Influence of anthropogenic activities on the existing environmental conditions of Kandla Creek (Gulf of Kutch)

P. V. Shirodkar[1,]*, U. K. Pradhan[1], Dearlyn Fernandes[1], Sonali R. Haldankar[1] and G. S. Rao[2]

[1]National Institute of Oceanography, CSIR, Dona Paula, Goa 403 004, India
[2]Kandla Port Trust, Vadinar Oil Terminal, Vadinar 361 010, India

Water characteristics of Kandla creek, monitored seasonally from 2002 to 2006 at four locations (mouth, cargo jetty, oil jetty and junction), indicated significant increases in nutrients, petroleum hydrocarbons (PHc) and phenols from anthropogenic additions, while increases in turbidity, total suspended solids (TSS) and salinity from natural effects. Principal Component Analyses (PCA) of the data indicated port activities contaminating the creek water by fall out from loading and unloading of fertilizer and raw materials; petroleum, oil and lubricants (POL) and the boat traffic. Strong macro tidal currents increase turbidity and TSS, while the high salinity water from creek tributaries formed from intense evaporation during summer, and the seepage of brines in the creek from nearby salt pans during monsoonal drainage increase the salinity of creek water. Despite the presence of large nutrients, the decreasing chlorophyll *a* (Chl *a*) and primary productivity (PP) during monsoon indicated detrimental effects of turbidity, suspended solids, phenols and PHc.

The quality of creek water evaluated based on overall index of pollution (OIP), calculated from the water quality index (WQI) of each parameter, suggested polluted water at junction, oil jetty and at cargo jetty; while a slightly polluted water at the creek mouth during pre-monsoon and monsoon seasons. During post-monsoon, the slightly polluted water was observed at all the four locations. The study indicated that the strong ebb currents in the creek however transport anthropogenic nutrients, PHc and phenols to the inner Gulf of Kutch.

Keywords: Anthropogenic contaminants, environ mental factors, Gulf of Kutch, Kandla creek, water characteristics.

CREEKS are synonymous to estuaries where the mixing of freshwater and salt water and the stirring up by tides takes place. The hydrographic conditions of the creek are peculiar and affect their flora and fauna. Kandla creek, one of the major creeks of the Little Rann (Figure 1), is located in the eastern region of the Gulf of Kutch (GoK). It receives negligible freshwater flow, except during monsoon and is influenced by macrotides (7.2 m tidal range). The Kandla port, which handles various types of voluminous cargo, largely oil and petroleum products (POL – petroleum, oil and lubricants), industrial chemicals, fertilizers, food grains, ores, etc. is located along the western bank of Kandla creek[1–5]. The various port activities act as potential sources of waste generation and contaminate the creek water. The strong macrotidal currents in the creek drain these contaminants into the adjoining inner GoK, which is highly productive, having identified areas of Marine Sanctuary and Marine National Park[6]. The contaminants on entering the inner GoK can exert stress on the Marine Sanctuary and Marine National Park and is a cause of concern. In order to understand the seasonal variability in physico-chemical characteristics of creek water in relation to anthropogenic flow and their impacts on water quality and the biological characteristics, this study was carried out at four selected locations in Kandla creek, continuously over five years period from 2002 to 2006 under the environmental monitoring programme of the Kandla Port Trust (KPT).

Material and methods

Study area and its anthropogenic set-up

Kandla creek (22°55′–23°05′N and 70°05′–70°02′E) is one of the major creeks along the NW coast of India supplying water to the inner GoK, which is an east–west oriented indentation. GoK is 75 km wide at the mouth and after running about 170 km away from the Arabian Sea towards east, narrows down into a constriction at 70°20′E at Sathsaida Bet and then bifurcates into a creek system called the Little Rann (Figure 1). The Little Rann has a network of many small and large creeks, intermingled with marshy tidal flats rich in fine clays. Kandla creek is one of the major tributaries of this creek system, which

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*For correspondence. (e-mail: shirod@nio.org) empties into the inner GoK. Two large creeks, Sara and Phang creeks join the Kandla creek and act as its tributaries. Besides that, one more creek, Nakti creek also joins the Kandla creek at the confluence of Sara and Phang creeks. All these creeks bring water from Little Rann into the Kandla creek, which has a fairly good depth and stable banks. The width of the creek channel varies from 200 m in the upstream to 1000 m at the mouth and the depth varies from 8 to 12 m, while the tidal height ranges from 0.83 to 7.2 m, with tidal currents varying from 0.08 to 2 m/s (ref. 7).

Kandla port is located along the western bank of Kandla creek. It is well protected from strong monsoon winds and high waves of the coast, so is operational throughout the year and therefore acts as an all-weather port. Various industrial-chemical manufacturing units, fertilizer-manufacturing industry (IFFCO), salt manufacturing units with saltpans rich in brines occur around the Kandla creek. There are a total of six jetties in the creek used by the KPT, Indian Oil Corporation and IFFCO (Figure 1) for handling liquid bulk, POL, fertilizers, raw materials, industrial chemicals, iron and steel, food grains, metal and its products, mineral ore and other dry cargo, etc. The port facilitates extensive traffic of oil tankers, freighters, passenger cargo vessels, ore carriers, fishing boats and container vessels in Kandla creek. These activities generate different types of waste, which act as potential sources of contamination.

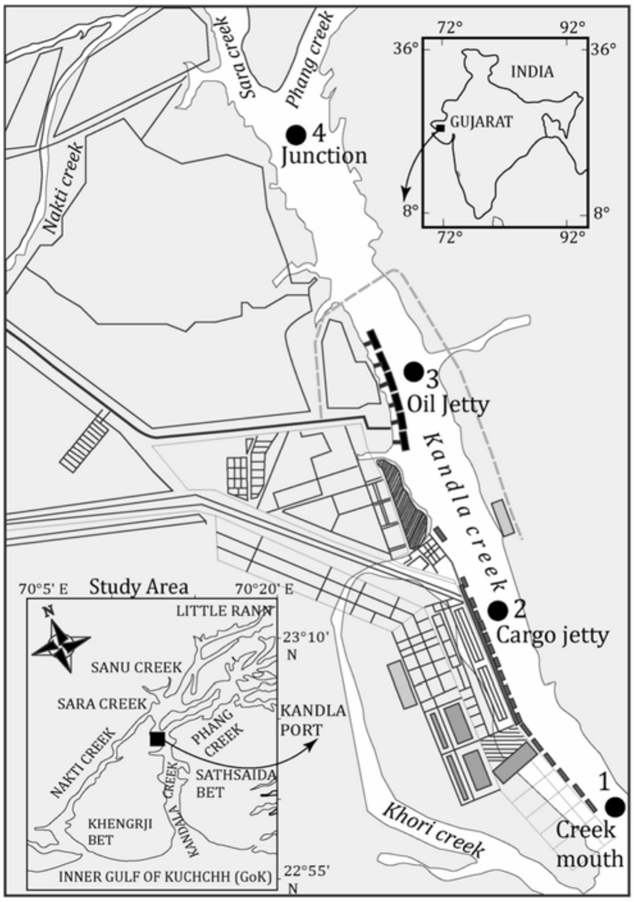

Figure 1. Sampling locations (•) in Kandla creek and the surrounding jetty facilities of Kandla port.

