Environ Monit Assess (2007) 127:283–291
DOI 10.1007/s10661-006-9279-5

ORIGINAL ARTICLE

Eutrophication status of marine environment of Mumbai and Jawaharlal Nehru ports

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Received: 8 August 2005 / Accepted: 8 May 2006 / Published online: 7 September 2006

Abstract The marine environment of Mumbai and Jawaharlal Nehru ports was monitored for some environmental and biological parameters during three different periods between 2001 and 2002. The results are compared with the records available since 1960s. With the passage of time the environmental status underwent changes, probably due to the increase in anthropogenic activities in the metropolis. The nutrient level especially the nitrate concentration has increased gradually over the years with a simultaneous decrease in dissolved oxygen, indicating increase in the biological activity. Characterization of this environment based on Assessment of Estuarine Trophic Status (ASSETS) model indicates that the current status is poor and may get worsen in future if no appropriate management policies are put into place.

Keywords Anthropogenic · Environment · Eutrophication · Jawaharlal Nehru · Marine · Modeling · Mumbai · Nutrients

1 Introduction

Unprecedented increase of human activities, in and around Mumbai, has imposed considerable stress on the surrounding marine environment, including Mumbai harbour. Mumbai is one of the fastest growing regions of India. Its population has increased from 4 million in 1960 to 7.7 million in 1971. It is projected to increase from 18.3 million as per 2001 census to 22.4 million in 2011. This increase in population are well on the potential expansion of trade through shipping is likely to worsen the situation unless management policies are put into place (Acharya and Nangia, 2004).

Review of literature indicates that the marine environment, especially western side of Mumbai, Thane Creek, Dharamtar Creek and offshore areas have been investigated for chemical, biological and physical parameters as early as forties. During Port Biological Baseline Surveys of Global Ballast Water Management Program (GloBallast), a GEF/UNDP/IMO initiative, we had an opportunity to collect samples from Mumbai and Jawaharlal Nehru harbours for wide range of parameters. Sampling was done on three different occasions at predetermined stations during the year 2001–2002. The results have been discussed in relation to changes in anthropogenic activities over few decades. Efforts have been made to classify the ecosystem using the Assessment of Estuarine Trophic Status (ASSETS) model approach (Bricker *et al.*, 2003), which deals with indices of three components, such as Pressure–Overall Human Influence, State–Overall Eutrophic Condition and Response–Determination of Future Outlook. In brief the ASSETS approach is an integral framework that takes into account nutrient role and its implications in biological and chemical characteristics.

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1.1 Description of the environment

Mumbai harbour is a natural harbour situated on the west coast of India (18° 54′N; 72° 40′E). It is a semi-enclosed basin which opens into the Arabian Sea at its southwesterly side. On the upstream, it is connected by Thana-Creek, which receives waste from heavily industrialized Thane-Belapur belt. In addition the Mumbai metropolis waste, which is discharged through various points also influences the harbour environment (Naidu and Shringapure, 1975; Zingde *et al.*, 1979; Deshmukh and Nair *et al.*, 1981; Kagwade, 1987; Zingde *et al.*, 1989; Ramaiah *et al.*, 1992; Ramaiah and Nair, 1993; Ramaiah and Nair, 1997; Ramaiah and Nair, 1998; Swami *et al.*, 2000; Zingde and Govindan, 2000).

This paper presents eutrophication status of marine environment of mumbai and jawaharlal nehru ports.

2 Materials and methods

2.1 Sampling locations and methodology

Sampling stations were selected based on the type of habitats. These habitats were characterized as enclosed docks, semi enclosed docks, ship building/repair docks, tidal berths, fishery jetty, recreational area, navigational channel, ship breaking yards, area of low circulation and potential sedimentation, etc. Total 36 stations were selected in the harbours of Mumbai and Jawaharlal Nehru. Sampling was carried out during November 2001, May 2002 and November 2002, representing post-monsoon, pre-monsoon and post-monsoon respectively. Data for monsoon season could not be collected due to inclement weather conditions.

Water samples were collected from sub-surface and near-bottom level using Niskin water sampler and analyzed for salinity, dissolved oxygen, nutrients, suspended matter, and chlorophyll *a*. Temperature and pH were also recorded simultaneously. Samples were collected in triplicate. Standard procedures were used for the analyses of these parameters (Parsons *et al*., 1984). In addition, secchi depth was measured at all the stations in the study area. The results of each parameter for more than one station within the same habitat were averaged to represent the locality. Thus 18 localities, as indicated in Fig. 1(1–18) within both the harbours, were formed. In addition, two stations off Mumbai coast were selected for reference and comparison purpose. These reference stations (19–20; Fig. 1) were considered to be far off from probable influence of any anthropogenic activities. The values of each parameter for different depths (sub-surface and near-bottom) and sampling periods (3 times) were averaged to get annual value for the water column.

Apart from these, efforts were also made to collect macroalgae from submerged and moored structures, as well as from intertidal rocky area. Collection of algae from the submerged structures was made through diving.

2.2 ECO-modeling

Efforts have been made to classify and grade the environment, under study, using an integrated methodology for Assessment of Estuarine Trophic Status (ASSETS). A detailed methodology on this approach is given by Bricker *et al.*, 2003. The methodology, in brief, involved development of Indices for Pressure–Overall Human Influence (OHI), State—Overall Eutrophic Condition (OEC) and response–Determination of Future Outlook (DFO) and combines the three components into one overall ASSETS rating using a matrix that assigns a grade to the environmental system under study. OHI was calculated on the basis of dissolved inorganic nitrogen input in the system, which was then subjected to classification into one of the five grades. These grades are Low, Moderate low, Moderate, Moderate high and High and scored as 5, 4, 3, 2, and 1 respectively. Data collected on nitrate concentrations during three different periods of the years (2001–2002) are used for this purpose.

