dimensional scaling illustrating the similarities of fouling species composition on short-term panels among sites in Visakhapatnam harbour (S for Slipway Complex; O for Ore Berth; M for Marine Foreman Jetty) during the second year (numbers 13 to 24 represent the months February to January).

bour have slightly improved, pollution particularly due to eutrophication still prevails in the area but with a decreasing gradient from Marine Foreman Jetty to Ore Berth to Slipway Complex.

Spatial and temporal variations in fouling community structure

Three groups of fouling species, were identified in Visakhapatnam harbour waters, (1) marine species commonly found in low water dynamic environments, (2) opportunistic species with different degrees of tolerance to organic enrichment, and (3) typical euryhaline (brackish water species). These results correspond to previous observations in a Mediterranean lagoon (Koutsoubas *et al.* 2000; Mistri *et al.* 2001). Exclusive occurrence of certain species at each of the three sites might be due to their preference for specific environmental regimes (Yan *et al.* 1999) arising as a result of adaptation of individual species, particularly to salinity and pollution. While more of stenohaline species are likely to be confined to the respective regimes or test sites, euryhaline species are capable of occurring at all sites. As in the case of present study, Underwood & Chapman (2000) also note that community composition, population abundance, and species diversity in most habitats and ecosystems show a wide range of variation both on spatial and temporal scales and that heterogeneity exists in the physical factors, resource availability, and biological interactions.

As in the present study, a gradual decline in species count from Slipway Complex to Ore Berth to Marine Foreman Jetty was noticed by Balaji (1988). The attributed reason for this is the existence of a gradient of pollution in Visakhapatnam harbour though the extent of anthropogenic load was evidenced to have reduced.

The number of species occurring in common at the three sites and each of the two successively spaced sites is almost in direct proportion to the species richness at each site. Such similarity seems to be in accordance with the variability of environmental features including pollution that are greatly influenced by adjacent bay waters and to a limited extent by inputs (mostly polluted) from 'Mehadrigedda' besides tolerance limits of individual species to different water quality parameters. More successful spatial competitors such as mussels and barnacles frequently overgrow or displace other fouling species (Richmond & Seed 1991); therefore, distantly spaced but diverse fouling communities also attain certain degree of similarity, especially at 'multiple stable points' during fouling development. However, various biological processes in operation in the entire ecosystem, though highly complicated to be comprehended will have their own effect in determining the species composition (Heck Jr. & Valentine 2007).

The number of species recruited on both short-term and long-term panels was higher during the first year than the second year at all the sites except at Ore Berth on short-term panels. This may be attributed to the fact that influencing parameters (salinity, phosphate, and silicates) were comparatively stable during the first year. Relatively less variable environmental conditions prevailing in the harbour during first year appeared to have favoured recruitment of more taxa compared to widely fluctuating water characteristics that may have impeded recruitment during second year. Relevance of variability of an environmental parameter in understanding its effect on biological diversity was highlighted by Beneditti-Cecchi (2003). Additional factors that may have contributed to variations in species richness at Ore Berth during second year include the observed preponderance of seaweeds that can act as filters to the incumbent larvae (Olafsson 1988) and heavy deposition of silt and oil on wooden panels that stand as obstacles in recognition of the substratum by fouling larvae (Emara & Belal 2004; Mahoney & Noyes 1982). Other biological factors such as predation and grazing might have also played a role in determining species richness and abundance at the three sites (Ayling 1981).

In comparison with the past data of Balaji (1988) (reported 99 species), a total of 68 fouling species were recorded during the present study at Slipway Complex. Of these, only 15 taxa, namely, *O. bidentata* Clark, 1875, *Halecium* sp., *Pedicellina cernua* (Pallas, 1774), *B. neritina*, *Hippoporina americana* (Verrill, 1875), *Jellyella tuberculata* (Bosc, 1802), *Bowerbankia gracilis* Leidy, 1855, *Z. verticillatum*, *S. vermicularis, H. elegans, A. amphitrite amphitrite*, *A. triaenonyx*, *Sphaeroma walkeri* Stebbing, 1905, *C. cuttackensis* and *S. cucullata* were found in common. Similarly, while Balaji (1988) collected 27 species from Marine Foreman Jetty, the current inventory accounted for only 18 species. Among them, only 4 species, *viz.*, *B. cingulata*, *A. amphitrite amphitrite*, *A. triaenonyx* and *M. sallei* occurred during both the periods of investigations. The reasons for these deviations, in addition to heterogeneity of habitat as mentioned above, are probably the preference of stationary substrata by certain species over introduced panels that are susceptible to movement due to currents and tides [i.e., occurrence of long-lived residents on immovable harbour installations as opposed to short-lived species on transient (test panel) habitats], and long-term temporal variations resulting from a variety of ecosystem processes. Recruitment of many epibiotic species was found to be greater on concrete than wooden panels (Coe 1932). Foster & Willan (1979) recorded four Lepadidae species that attached to an oil-drilling platform newly towed from Japan to New Zealand, but subsequent observations by Foster (1987) revealed that these organisms were eliminated from the fouling community after the platform was fixed on its permanent location. Similarly, Yan *et al.* (2000) found that all species of Lepadomorpha in offshore waters of Northern South China Sea settled only on floating and moving objects such as buoys, panels, chains, and nylon ropes, but were never attached to concrete anchor or bundles of surplus anchor chains which are more or less fixed on the sea floor. Further, Glasby *et al.* (2007) reported that more of native epibiota tend to recruit on fixed (sandstone) panels rather than on panels that are not fixed. Perkol-Finkel *et al.* (2008) found that such differences are associated with the hydrodynamic characteristics of floating and fixed habitats.