Sampling strategy and analyses

The periodic measurements of physico-chemical and biological parameters in Kandla creek were carried out under the environmental monitoring programme sponsored by the KPT administration. Water samples were collected regularly twice every season – pre-monsoon (February–May), monsoon (June–September) and post-monsoon (October–January) from surface, mid-depth and near bottom levels at four key locations (Figure 1) using a hired boat. With regard to anthropogenic activities, the sampling locations selected were cargo jetty and oil jetty, besides the two naturally influenced locations, one at the mouth of the creek and the other at the junction, where Sara and Phang creeks meet the Kandla creek.

The dissolved oxygen (DO) and biological oxygen demand (BOD_5) were measured according to Winkler's method, whereas standard methods were used for the analysis of dissolved inorganic nutrients[8]. Petroleum hydrocarbons (PHc) and phenolic compounds were measured by the spectrofluorometric and spectrophotometric methods respectively[9,10]. Nephelometry was used for turbidity measurements and total suspended solids (TSS) were measured by the filtration method[10]. Chlorophyll *a* (Chl *a*) and phaeophytin measurements were made using the Turner Fluorometer[11] and primary productivity (PP) by ^{14}C technique, wherein, radioactivity was measured using Perkin Elmer–Wallac 1409-011 Liquid Scintillation Analyser. The apparent oxygen utilization (AOU) value was obtained by subtracting the measured DO value from the saturation value computed at potential temperature of water and total pressure of 1 atm[12].

Data treatment

The multivariate ordination techniques were applied to segregated data matrices of three different seasons, containing 20 variables. This reduced the number of dimensions in data sets to two or three and allowed better detection of major trends or underlying patterns of variation in the data. The resulting ordination plots provided easy visualization of these patterns, which often represent a significant proportion of variability in the data[13]. Redundancy analysis (RDA) was used to explore the relationships between the measured physico-chemical and biological variables. RDA is a constrained form of principal component analysis (PCA), where the ordination axes are constrained to be linear combinations of environmental variables[14,15]. Data reduction techniques, such as PCA have been applied using R-mode varimax factor analyses for evaluating the dominant variables influencing the water quality of Kandla creek (using sorted values more than 0.4)[16–19]. The factor analysis has been carried out separately for data set of each season using the computer program SPSS 16.0 and STATISTICA 6.0 and the results are shown in Table 1. The observed scree plot was used to identify the number of principal components (PCs) to be retained in order to comprehend the underlying data structure[20]. The loadings of PCs were considered as strong (>0.75), moderate (0.5–0.75) and weak (0.4–0.5)[21–23]. The varimax normalized rotation (VNR) distributes the PC loadings such that their dispersion is maximized by minimizing the number of large and small coefficients[24]. To examine the reliability of these data for factor analysis through Kaiser–Meyer–Olkin (KMO), which measures the sampling adequacy[25], the obtained values of 0.850 and Cornbach's alpha of 0.892 (significance 0.05–0.01) were found during the analysis. Spearman's correlation matrix was used to identify the significantly correlated variables within the measured environmental data.

The water quality status in Kandla creek during the three seasons was evaluated using water quality index (WQI). For each water quality parameter, the WQI was measured individually by using the equation obtained from the value function curve in which, the concentration of the parameter is taken on *Y*-axis and the index value on *X*-axis and were plotted for each of the parameters. These measured values were then transformed into a single number, called the overall index of pollution (OIP), representing the overall quality of water at that particular location[26]. The OIP value was thus estimated as the average of all the pollution indices (P_i) for individual water quality parameters as per the mathematical expression:

$$\text{OIP} = \textstyle\sum_i P_i/n,$$

where P_i = pollution index for ith parameter, and i = 1, 2, ... , n; n = number of parameters.

Results

The data on various physico-chemical and biological characteristics along with their ranges of variation over different seasons are shown in Table 2. The spatial variation of different water quality parameters during the three seasons is shown in box and whisker plots (Figure 2 *a–r*). Box plots with long whiskers at the top of the box indicate that the underlying distribution is skewed towards high concentration[16] and those with a large spread indicate wide variations of parameters over different seasons.

Hydrographic characteristics

The creek water shows average high pH (>8), with an apparent increase from the mouth towards the junction during the pre-monsoon as compared to monsoon and the post-monsoon season. During monsoon, the pH though shows considerable variations, the average values show a decrease from the mouth towards the junction. During post-monsoon, the pH varies widely but the average values remain much below pH 8, and so are lower than those of pre-monsoon and the monsoon seasons (Figure 2 *b*). Salinity shows a narrow range, envisaging average high values gradually increasing from the mouth towards the junction during the pre-monsoon, due to dissolved salts formed from intense evaporation of water in the creek system and brought by the tributaries into Kandla creek. The monsoon season on the contrary shows significantly large variations in salinity, more prominent at the mouth and the junction locations, followed by that at oil jetty, indicating increasing values from the mouth towards the junction. This is due to the cumulative effect of the seepage of high salinity brines from the nearby salt pans into the creek water from monsoonal drainage and the dissolved salts formed during summer season and brought by the tributaries into Kandla creek. During post-monsoon, the salinity shows a significant decrease relative to other two seasons with values remaining nearly similar at all the four locations (Figure 2 *c*). Dissolved oxygen (DO) shows a narrow range of variation during pre-monsoon and a wider range during the monsoon with a gradual decrease in DO from the mouth towards the junction. During post-monsoon, the DO remains significantly high with a narrow range of variation, indicating an apparent decrease from the mouth towards the junction (Figure 2 *d*). DO solubility shows low variations during pre-monsoon while slightly wider variations during the monsoon season with a decrease from the mouth towards the junction. The post-monsoon season on the contrary shows a large variability at all the four locations, indicating apparent increase from the mouth towards the junction location (Figure 2 *e*). BOD shows increasing variations from the mouth towards the junction, except oil jetty, with average high values during the pre-monsoon, relative to other seasons. During monsoon, the variations are narrow and the values decrease at the mouth and oil jetty, but shows an apparent increase at cargo jetty and the junction location relative to pre-monsoon. However, the average BOD shows low values, with a decrease from the mouth towards the junction. During post-monsoon, the BOD varies widely at all the four locations and indicates increasing values from the mouth towards the junction. In general, the elevated levels of BOD however were observed at oil jetty, cargo jetty and the junction location (Figure 2 *f*). Total suspended solids (TSS) show wide variations, with increasing values from the mouth towards the junction during the pre-monsoon. The TSS values