For calculation of index for the state–OEC, five parameters, indicative of primary (early) and secondary (advanced) symptoms of eutrophication are considered. These parameters are Chlorophyll *a* and macroalgae as primary symptoms, whereas, dissolved oxygen, submerged aquatic vegetation (SAV), and occurrence of nuisance and/or toxic algal blooms (NTB) are considered for secondary symptoms. Each of the parameters is assigned an expression value ranging from 0.25 for a low concentration/observation to 1 for a high concentration/observation. Depending on the ranges, the expression values are categorized into different levels as Low, Moderate and High. Finally the primary and secondary symptoms are compared with a matrix proposed by Bricker *et al*. (2003), to determine an overall

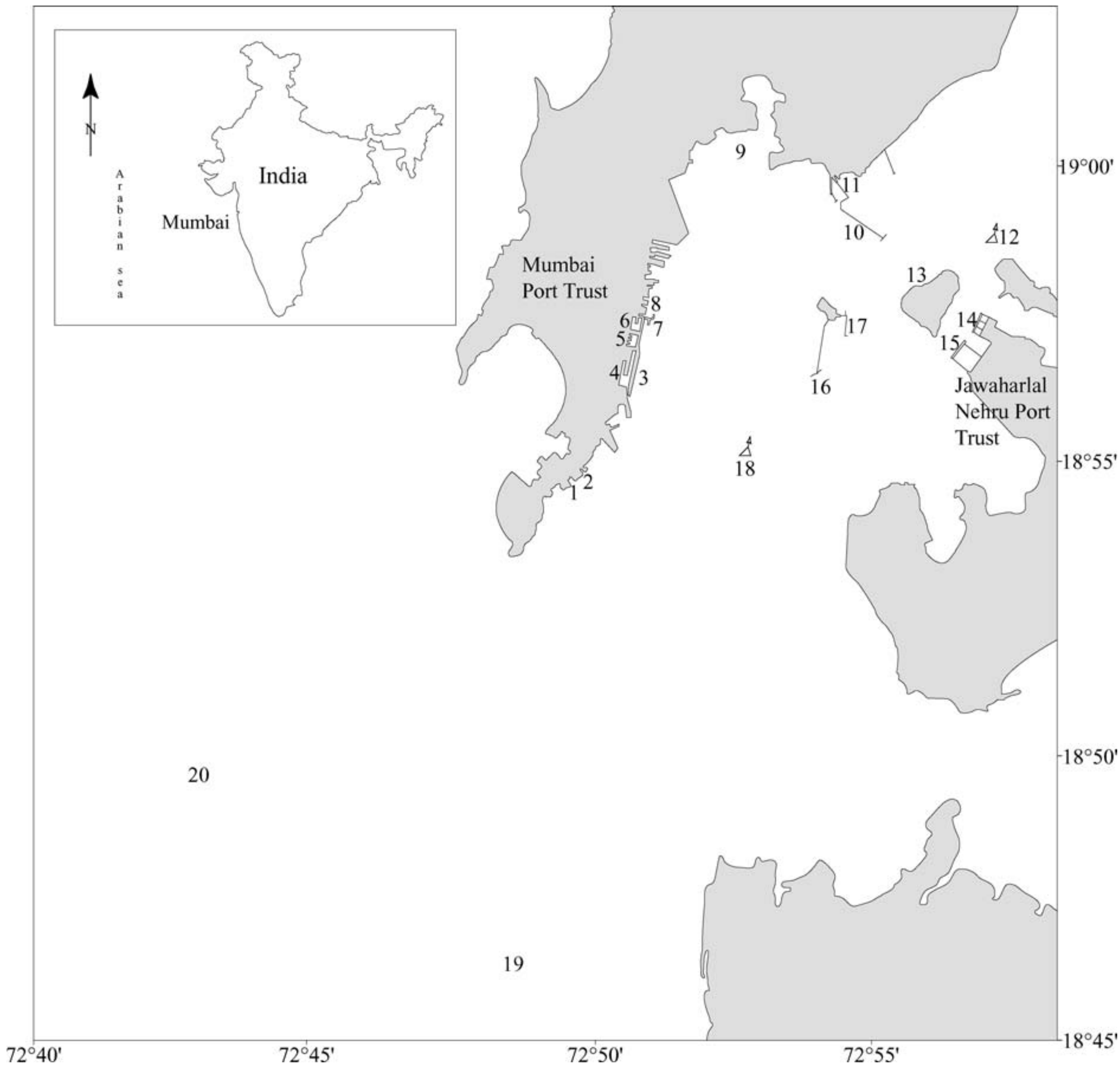

Fig. 1 Sampling locations at Mumbai and Jawaharlal Nehru ports (1–18) and Offshore (19–20). (1) Sasoon Dock; (2) Apollo Bandar; (3) Harbour Wall; (4) Indira Dock; (5) Victoria Dock; (6) Princess Dock; (7) Ferry Warf; (8) Kasara Basin; (9) Mahul Creek; (10) Old Pipav; (11) New Pipav; (12) JNP Marker Buoy; (13) Elephanta; (14) JNP Container Berth; (15) JNP Bulk Berth; (16) Jawahar Dweep Berth1; (17) Jawahar Dweep Berth 3–4; (18) MP Marker Buoy; (19) Offshore South; (20) Offshore North

ranking of eutrophic conditions for the ecosystem under study.