Generally, species richness, diversity, and evenness values were reduced from Slipway Complex to Ore Berth to Marine Foreman Jetty. Marine Foreman Jetty is a relatively polluted site compared to the other two sites and pollution is known to cause deleterious effects to fouling organisms by affecting their species richness, diversity, and evenness (Balaji 1988; Balaji & Satyanarayana Rao 2004; Ismail & Azariah 1978; Ramadan *et al*. 2006; Swami & Udhayakumar 2008). In addition to the influence of cleaner bay waters, abundant growth of barnacles on breakwater boulders and wharf structures adjacent to Slipway Complex likely contributed to improved water quality as this group of animals are reported to remove nitrogen and phosphorous from the ambient water (Geraci *et al*. 2008). High siltation due to constant dredging activities also might have impeded the recruitment of foulers and affected their diversity at Marine Foreman Jetty (Marques-Silva *et al*. 2006). Further, these observations are in concurrence with the findings of Johnston & Roberts (2009) who found that contaminants reduce the richness and evenness of marine communities.

As expected, dominance of fouling forms is in contrast to diversity, and evenness by a way of a reverse trend *i.e.,* gradual scaling up of dominance from Slipway Complex to Ore Berth to Marine Foreman Jetty during both the years. Such interrelationships between these community parameters are in accordance with the established principle, which states that dominance decreases with increasing diversity and evenness (Magurran 1988). Much the same way, species richness, diversity, and evenness on long-term panels generally increased while dominance decreased with increasing panel exposure time during both years at the three sites, but for Marine Foreman Jetty these indices varied inconsistently. One of the main reasons for such contradiction is sloughing of some foulers from the panels due to their own increasing weight (Balaji 1988). With augmented exposure of panels, stability of the communities had also increased as suggested by the increase in evenness and decrease in dominance. During the present study, the type of dominant biofouling species changed on monthly basis, but the dominancy pattern repeated on a seasonal basis as pointed by Hoagland & Crocket (1979).

The changes in species richness and abundance of biofouling species suggest that a significant temporal change has occurred in the fouling communities at Visakhapatnam harbour over a span of about two and a half decades. For example, the stenohaline species *H. elegans* was totally absent during the earlier study by Balaji (1988), but was sporadically present in this study at Marine Foreman Jetty likely due to relatively narrow fluctuations in salinity (19.1 to 33.8) than what was previously reported (12.5 to 31.0). Reduction in salinity fluctuations at this jetty in recent years is due to diversion of city's drain water to a sewage treatment plant resulting in ephemeral freshwater discharge through Southern Lighter Channel and slightly elevated salinity levels. However, no bryozoan was recorded from this site during the present investigation even though certain species of this group are known to occur in localities with low salinity fluctuations (Cook 1968; Maturo 1968; Satyanarayana Rao & Ganapati 1978) probably because of pollution stress (Koçak 2007; Satyanarayana Rao & Ganapati 1978) or due to the time required for the organisms to recolonize the habitat already occupied by the opportunistic species.

Among the various parameters, salinity, and pollution factors like BOD, nitrite, phosphates and silicates were the most significant factors determining biofouling community structures and compositions at Visakhapatnam harbour. Sahu *et al*. (2011) also observed that salinity influenced biofouling settlement at Kalpakkam. Ramadan *et al*. (2006) and Swami & Udhayakumar (2008) documented that pollution adversely affected fouling composition by reducing species richness, diversity, and evenness. Hence, the formation of a divergent biofouling community at Marine Foreman Jetty (clearly distinct from Slipway Complex and Ore Berth) may be due to the combined effect of salinity and pollution.

Species richness and composition of biofoulers in Visakhapatnam harbour have changed dramatically over the past two and half decades. Since salinity and pollution influence the structure and composition of biofouling, any change in these factors can affect the biota. Temporal changes in biofouling communities can be a hindrance to biofouling management, which leads to further economic loss.

Conclusions

Three distinct groups of foulers were identified at Visakhapatnam harbour *viz.* marine species commonly found in low water dynamic environments, opportunistic species with different degrees of tolerance to organic enrichment, and typical brackish water species. Species richness, diversity, and evenness decreased from Slipway Complex to Ore Berth to Marine Foreman Jetty in association with a gradual increase in pollution and a decrease in salinity. Salinity, BOD, nitrite, phosphate, and silicate are considered to be the major influencing environmental parameters determining the structure of biofouling communities at Visakhapatnam harbour. Temporal shifts in biofouling structure and composition at this harbour over the years are possibly due to changes in influencing environmental parameters. Such changes in biofouling community can significantly affect the control methods used to overcome the biofouling problems associated with human infrastructure, which may become an additional economic burden.

Acknowledgements

Many thanks to the authorities of the Indian Council of Forestry Research and Education; Ministry of Shipping, Road Transport and Highways (Government of India); National Institute of Oceanography (Goa) and Visakhapatnam Port Trust for promoting the project and its activities. Special thanks to Dr. Rolando Bastida-Zavala, Dr. Richard Willan, Dr. (Mrs.) Shirley Slack-Smith, Dr. N. V. Subba Rao, Shri K. V. Surya Rao, Dr. Anil Mohapatra and Dr. V. K. Meenakshi for confirming the identification of foulers. Thanks to the Director, Zoological Survey of India, Kolkata, for support and encouragement.

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(Received on 18.07.2012 and accepted after revisions, on 02.09.2013)