Table 1. Varimax factor analysis using PCA and identified principal components during pre-monsoon, monsoon and post-monsoon season (% variance – % variance cumulative – % cumulative variance)

	(*a*) Pre-monsoon						(*b*) Monsoon						(*c*) Post-monsoon				
	PC1	PC2	PC3	PC4	PC5		PC1	PC2	PC3	PC4	PC5		PC1	PC2	PC3	PC4	PC5
PP	0.93					PHc	0.98					Temp	0.97				
PO_4–P	0.91					TSS	0.96					Sal	–0.95				
NO_2–N	0.89					Turb	0.90					PP	0.94				
Sal	–0.84					Sal	0.90					DO sol	–0.88				
NH_3–N	0.65			0.58		DO sol	–0.89					pH	0.87	–0.40			
TSS		0.89				Phenol	0.81					Chl *a*	0.79				
SiO_4–Si		0.88				SiO_4–Si	–0.64	0.45				NH_3	0.74				
Phenol	–0.46	0.80				Chl *a*	0.62					Phenol	–0.57	0.53			
pH	0.52	0.76				NO_2–N	–0.59		0.44			SiO_4–Si		0.97			
Turb		0.75	–0.47			BOD	–0.55					NO_2–N		0.95			
Temp	0.60	0.68				PO_4–P	0.44					NO_3–N		0.92			
NO_3–N	–0.51	0.62		0.50		PP		–0.94				PO_4–P		0.91			
AOU			0.84			Sacchi		–0.89				Phaeo		–0.69			0.43
Chl *a*			0.77			NO_3–N		0.70			0.41	AOU			–0.87		
DO sol		–0.41	0.72			pH			–0.87			DO	–0.46		0.83		
DO			–0.70			NH_3–N			0.84			BOD	–0.52		0.60		
Phaeo	0.47		0.69			AOU				–0.90		Turb				0.96	
BOD				0.86		DO	–0.48			0.83		TSS	–0.50			0.74	
Sacchi					0.85	Temp					0.75	Sacchi					0.82
PHc		0.41			0.66	Phaeo				0.43	0.60	PHc					0.48
Eigen	5.3	4.9	3.4	1.9	1.4	Eigen	7.1	3.1	2.2	2.1	1.5	Eigen	6.8	4.8	2.2	1.7	1.3
% var	26.4	24.7	16.9	9.3	6.9	% var	35.4	15.3	11.1	10.3	7.5	% var	34.0	23.8	10.8	8.3	6.6
Cumm.%	26.4	51.1	68.0	77.3	84.2	Cumm.%	35.4	50.7	61.7	72.1	79.6	Cumm.%	34.0	57.8	68.7	77.0	83.6

Table 2. Descriptive statistics (maximum, minimum, average, standard deviation and range) of physico-chemical parameters during different seasons

	Pre-monsoon					Monsoon					Post-monsoon				
Variables	Range	Minimum	Maximum	Average	Standard deviation	Range	Minimum	Maximum	Average	Standard deviation	Range	Minimum	Maximum	Average	Standard deviation
Temp	6.0	26.0	32.0	29.7	2.4	1.0	30.0	31.0	30.0	0.3	10.0	21.0	31.0	25.0	4.5
Sal	9.7	40.1	49.8	44.8	3.5	36.2	32.5	68.7	43.5	11.9	6.2	30.9	37.1	34.7	2.0
pH	0.6	7.6	8.2	8.0	0.2	0.9	7.4	8.3	8.0	0.2	0.6	7.5	8.1	7.8	0.2
Turb	767.8	77.2	845.0	483.9	201.2	924.9	84.1	1009.0	460.1	289.7	261.0	100.0	361.0	212.3	62.7
TSS	1526.0	100.0	1626.0	628.7	434.5	1484.0	97.0	1581.0	564.8	490.7	267.0	98.0	365.0	230.3	83.5
DO	1.2	5.0	6.2	5.8	0.3	2.1	4.2	6.3	5.2	0.6	2.6	4.9	7.5	6.3	0.4
DO sol	0.7	5.6	6.3	5.9	0.2	1.1	5.2	6.3	5.9	0.4	1.1	6.2	7.3	6.8	0.4
AOU	1.6	–0.4	1.2	0.2	0.4	2.4	–0.4	2.0	0.7	0.6	2.6	–0.5	2.1	0.5	0.5
BOD	5.0	0.6	5.6	1.4	1.3	1.9	0.2	2.1	0.7	0.5	2.6	0.2	2.8	1.3	0.7
PO_4–P	11.0	1.0	12.0	4.9	3.2	16.9	1.9	18.8	4.4	4.4	8.1	1.0	9.1	3.9	2.0
NO_3–N	15.0	1.0	16.0	6.0	4.3	12.5	0.0	12.5	7.0	3.3	10.6	3.6	14.2	8.3	3.1
NO_2–N	5.8	0.3	6.1	2.3	1.8	8.1	0.7	8.8	2.3	2.1	5.7	0.2	5.9	2.6	1.8
NH_3–N	18.0	1.1	19.1	5.6	4.3	7.7	1.3	9.0	4.3	2.2	16.1	1.0	17.1	6.0	4.7
SiO_4–Si	41.7	1.5	43.2	19.2	13.1	26.9	8.4	35.3	22.5	8.3	39.0	4.2	43.2	21.6	11.8
PHc	659.3	0.4	659.7	51.0	0.34	503.7	3.2	506.9	177.7	189.3	359.4	0.0	359.4	19.9	59.3
Phenol	14.0	1.0	15.0	7.0	5.1	15.4	3.0	18.4	8.9	4.5	40.0	0.0	40.0	9.1	8.3
Chl *a*	2.4	0.2	2.6	0.9	0.6	1.8	0.1	1.9	0.6	0.4	2.0	0.1	2.1	0.7	0.6
PP	1.7	0.0	1.7	0.5	0.6	1.2	0.1	1.3	0.5	0.5	1.9	0.0	1.9	0.7	0.7
Phaeo	2.0	0.1	2.1	0.6	0.5	1.4	0.1	1.5	0.3	0.3	1.4	0.1	1.5	0.3	0.3
Sacchi	0.4	0.1	0.5	0.2	0.1	0.1	0.1	0.2	0.1	0.0	0.2	0.1	0.3	0.2	0.0