Response- DFO of the ecosystem is graded into one of the three categories based on assessment of the susceptibility (dilution and flushing potential) and its future nutrient pressure.

The indices of OHI, OEC and DFO are put into combination matrix to provide an overall grade to the ecosystem, which fall into one of the five categories: High, Good, Moderate, Poor or Bad.

3 Results

Results of various physico-chemical parameters of the environment of Mumbai and Jawaharlal Nehru harbours have been presented in Fig. 2,Tables 1 and 2.The water temperature at both the harbours did not change significantly and varied between 29 to 30°C. There was no significant variations in the pH values (7.9–8.1). The Secchi depth values ranged between 0.1 to 1.0 m for harbour waters, whereas, for Mumbai

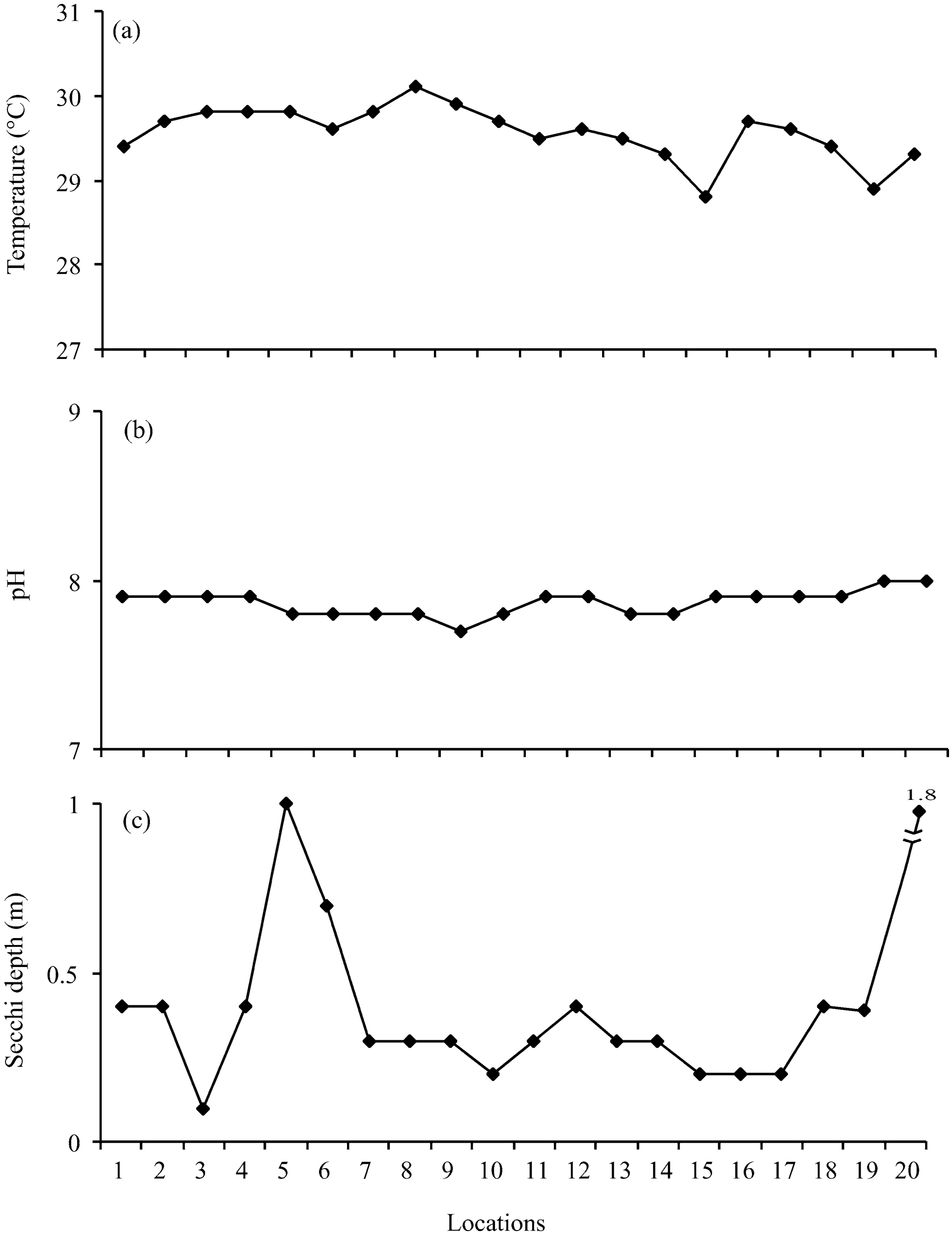

Fig. 2 Variations in temperature (a), pH (b) and secchi depth (c)

offshore sites it was 0.4–1.8 m indicating reduction of transparency due to high suspension of particulate matter in the harbour waters. The values for total suspended matter ranged between 25.3 to 159.9 mg L^{-1} with an average value of 92.9 mg L^{-1} in harbour waters, whereas, it varied from 51.2 to 57.4 mg L^{-1} for offshore waters. Salinity values varied between 34.8 to 35.8 PSU for the entire study area. The dissolved oxygen content of the seawater ranged between 2.7 to 5.3 mg L^{-1} with an average value of 4.3 mg L^{-1} for the water bodies of both the harbours. As against this, the offshore water at sub-surface level was found to contain comparatively higher amount of dissolved oxygen (6.0 mg L^{-1}).