Temperature (Temp), Salinity (Sal), Turbidity (Turb), Total suspended solids (TSS), Dissolved oxygen (DO), Biological oxygen demand (BOD), Oxygen solubility (DO sol.), Apparent oxygen utilization (AOU), Nitrate (NO_3–N), Phosphate (PO_4–P), Nitrite (NO_2–N), Ammonia (NH_3–N), silicate (SiO_4–Si), Petroleum hydrocarbon (PHc), Chlorophyll *a* (Chl *a*), Primary productivity (PP), Phaeophytin (Phaeo).

Units: Temp (°C), salinity (psu), pH (pH unit), TSS, DO, DO sol, AOU, BOD (mg/l^1), PO_4–P, NO_2–N, NH_3–N, NO_3–N, SiO_4–Si ($\mu mol/l^1$), turbidity (NTU), Sacchi (m), PHc, phenol (µg/l), Chl *a*, Phaeo (mg/m^{-3}) and PP ($mg/m^{-3}/h^{-1}$).

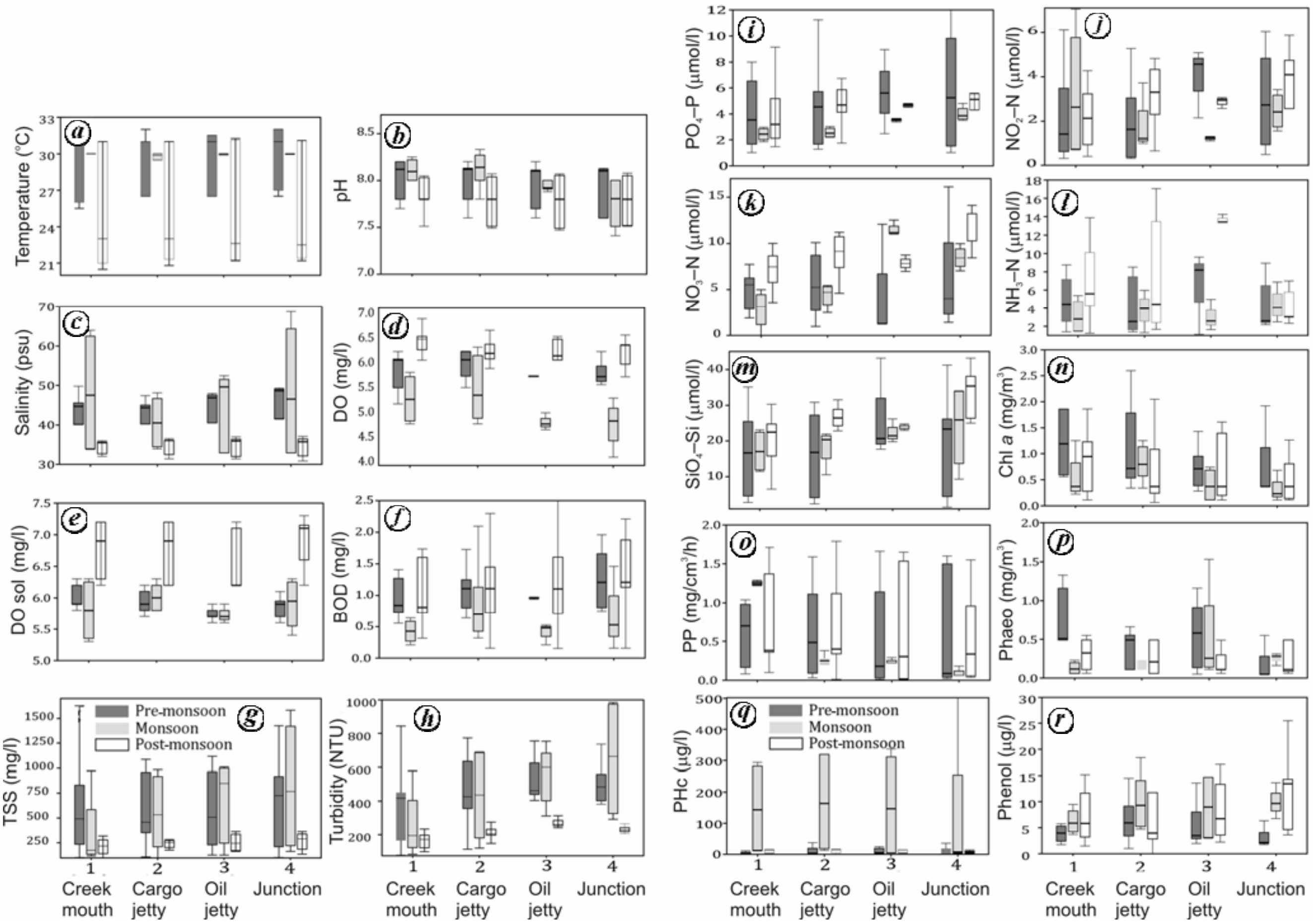

Figure 2. ***a*–*r***, Seasonal variability of physico-chemical and biological parameters at sampling locations in Kandla creek shown through box–whisker plot.

increase further during the monsoon at all the four locations, indicating highest values at the junction, which are due to tidal action and increased water flow from the tributaries bringing in suspended sediments into the creek. During post-monsoon, the TSS shows a consistent significant decrease at all the four locations (Figure 2 *g*). Turbidity apparently follows the trend of TSS and shows higher values of considerable variation with an increase from the mouth towards the junction location during pre-monsoon. The values increase still further during the monsoon, more prominently at the junction and at cargo jetty, with increases from the mouth towards the junction. During post-monsoon, a significant decrease in turbidity is observed at all the four locations, but indicate a trend of gradual increase from the mouth towards the junction (Figure 2 *h*).

Nutrient characteristics

The phosphate shows wide variations at all the four locations, with average high values, increasing from the mouth towards the junction during pre-monsoon. During monsoon, the phosphate decreases significantly at all the four locations and shows narrow ranges of variation, with an increase from the mouth towards the junction. During post-monsoon, the phosphate increases further and shows considerable variations, with increasing values from the mouth towards the junction (Figure 2 *i*). The nitrite shows higher values, ranging widely at all the four locations, with increases from the mouth towards the junction during the pre-monsoon. The highest values of nitrite are observed at oil jetty, followed by that at the junction. During monsoon, the nitrite increases exceptionally at the mouth location, but thereafter decreases significantly at the oil jetty and increases again at the junction, indicating a general decrease from the mouth towards the junction location. During post-monsoon, the values increase again from the mouth towards the junction, with a wide range of variation (Figure 2 *j*). The nitrate shows large variations, with increases from the mouth towards the junction during pre-monsoon, while during monsoon, its concentrations though vary within narrow limits, the trend of variation shows increasing values from the mouth towards the junction. During post-monsoon, nitrate increases still further with a wide range and indicates an increase from the mouth towards the junction (Figure 2 *k*). Ammonia varies widely, with alternate increase and decrease of the average values from the mouth towards the junction location during the pre-monsoon. During monsoon, the ammonia remains low with narrow ranges of variation but the values show an apparent increase from the mouth towards the junction. During post-monsoon, the ammonia increases further and shows higher values at oil jetty, cargo jetty and the mouth location, while the junction location show the lowest values with a narrow range of variation (Figure 2 *l*). The silicates indicate large variation at all the four locations with increases from the mouth towards the junction during pre-monsoon and monsoon seasons, while narrow ranges of variation, with highest average values during the post-monsoon, increasing from the mouth towards the junction (Figure 2 *m*).

Biological characteristics

Chlorophyll *a* shows wide variations, with a gradual decrease from the mouth towards the junction during the pre-monsoon. During monsoon, Chl *a* remains significantly low and indicates a decrease from the mouth towards the junction, while during the post-monsoon, the Chl *a* increases abruptly and shows elevated levels at all the four locations, with an average decrease from the mouth towards the junction. Lower Chl *a* is observed at the oil jetty and the junction location during all the three seasons (Figure 2 *n*). Primary productivity (PP) indicates large variations during the pre-monsoon and post-monsoon seasons with average decrease in values from the mouth towards the junction. During monsoon, the PP decreases significantly and shows the lowest values, with a narrow range of variation, except at the mouth location, with decreasing trend from the mouth towards the junction (Figure 2 *o*). The phaeophytin indicates higher values, with wide variation apparently decreasing from the mouth towards the junction location during the pre-monsoon. The higher phaeophytin values observed were at the mouth, oil jetty and at cargo jetty, while the lower values were observed near the junction. During monsoon, the phaeophytin decreases significantly at three locations with narrow ranges of variation, except oil jetty which shows large variation. During post-monsoon, the phaeophytin picks up again at all the four locations, but indicates average low values from the mouth towards the junction (Figure 2 *p*).

PHc and phenols

During the pre- and post-monsoon seasons, the PHc remain significantly lower with narrow ranges of variation, while it increases largely during the monsoon season at all the four locations, with average increasing values from the mouth towards the junction. This increase is more significant at the junction location, oil jetty and at cargo jetty (Figure 2 *q*). The phenolic compounds show lower values with a narrow range of variation during the pre-monsoon with decreasing values from the mouth towards the junction, but a wider range of variation with increasing values from the mouth towards the junction during the monsoon. The average high values of phenols were observed at cargo jetty, oil jetty and the junction location during monsoon. During post-monsoon, the phenols vary widely with average increasing values from the mouth towards the junction (Figure 2 *r*).

Discussion

The extracted factors indicate significant differences in loadings during the pre-monsoon, monsoon and post-monsoon seasons, with dominant factors influencing the quality of water, which impact the biological characteristics in Kandla creek differently over three different seasons.

Pre-monsoon season

A total of five PCs explain 84.2% of total variance during the pre-monsoon season (Table 1 *a*). PC1 explains 26.4% cumulative variance and is associated with strong positive loadings of primary productivity, phosphates, nitrite; moderate positive loadings of ammonia, temperature, pH and low positive loading of phaeophytin, with strong negative loading of salinity, moderate negative loading of nitrate and a weak negative loading of phenol. PP correlates positively ($p = 0.01$) with phosphate ($r = 0.65$), nitrite ($r = 0.64$) and ammonia ($r = 0.46$) and negatively with nitrate ($r = –0.63$), suggesting phytoplankton growth and utilization of nitrate. This can be seen from Figure 2 *o*, which indicates large variation in PP, with increasing values from mouth to junction during pre-monsoon. However, the nitrate being more stable, its contribution to photosynthesis could be limited in the presence of high nitrogenous source such as ammonia. This factor can therefore be termed as productivity factor. PC2 explains 51.1% cumulative variance and is associated with strong positive loadings of suspended solids, silicates, phenol and pH; moderate positive loading of turbidity, temperature, nitrate and weak positive loading of PHc; with a weak negative loading of DO solubility. The significant positive correlations ($p = 0.01$) of TSS and turbidity with silicates ($r = 0.91$ and 0.76 respectively), phenols ($r = 0.48$ and 0.49 respectively), pH ($r = 0.60$ and 0.43 respectively) and nitrate ($r = 0.39$ and 0.44 respectively) and negative with DO solubility ($r = –0.56$ and –0.53 respectively) suggested that the strong tidal currents in the creek, ultimately increase the TSS, turbidity and silicates and decrease the solubility of DO. Figure 2 *e* indicates low values of DO solubility, with minor variability, with a decrease from the mouth towards the junction during the pre-monsoon, while the TSS (Figure 2 *g*) and turbidity (Figure 2 *h*) indicate an opposite trend. The high tidal currents also bring in phenols originating from a point source (oil jetty and cargo jetty – Figure 2 *r*), relative to PHc (Figure 2 *q*) and are added to the creek water. This factor can be termed as a tidal factor. PC3 contributes 68% cumulative variance and indicates strong positive loadings of AOU and Chl *a*; moderate positive loading of DO solubility and phaeophytin with moderate negative loading of DO and a weak negative loading of turbidity. The significant positive correlation of Chl *a* with phaeophytin ($p = 0.01$ and $r = 0.71$) and negative with turbidity ($r = –0.45$) reveals that the production of Chl *a* and its proportionate degradation to phaeophytin is a continuous process, which is mediated by high turbidity prevailing in creek water. Figure 2 *h* shows increasing turbidity from the mouth towards the junction location, whereas Figure 2 *n* shows a decrease in Chl *a* from the mouth towards the junction during the pre-monsoon season. This also affects the solubility of DO in water as can be seen from Figure 2 *e*, which shows a decrease from the mouth towards the junction during pre-monsoon and hence, this factor can be termed as a turbidity factor. PC4 explains 77.3% cumulative variance and indicates a strong positive loading of BOD and moderate positive loadings of ammonia and nitrate. The ammonia and nitrate do not correlate significantly with BOD, while ammonia is negatively correlated with nitrate ($r = –0.47$), indicating that their sources are different. This suggested that the creek water gets contaminated with nitrate and ammonia from anthropogenic inputs and their concentrations reflect on their accumulation or utilization by photosynthetic organisms. The addition of these contaminants to the creek water is mostly by fallouts from fertilizer industry and from loading and unloading of oil at oil jetty and this can be seen from Figure 2 *k* and *l* during the pre-monsoon. This factor can be termed as the industrial factor. Lastly, the PC5 explains 84.2% cumulative variance and indicates strong positive loading of transparency (light penetration as measured by Sacchi disk) and a moderate positive loading of PHc, with no correlation between the two. This suggested that PHc in the creek water arise due to addition from the fallout from loading and unloading of oil and petroleum products, boat traffic and from other external additions. This addition is slightly more at oil jetty and the junction location relative to other two locations during the pre-monsoon. This factor is termed as a petroleum hydrocarbon (PHc) contamination factor.