As regards nutrients such as nitrate, nitrite, phosphate and silicate, the concentrations ranged from

Table 1 Annual average values of Dissolved Oxygen (DO), Salinity, Chlorophyll *a* and Suspended Particulate Matter (SPM) at different locations

Station/ Location	D. O. ($mg\,L^{-1}$)	Salinity (PSU)	Chlorophyll *a* ($mg\,L^{-1}$)	S.P.M ($mg\,L^{-1}$)
1	4.8 ± 0.4 ($n = 18$)	35.7 ± 0.4 ($n = 18$)	4.6 ± 1.6 ($n = 12$)	93.3 ± 26.7 ($n = 4$)
2	4.3 ± 0.4 ($n = 18$)	35.6 ± 0.3 ($n = 18$)	5.2 ± 0.8 ($n = 12$)	63.1 ± 36.8 ($n = 4$)
3	4.0 ± 0.7 ($n = 18$)	35.4 ± 0.4 ($n = 18$)	6.5 ± 2.4 ($n = 9$)	86.4 ± 91.1 ($n = 8$)
4	3.6 ± 0.4 ($n = 30$)	35.6 ± 0.3 ($n = 30$)	3.2 ± 1.8 ($n = 12$)	25.3 ± 10.5 ($n = 6$)
5	3.4 ± 0.7 ($n = 15$)	35.3 ± 0.3 ($n = 30$)	6.3 ± 4.7 ($n = 18$)	38.1 ± 44.9 ($n = 8$)
6	3.2 ± 0.7 ($n = 48$)	35.3 ± 0.5 ($n = 48$)	3.7 ± 1.8 ($n = 16$)	22.4 ± 4.2 ($n = 5$)
7	3.9 ± 0.8 ($n = 30$)	35.3 ± 0.4 ($n = 30$)	4.7 ± 1.7 ($n = 18$)	72.2 ± 45.8 ($n = 10$)
8	2.7 ± 0.5 ($n = 30$)	35.0 ± 0.4 ($n = 30$)	5.7 ± 1.5 ($n = 18$)	36.8 ± 21.6 ($n = 10$)
9	4.6 ± 0.4 ($n = 18$)	34.8 ± 0.86 ($n = 18$)	8.6 ± 0.3($n = 10$)	31.5 ± 13.0 ($n = 10$)
10	4.4 ± 0.3 ($n = 24$)	35.0 ± 0.56 ($n = 24$)	5.8 ± 2.7 ($n = 13$)	133.3 ± 164.1 ($n = 10$)
11	4.8 ± 0.1 ($n = 24$)	35.3 ± 0.61 ($n = 24$)	4.1 ± 2.4 ($n = 15$)	81.9 ± 106.7 ($n = 7$)
12	4.9 ± 0.6 ($n = 12$)	35.8 ± 0.80 ($n = 12$)	3.6 ± 2.3 ($n = 10$)	85.6 ± 53.3 ($n = 10$)
13	4.7 ± 0.2 ($n = 18$)	35.4 ± 0.87 ($n = 18$)	3.5 ± 2.2 ($n = 10$)	76.1 ± 85.7 ($n = 9$)
14	5.3 ± 0.2 ($n = 30$)	35.4 ± 0.64) ($n = 24$)	6.3 ± 2.0 ($n = 15$)	72.8 ± 64.4 ($n = 10$)
15	5.3 ± 0.2 ($n = 24$)	35.4 ± 0.54 ($n = 24$)	5.1 ± 2.3 ($n = 15$)	159.9 ± 115.4 ($n = 6$)
16	4.6 ± 0.5 ($n = 18$)	35.5 ± 0.60 ($n = 18$)	3.5 ± 1.9 ($n = 10$)	108.2 ± 136.7 ($n = 6$)
17	4.9 ± 0.7 ($n = 24$)	35.7 ± 0.65 ($n = 24$)	4.3 ± 1.6 ($n = 19$)	121.6 ± 106.1 ($n = 10$)
18	5.0 ± 0.3 ($n = 12$)	35.5 ± 0.33 ($n = 18$)	3.9 ± 2.1 ($n = 10$)	52.4 ± 22.3 ($n = 6$)
19[a]	6.0 ± 1.4 ($n = 9$)	35.7 ± 0.23 ($n = 18$)	2.6 ± 2.0 ($n = 10$)	51.2 ± 43.3 ($n = 9$)
20[a]	6.0 ± 0.6 ($n = 9$)	35.6 ± 0.24 ($n = 18$)	2.6 ± 2.5 ($n = 10$)	57.4 ± 65.6 ($n = 10$)

(1) Sasoon Dock; (2) Apollo Bandar; (3) Harbour Wall; (4) Indira Dock; (5) Victoria Dock; (6) Princess Dock; (7) Ferry Warf; (8) Kasara Basin; (9) Mahul Creek; (10) Old Pipav; (11) New Pipav; (12) JNP Marker Buoy; (13) Elephanta; (14) JNP Container Berth; (15) JNP Bulk Berth; (16) Jawahar Dweep Berth1; (17) Jawahar Dweep Berth3-4; (18) MP Marker Buoy; (19) Offshore South; (20) Offshore North.

[a] Values for sub-surface waters.

11–36.2, 0.4–6.4, 1 to 5.2 and 11.3–23.9 μM respectively (Table 2). In general, the nitrate concentrations in the waters of both the harbours appeared to be higher (11–36.2 μM) than the concentrations at offshore region (5.8–9.2 μM).

The annual average values for chlorophyll *a* ranged between 3.2 to 8.6 mg M^{-3} in harbour waters whereas, in offshore region it was 2.6 mg M^{-3} (Table 1).