Monsoon season

During monsoon, a total of five PCs explain 79.6% of the variance (Table 1 *b*). PC1 explains 35.4% cumulative variance and is associated with strong positive loadings of PHc, TSS, turbidity, salinity, phenol; moderate positive loading of Chl *a* and a weak positive loading of phosphate. This factor also shows strong negative loadings of DO solubility, moderate negative loadings of silicate, nitrite and BOD, with a weak negative loading of DO. The factor indicates large number of parameters influencing the quality of water in Kandla creek, with stronger loadings of PHc, TSS, turbidity and salinity, which are much stronger than those observed during the pre-monsoon season. This is due to the fact that during monsoon, the Little Rann gets flooded and the vast mud flats which get inundated bring in large amounts of water rich in soft marine clays. This increases the flux of sediments and thus increases the suspended solids and turbidity in Kandla creek water. Figure 2 *g* and *h* indicate the increases in TSS and turbidity from the mouth to the junction in Kandla creek during monsoon, confirming that the water from Little Rann brings in large amounts of suspended solids and also increases the turbidity of creek water. Besides this, the increasing water flow during monsoon brings in evaporated salts in dissolved form, formed during hot summer in the tributaries of the creek, while the monsoonal land drainage increases the seepage of brines from the nearby saltpans into the creek. The cumulative effect of the two increases the salinity of creek water. Such increases in salinity are observed in the creek, from cargo jetty towards the junction location during the monsoon (Figure 2 *c*). The monsoonal runoff also brings in PHc and phenols from the nearby jetties and its surrounding areas and adds it to the creek water. These PHc are the fallouts from loading and unloading activities in the creek and from boat traffic. This can be seen from Figure 2 *q* and *r*, which shows high PHc and phenols at all the four locations during monsoon, with considerable variations in phenols at oil jetty and cargo jetty. The significant positive correlations of PHc with phenol ($r = 0.75$) and salinity ($r = 0.86$) and of salinity with phenol ($r = 0.65$) confirms the same. The turbidity and TSS correlate significantly with each other ($r = 0.93$), while the positive correlations of DO solubility with DO ($r = 0.47$) and negative with TSS ($r = –0.52$) and turbidity ($r = –0.4$), suggested a reduction in DO solubility during increases in TSS, turbidity and salinity.