In general the locality is poorly represented by macro algae and is found mostly at intertidal areas. The community comprised of 27 species belonging to 4 classes, of which Chlorophyta was dominant followed by Rhodophyta. Of the 27 species only 41% were found on submerged structures and the rest in the intertidal region. These results lead to an inference that the low transparency of water caused by high suspension of particulate matter could be the causative factor for limiting the growth of algae, in spite of high amount of nutrients in the area.

3.1 ECO-modeling

Table 4 shows aggregation of pressure (OHI), state (OEC) and response (DFO) components to provide an overall classification grade to the ecosystem of Mumbai and Jawaharlal Nehru harbours.

The OHI was calculated using the equation of Bricker *et al.* (2003), which requires the components, such as Offshore salinity (35.6PSU), Harbour water salinity (35.4PSU), Human derived land inputs (7.29 kg/s) (Zingde and Govindan, 2000) and nitrogen present in the offshore waters (10.1×10^{-9}). The value obtained for OHI by using the above parameters is 0.99, which falls under High category (>0.8) and represents grade 1 as per Table 4.

Logical decision process, proposed by Bricker *et al.* (2003) is used to determine overall eutrophication condition (OEC). For primary symptoms, chlorophyll *a* concentrations and algal growth were considered from

Table 2 Annual average values of nutrient concentrations at different locations

Station/ Location	Concentration (μM)			
	NO_3^- N	NO_2^- N	PO_4^{3-} P	SiO_2^{3-} Si
1	11 ± 7.3 ($n = 6$)	2.5 ± 1.6 ($n = 6$)	1.5 ± 0.9 ($n = 6$)	13.5 ± 4.9 ($n = 6$)
2	15.8 ± 5.6 ($n = 6$)	2.0 ± 0.9 ($n = 6$)	2.2 ± 1.0 ($n = 6$)	11.3 ± 2.7 ($n = 6$)
3	17.6 ± 3.0 ($n = 6$)	3.1 ± 1.4 ($n = 6$)	1.9 ± 1.6 ($n = 6$)	16.1 ± 5.7 ($n = 6$)
4	27.3 ± 5.3 ($n = 10$)	2.7 ± 1.3 ($n = 10$)	2.6 ± 2.0 ($n = 10$)	13.4 ± 3.8 ($n = 10$)
5	19.9 ± 4.6 ($n = 10$)	5.8 ± 5.1 ($n = 10$)	2.1 ± 0.8 ($n = 10$)	16.8 ± 7.8 ($n = 10$)
6	19.7 ± 5.6 ($n = 16$)	5.6 ± 3.6 ($n = 16$)	2.4 ± 1.2 ($n = 16$)	19.2 ± 4.7 ($n = 16$)
7	16.3 ± 10.2 ($n = 10$)	4.4 ± 3.0 ($n = 10$)	2.0 ± 0.8 ($n = 10$)	21.4 ± 7.3 ($n = 10$)
8	22.9 ± 4.8 ($n = 10$)	5.4 ± 4.2 ($n = 10$)	2.9 ± 1.2 ($n = 10$)	23.2 ± 6.2 ($n = 10$)
9	26.7 ± 19.1 ($n = 6$)	6.4 ± 4.4 ($n = 6$)	5.2 ± 4.3 ($n = 6$)	20.4 ± 10.7 ($n = 6$)
10	36.2 ± 17.5 ($n = 8$)	3.2 ± 2.2 ($n = 8$)	2.6 ± 0.8 ($n = 6$)	22.1 ± 4.9 ($n = 8$)
11	20.6 ± 13.2 ($n = 8$)	3.8 ± 3.5 ($n = 8$)	1.0 ± 1.3 ($n = 8$)	16.6 ± 8.1 ($n = 8$)
12	17.3 ± 16.4 ($n = 4$)	0.4 ± 0.1 ($n = 4$)	2.5 ± 1.6 ($n = 4$)	13.0 ± 13.3 ($n = 4$)
13	25.4 ± 13.0 ($n = 6$)	1.9 ± 0.8 ($n = 4$)	3.5 ± 1.0 ($n = 6$)	24.2 ± 5.9 ($n = 6$)
14	16.8 ± 6.0 ($n = 6$)	0.6 ± 0.4 ($n = 8$)	1.9 ± 0.4 ($n = 6$)	17.1 ± 7.3 ($n = 6$)
15	18.5 ± 3.2 ($n = 10$)	1.3 ± 0.6 ($n = 10$)	1.7 ± 0.8 ($n = 10$)	23.9 ± 4.1 ($n = 10$)
16	20.9 ± 5.5 ($n = 6$)	1.1 ± 0.3 ($n = 6$)	2.5 ± 0.6 ($n = 6$)	20.3 ± 2.9 ($n = 6$)
17	22.7 ± 6.6 ($n = 8$)	0.9 ± 0.3 ($n = 8$)	2.1 ± 1.2 ($n = 6$)	18.2 ± 6 ($n = 10$)
18	13.4 ± 4.8 ($n = 6$)	1.9 ± 0.9 ($n = 6$)	1.5 ± 1.0 ($n = 6$)	12.8 ± 5.6 (n = 6)
19	5.8 ± 2.8 ($n = 6$)	1.2 ± 1.8 ($n = 6$)	1.4 ± 1.2 ($n = 6$)	13.0 ± 6.1 ($n = 6$)
20	9.2 ± 4.2 ($n = 6$)	0.8 ± 0.9 ($n = 6$)	1.0 ± 0.5 ($n = 6$)	13.7 ± 4.7 ($n = 6$)

the recent observations. The 90th percentile for chlorophyll *a* and 10th percentile for dissolved oxygen were used to determine the concentrations. The 90th percentile value for chlorophyll *a* is 5.2 mg M^{-3}, which falls into a medium range and accordingly an expression value of 0.5 is assigned (Table 3).With regard to macroalgae the growth is scanty as per the recent observation, hence the symptom level is considered as "unknown", and assigned an expression value of 0.25 (Table 3). Secondary symptoms comprised of dissolved oxygen, submerged aquatic vegetation (SAV) and nuisance and toxic algal blooms. In case of dissolved oxygen 10th percentile value (3.2 mg L^{-1}) is taken for expressing secondary symptoms, which suggests biologically stressed conditions (Bricker *et al.*, 2003). The expression values, as per logical decision process, for dissolved oxygen, SAV and nuisance and toxic algal blooms were 0.5, 0, 0 respectively (Table 3).

These expression values were then used to calculate Primary and Secondary symptoms by using a formula suggested by Bricker *et al.* (2003), and are found to be 0.37 and 0.5 respectively. Then these two scores are combined by the matrix for determination of OEC (Bricker *et al*. 1999) and these values are found to be falling under moderate level of expression of symptoms (>0.3 to ≤0.6), which suggests as per Table 4,that the level of expression of eutrophic condition is substantial and could be graded as 3.

Table 3 Logical decision process for determination of overall eutrophic condition

Parameter	Symptom level	Spatial coverage	Frequency	Grade	Value
Primary symptoms					
Chlorophyll *a*	Medium	High	Episodic	Moderate	0.5
Macro algae	Unknown	Any spatial coverage	Unknown	Moderate	0.25
Secondary symptoms					
Dissolved oxygen	Biological stress	High	Periodic	Low	0.5
SAV	No losses	Not applicable	Not applicable	Not applicable	0
Nuisance & toxic bloom	No problem	Not applicable	Not applicable	Not applicable	0

Table 4 Aggregation of pressure (OHI), state (OEC) and response (DFO) components to provide an overall classification grade (So: Bricker *et al.*, 2003)

Grade	5	4	3	2	1
Pressure (OHI)	Low	Moderate low	Moderate	Moderate high	Low
State (OEC)	Low	Moderate low	Moderate	Moderate high	High
Response (DFO)	Improve high	Improve	No change	Worsen low	Worsen
Metric		**Combination matrix**			**Class**
P		5 5 5 4 4 4			High
S		5 5 5 5 5 5			
R		5 4 3 5 4 3			
P		5 5 5 5 5 5 5 4 4 4 4 4 3 3 3 3 3 3			
S		5 5 4 4 4 4 4 5 5 4 4 45 5 5 4 4 4			Good
R		2 1 5 4 3 2 1 2 1 5 4 3 5 4 3 5 4 3			
P		5 5 5 5 5 4 4 4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 2 2 2 1 1			
S		3 3 3 3 3 4 4 3 3 3 3 3 5 5 4 4 3 3 3 4 4 4 4 4 3 3 3 2 3 3			Moderate
R		2 1 5 4 3 2 1 5 4 3 2 1 2 1 2 1 5 4 3 5 4 3 2 1 5 4 3 5 5 4			
P		4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 1 1 **1** 1 1			
S		2 2 2 2 2 3 3 2 2 2 2 2 3 3 2 2 2 2 3 3 **3** 2 2			Poor
R		5 4 3 2 1 3 2 5 4 3 2 1 2 1 4 3 2 1 3 2 **1** 5 4			
P		3 3 3 3 3 2 2 2 2 2 1 1 1 1 1 1 1 1			
S		1 1 1 1 1 1 1 1 1 1 2 2 2 1 1 1 1 1			Bad
R		5 4 3 2 1 5 4 3 2 1 3 2 1 5 4 3 2 1			

With regard to DFO, this area is described to have a tidal range of 4 m. The simulation of the tidal currents carried out with MIKE-21 software indicates that even 4 m tidal range is not effective in flushing out bay waters within a tidal cycle. The data collated over the 4 decades on the amount of sewage discharge (single value for each decade) in the harbour waters shows an upward trend (Fig. 3a).If this trend continues, it will lead to further increase of nutrient pressure in future. Therefore, nutrient related symptoms are likely to worsen and hence graded 1 (Table 4).

In summary the grades allocated for the environment are 1, 3 and 1 for OHI, OEC and DFO respectively. These grades when compared with ASSETS matrix in Table 4 grades the environment as POOR.

4 Discussion

Pollution status of any given environment can be assessed either through monitoring of specific pollutant or changes in inherent biotic and abiotic parameters. In case of pollution caused by domestic wastewater including sewage, the degree of pollution can be assessed through changes in some of the biological and environmental factors, especially enrichment of nutrients. Nutrient enrichment of coastal areas may have far reaching consequences, such as fish kill, interdiction of shellfish aquaculture, loss or degradation of sea grass beds and smothering of bivalves and other benthic organisms (Twilley *et al.*, 1985; Burkholder *et al.*, 1992; Rabalais and Harper, 1992; Joint *et al.*, 1997; Glasgow and Burkholder, 2000; McGlathery, 2001). These events can have significant economic and social implications (Turner *et al.*, 1998).