Phosphate and nitrate are the two important parameters responsible for good Chl *a* generation and thus for productivity. The factor indicates weak positive loading of phosphate, but no nitrate loading. Moreover, the insignificant correlations of phosphate with BOD, nitrite, ammonia, silicates, PHc and Chl *a* but significant with turbidity ($r = 0.56$), TSS ($r = 0.44$) and phenols ($r = 0.42$) suggested that phosphate is added to the creek water during increasing TSS and turbidity. While the significant positive correlations of BOD with nitrite ($r = 0.38$), ammonia ($r = 0.52$) and silicates ($r = 0.45$) but negative with TSS ($r = –0.44$), turbidity ($r = –0.48$), PHc ($r = –0.49$), phenols ($r = –0.52$) and Chl *a* ($r = –0.40$) suggested the contributions of nitrite and ammonia to the creek water through point sources. Moreover, the insignificant correlations of Chl *a* with phosphate ($r = –0.10$) and significant negative correlations with nitrite ($r = –0.46$), ammonia ($r = –0.48$) and silicates ($r = –0.79$) suggested that the increasing turbidity and TSS decrease the solubility of DO in creek water and weaken the photosynthetic process. This can be seen from Figure 2 *n*, which shows low Chl *a*, decreasing from the mouth towards the junction during monsoon, relative to pre- and post-monsoon seasons, whereas the TSS (Figure 2 *g*) and turbidity (Figure 2 *h*) show an increase from the mouth towards the junction. So, this component can be termed as the external flow factor. PC2 explains 50.7% cumulative variance and is associated with moderate positive loading of nitrate, weak positive loading of silicates; strong negative loadings of PP and light penetration as measured by Sacchi depth. The PP does not correlate significantly well with nitrate and silicates but indicates a good negative trend, while nitrate and silicates correlate significantly with each other ($r = 0.56$) suggesting a common source and that they are added to the creek water from upstream (Figure 2 *k* and *m*). Similarly, the PP correlates positively with Sacchi depth ($r = 0.71$) and this suggested that when light penetration increases, the PP increases by partially utilizing nitrate as a nitrogen source. This can be seen from Figure 2 *n*, where PP shows a decrease from the mouth towards the junction when TSS (Figure 2 *g*) and turbidity (Figure 2 *h*) increase from the mouth towards the junction, both of which decrease the light penetration during their increases and vice versa. The decrease in PP due to lack of water transparency and light penetration is also reflected in the strong negative loading of PP. The low transparency arises from turbid waters and this component is therefore termed as a turbidity factor. The PC3 explains 61.7% cumulative variance and indicates strong positive loading of ammonia, weak positive loading of nitrite and a strong negative loading of pH. Ammonia correlates positively with nitrite ($p = 0.05$; $r = 0.44$) indicating a common source while both correlate negatively with pH. The pH of creek water decreases from the mouth towards the junction during monsoon (Figure 2 *b*) and this suggested the addition of ammonia and nitrite to creek water from the upstream of the creek, which is due to cumulative effect of the fallout from fertilizer industry; loading and unloading of fertilizers and raw materials at IFFCO jetty and the oil and oil products at the oil jetty. This factor can therefore be termed as an industrial factor. PC4 explains about 72% cumulative variance and shows strong positive loading of oxygen DO, weak positive loading of phaeophytin and a strong negative loading of AOU. The DO correlates negatively with AOU ($r = –0.76$) and with phaeophytin ($r = –0.4$), while AOU and phaeophytin correlate positively with each other ($r = 0.4$). This indicated that during monsoon, when the oxygen content of creek water increases, its utilization decreases and in well-oxygenated water, the degradation of Chl *a* is less which gives low phaeophytin. So, this component can be termed as a DO factor. Lastly, PC5 explains 79.6% cumulative variance and is due to moderate positive loadings of temperature and phaeophytin and a weak positive loading of nitrate. The correlation of phaeophytin with temperature is not significant but is significant with nitrate ($r = 0.51$). The phaeophytin is the inactive form of Chl *a* and this factor suggests that the presence of nutrients, generation of Chl *a* and its degradation to phaeophytin is a process mediated by high turbidity. This factor thus indicates that despite good availability of nitrates and good water temperatures from solar warming of the creek water, appreciable amount of Chl *a* is degraded to phaeophytin. This factor is therefore termed as the degradation factor.

Post-monsoon season

During post-monsoon, five PCs explain about 83.6% of the total variability (Table 1 *c*). PC1 explains 34% cumulative variance and is associated with strong positive loadings of temperature, PP, pH, Chl *a*; moderate positive loading of ammonia; strong negative loadings of salinity and DO solubility; moderate negative loadings of phenol, BOD and TSS and a weak negative loading of DO. Ammonia does not correlate well with BOD, but it correlates well with Chl *a* and PP ($r = 0.52$ and 0.51 respectively). This shows that ammonia in creek water arises from the contaminations from industrial and port activities and activates the photosynthetic process in the presence of sunlight during post-monsoon. The negative loading of DO in relation to strong negative loading of salinity, which is accompanied with negative loadings of phenol, BOD and TSS with their significant correlations with salinity, indicate that the oxygen produced during the photosynthetic process is utilized for the oxidation of organic matter present in suspended sediments. The significant negative correlations of PP and Chl *a* with TSS ($r = –0.59$ and –0.47 respectively) and phenols ($r = –0.78$ and –0.51 respectively) suggested the impact of TSS and phenols on PP during the post-monsoon. This factor can thus be termed as the productivity factor. PC2 accounts for 57.8% cumulative variance and is associated with strong positive loading of silicate, nitrite, nitrate and phosphate, with moderate positive loading of phenol; moderate negative loading of phaeophytin and a weak negative loading of pH. This factor indicates elevated levels of dissolved inorganic nutrients in the creek during post-monsoon, along with moderate levels of phenols. The negative correlations of pH with nitrite ($r = –0.35$), nitrate ($r = –0.45$), silicate ($r = –0.41$), phosphate ($r = –0.38$) and phenols ($r = –0.73$) and the positive correlations of nutrients with each other indicated that the soluble nitrogenous species in creek water result from port activities. Figure 2 *i*, *j*, *k* and *m* indicates high amounts of phosphate, nitrite, nitrate and silicates respectively, increasing from the mouth towards the junction location, so this factor can be termed as a nutrient factor. PC3 explains 68.7% cumulative variance and accounts for strong positive loading of DO, moderate positive loading of BOD, with strong negative loading of AOU. This factor indicates well-oxygenated water but no significant DO utilization despite the presence of some organic load from point sources in the creek water (Figure 2 *d* and *f*) as can be seen from their correlations. This factor can therefore be termed as the DO factor. PC4 explains 77% cumulative variance and shows strong positive loadings of turbidity and TSS, with a significant positive correlation ($p = 0.01$; $r = 0.6$) between the two. This explains that the turbidity of the water is due to re-suspension of fine sediment particles in the creek water brought about by the tidal currents and the water flow from the creek system. Figure 2 *g* which shows low levels of TSS indicates their apparent increase from the mouth towards the junction with a similar trend exhibited by turbidity (Figure 2 *h*). This component is termed as a turbidity factor. PC5 explains 83.6% cumulative variance and shows strong positive loading of transparency based on light penetration by Sacchi depth, with weak positive loadings of PHc and phaeophytin. The phaeophytin is a degradation product of Chl *a*. This factor indicates no significant correlation between PHc and phaeophytin, and this factor can therefore be termed as a PHc contamination factor.

The existing environmental conditions of Kandla creek have been deduced based on the RDA correlation bi-dimensional plot as given in Figure 3 *a–d*, obtained by the correlation between physico-chemical parameters and the identified factors during each season as well as annual period. In this plot, the lines pointing in the same direction reflect high positive correlation between the variables or PCs whereas the lines pointing in opposite directions indicate a high negative correlation. Variables with long lines have the greatest variance in the data set[27]. The absolute PC scores obtained were plotted against different sampling regions, influenced over different seasons and the large spread around the median in the box–whisker plot (Figure 4 *a–f*) indicates an important seasonal contribution to the variance of components.