In recent times Mumbai's population and industries have grown to a larger extent, resulting in generation of over 2485 MLD of wastewater including sewage. This has exerted enormous pressure on the adjacent marine environment, including harbour. Apart from receiving local sewage and industrial waste, the harbour environment is also subjected to inoculation of non-native waters containing wide range of pollutants and biota through ships' ballast. Data collected through ballast water reporting forms (under GloBallast program) from 4581 vessel visits for the period from 2000–2002, was 2,619,625 tonnes of ballast water received by Mumbai and Jawaharlal Nehru harbours through national and international shipping. (Anil *et al.*, 2003).

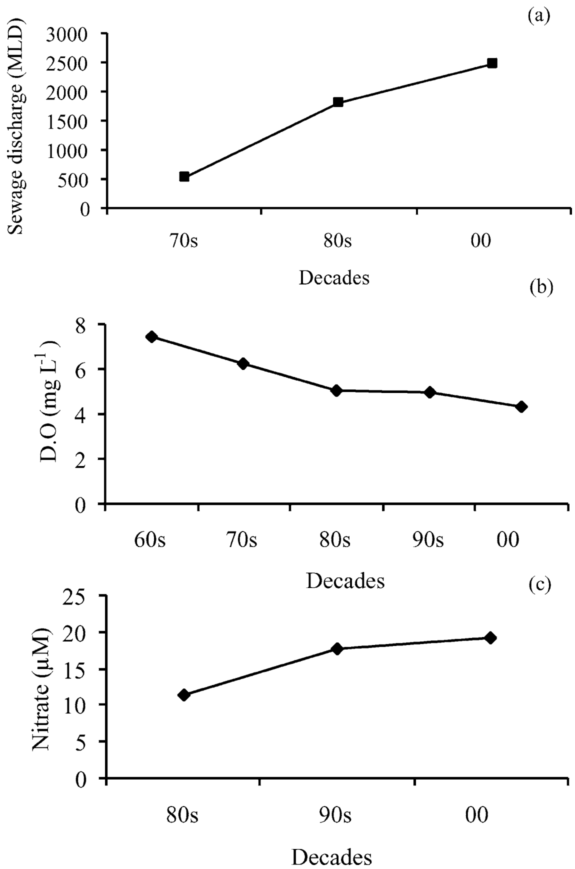

Fig. 3 Variations in Sewage (a), Dissolved oxygen (b) and Nitrate (c) content in Mumbai Harbour for different decades (data points, $n = 1–4$)

In order to assess the present status of environmental degradation, we have collated data on some of the environmental parameters from published literature (Naidu and Shringapure, 1975; Zingde *et al.*, 1979; Deshmukh and Nair *et al.*, 1981; Kagwade, 1987; Zingde *et al.*, 1989; Ramaiah et al., 1992; Ramaiah and Nair, 1993; Ramaiah and Nair, 1997; Ramaiah and Nair, 1998; Swami *et al.*, 2000; Zingde and Govindan, 2000) from the 1960s onward and compared with the present set. The data on sewage discharge has also been collected for different decades and compared with the changes in concentrations of parameters. Dissolved oxygen is the most essential component for the marine life. Dissolved oxygen content exhibited a gradual decrease (Fig. 3b), over the last 5 decades. Decrease of DO level in harbour waters suggests higher rate of utilization, which could be due to increase of organic waste in the environment. Though data is limited, the wastewater discharge over the years indicates a profound influence on dissolved oxygen and nitrate concentrations (Fig. 3c). Zingde and Govindan, (2000), report that wastewater of Mumbai contains 35 mg L^{-1} of total nitrogen and could be the causative factor for increase of nitrate concentrations in the environment.

As per the output of eco-model the ecosystem of Mumbai and Jawaharlal Nehru harbours falls under poor category. There could be number of reasons for grading this ecosystem as poor. Some of these reasons could be attributed to low fresh water influx as evident from salinity data during the period of investigation, low dilution and flushing potential (Gupta *et al.*, 2004), which all contribute to making this system highly susceptible. In addition to other factors, low flushing increases the coupling between pressure (OHI) and state (OEC). Higher salinity and temperature during non-monsoon periods also tend to offer low oxygen storage capacity (% saturation) to the ecosystem under study, resulting higher pressure. Oxygen saturation, in general, is in the range of 37.0–81.7% in harbour, which means that consumption is slightly higher than production. As against this the oxygen saturation for surface waters (96%) of offshore was higher than the harbour environment suggesting low dilution and/or flushing of bay water. These results suggest that the ecosystem of Mumbai harbour is highly influenced by human activities, both in terms of pressure (OHI) and the state (OEC).

The ASSETS approach grades Mumbai and Jawaharlal Nehru environment as poor. The investigation primarily suggests that the release of wastewater into the marine environment could be the causative factor for the degradation of the environment and calls for appropriate management measures to improve the health of the environment. In view of this, it seems to be appropriate to ensure reduction of organic load from the effluent to whatever extent possible through treatment at various stages. The treated effluents may then be discharged to the farthest marine point, which will ensure proper dilution and dispersion through diffusers. The point of discharge(s), could be identified after due scientific study to that effect. In addition it is pertinent to monitor the environment on regular basis to know the health of the environment.

Acknowledgements Authors are grateful to the Director, N.I.O. for his support and constant encouragements. Thanks are also due to Mr. S. Chakrabarthy and Mr. A. Chatterjee former and present country focal point respectively for Ballast Water Management Program in India. Logistic support provided by Dr. G. Joshi, CFP-A (BWMP) and Capt. Karkare, MPT during field work is also greatly acknowledged. We are also thankful to Dr. A.C. Anil and team members for their support and constructive suggestions. This is a NIO Contribution No. 4147

References

Acharya, A., & Nangia, P. (2004). Population growth and changing land-use pattern in Mumbai metropolitan region of India. *Caminhos de Geografia*, *11* (11), 168–185.

Anil, A.C., Clarke, C., Hayes, T., Hilliard, R. Joshi, G. Krishnamurthy, V., Polglaze, J., Sawant, S.S., & Raaymakers, S. (2003). Ballast water risk assessment: Ports of Mumbai and Jawaharlal Nehru, India. *IMO GloBallast Monograph Series*, No. 11. pp. 1–63.

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P., & Farrow, D.R.G. (1999). National estuarine eutrophication assessment: Effects of nutrient enrichment in the nation's estuaries. Silver Spring, MD: NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science, pp. 71.

Bricker, S.B., Ferreira, J.G., & Simas, T. (2003). An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling*, *169*, 39–60.

Burkholder, J.M., Mason, K.M., & Glasgow, Jr. H.B. (1992). Water column nitrate enrichment promotes decline of eelgrass *Zostera marina*: evidence from seasonal mesocosm experiments. *Marine Ecology Progress Series*, *81*, 163–178.

Deshmukh, V.D., & Kagwade, P.V. (1987). Larval abundance of non-peannid prawns in the Bombay harbour. *Journal of Marine Biology Association of India*, *29*, 291–296.

Glasgow, H.B., & Burkholder, J.M. (2000). Water quality trends and management implications from a five-year study of a eutrophic estuary. *Ecology Application*, *10* (4), 1024–1046.

Gupta, I., Dhage, S., Chandorkar, A.A., & Srivastav, A. (2004, Numerical modeling for Thane Creek, *Environment Modelling Software*, *19*, 571–579.

Joint, I., Lewis, J., Aiken, J., Proctor, R., Moore, G., Hingman, W., & Donald, M. (1997). Interannual variability of PSP (Paralytic Shellfish Poisoning) outbreaks on the north east UK coast. *Journal of Plank. Research*, *19*, 937–956.

McGlathery, K.J. (2001). Macroalgal blooms contribute to the decline of seagrass in nutrient-enrihed coastal waters. *Journal of Phycology*, *37*(4), 453–456.

Naidu, J.R., & Shringarpure, S.G. (1975). Hydrological characteristics of the Bombay harbour bay. *Journal of Marine Biological Association of India*, *17*, 82–86.

Nair, V.R., Gajbhiye, S.N., & Desai, B.N. (1981). Distribution of chaetognaths in the polluted and unpolluted waters around Bombay. *Indian Journal of Marine Science*, *10*, 66–69.

Parsons, T.R., Maita, Y., & Lalli, C.M. (1984). *A manual of chemical and biological methods for seawater analysis*. Oxford: Pergamon Press.

Rabalais, N.N., & Harper, D.L., Jr. (1992). Studies of benthic biota in area affected by moderate and severe hypoxia. In: National Oceanic and Atmospheric Administration, Coastal Ocean Program Office, Nutrient Enhanced Coastal Ocean Productivity, Proceedings of a Workshop, Louisiana university Marine Consortium, October 1991. Sea Grant Program, Texas A and M University, Galveston, TX, TAMU-SG-92–109. pp. 150–153.

Ramaiah, N., Abbas, M.S., & Nair, V.R. (1992). Distribution of decapod larvae in the Bombay harbour–Thana–Bassein Creek region. *Journal of Indian Fisheries Association*, *22*, 21–32.

Ramaiah, N., & Nair, V.R. (1993). Population abundance and species composition of chaetognaths in the Bombay harbour–Thana and Bassein Creek estuarine complex. *Indian Journal of Marine Science*, *22*, 89–93.

Ramaiah, N., & Nair V.R. (1997). Distribution and abundance of copepods in the pollution gradient zones of creek, west coast of India. *Indian Journal of Marine Science*, *26*, 20–25.

Ramaiah, N., & Nair, V. R. (1998). Phytoplankton characteristics in a polluted harbour–Thana–Bassein creek estuarine complex. *Indian Journal of Marine Science*, *27*, 281–285.

Swami, B., Suryawanshi, U.G., & Karande, A.A. (2000). Water quality status of Mumbai (Bombay) harbour—an update. *Indian Journal of Marine Science*, *29*, 111–115.

Turner, R.K., Adger, W.N., & Lorenzoni, L. (1998). Towards integrated Modelling and Analysis in Coastal Zones: Principles and Practices, LOICZ Reports and studies. No. 11, iv, LOICZ IPO, Texel, The Netherlands, pp. 122.

Twilley, R.R., Kemp, W.M., Staver, K.W., Stevenson, I.C., & Boranton, W.R. (1985). Nutrient enrichment of estuarine submersed vascular plant communities. I. Algal growth and effects on production of plants and associated communities. *Marine Ecological Progress Series*, *23*, 179–191.

Zingde, M.D., Trivedi, S.K., & Desai, B.N. (1979). Physico-chemical studies on coastal pollution off Bombay. *Indian Journal of Marine Science*, *8*, 271–277.

Zingde, M.D., Bhosle, N.B., Narvekar, P.V., & Desai, N.B. (1989). Hydrography and water quality of Bombay harbour. *Environment of Strategic Bioscience*, 37–58.

Zingde, M.D., & Govindan, K. (2000). Health status of the coastal waters of Mumbai and regions around. In: Sharma, V.K., (ed.) *Environmental problems of coastal areas in India* (pp. 119–132). New Delhi: Publisher, Bookwell.