The RDA plot shows that during pre-monsoon, the tidal and industrial factors play an important role and result in elevated levels of suspended solids, which gives rise to increased turbidity in the creek water (Figure 3 *a*). The spatial variability shows that the tidal factor is more prominent near the mouth region of the creek and is effective at cargo jetty throughout the year (Figure 4 *a*) and the industrial factor is more effective near the oil jetty during all the seasons (Figure 4 *b*). The increases in BOD and PHc from mouth to junction location, resulting from industrial and port activity, show high ranges of variations near the cargo and oil jetty during monsoon (Figure 3 *b*). During post-monsoon, turbidity plays a major role in transportation of inorganic nutrients to the creek system (Figure 3 *c*). However the spatial variability of productivity shows clear pictures of significant productivity near the mouth region during all the seasons (Figure 4 *c*). The annual picture, the macrotidal condition of the creek system plays a major role in causing turbid conditions which supports the elevated levels of inorganic nutrients and petroleum compounds (Figure 3 *d*). During post-monsoon, the nutrient factor plays an important role, along with the turbidity, which increases due to tidal factor, and indicates a narrow range of variation (Figure 4 *d*). This suggests an effective nutrient load in the creek system supporting the productivity during post-monsoon. The spatial distribution of nutrient factor shows increasing variations from the junction towards the mouth of the creek, indicating the addition of nutrients to the creek system from its upstream region (Figure 4 *d*). However, the productivity during this season shows higher range of variation near the cargo jetty indicating very low to high productivity as per nutrients availability, spilled over by loading and unloading activities at the jetties, with an increase towards the mouth region. During monsoon, the DO factor is associated with pH and indicates well-oxygenated water with increasing alkaline conditions in the creek. The spatial variability shows good oxygenation of water at all the four locations, with lesser variation at the mouth during monsoon season (Figure 4 *e*). Petroleum hydrocarbon factor shows high values of PHc, with a narrow range of variation during the post-monsoon, exerting more influence towards the mouth region due to large boat traffic, away from industrial sites (Figure 4 *f*).

The contaminants entering the Kandla creek from various natural and anthropogenic sources, irrespective of the extent of their source contribution, ultimately affect the quality of creek water. Understanding of the changes in the quality of creek water and evaluation of the type of water, at each location in the creek during the three seasons was done based on overall index of pollution (OIP) values calculated using the water quality index (WQI)[26]. The seasonal averages of the OIP values at four locations in the creek from 2002 to 2006, indicated higher values during the pre-monsoon and monsoon suggesting deteriorating water quality during these seasons. During post-monsoon, the OIP values however were found to be lower (Figure 5). At the junction location, oil jetty and to some extent at cargo jetty, the higher OIP values observed were between 4 and 5, which suggested polluted water, while at the mouth, the OIP values were between 2 and 4, suggesting slightly polluted water during the pre-monsoon and monsoon. During post-monsoon, the OIP values at all the four locations were within 2–3, suggesting slightly polluted water in Kandla creek (Figure 5).

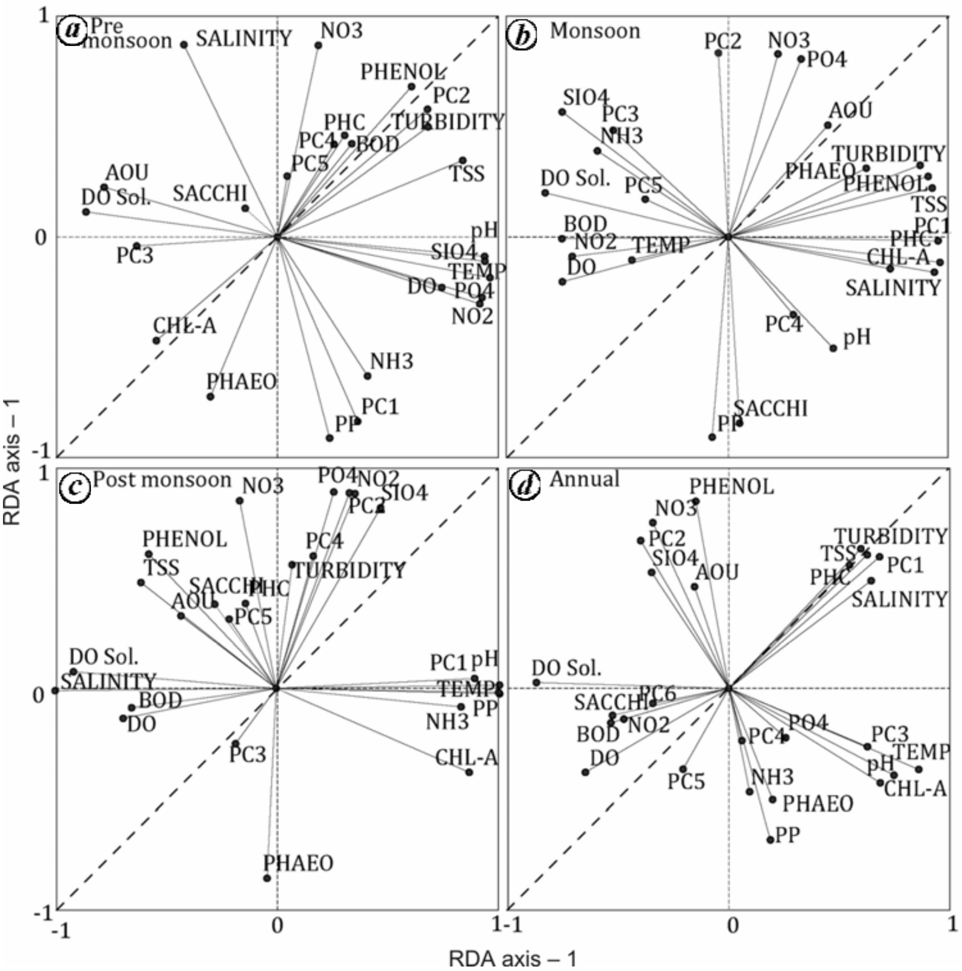

Figure 3. ***a–d***, RDA ordination diagram-interrelationship among the physico-chemical and biological parameters with PCs during different seasons. Pre-monsoon: PC1, Productivity; PC-2, Tidal; PC-3, Turbidity; PC-4, Industrial; PC5, PHc. Monsoon: PC1, External flow; PC-2, Turbidity; PC-3, Industrial; PC-4, Dissolved oxygen; PC5, Degradation. Post-monsoon: PC1, Productivity; PC-2, Nutrient; PC-3, Dissolved oxygen; PC-4, Turbidity; PC5, PHc. Annual period: PC1, Tidal; PC-2, Industrial; PC-3, Productivity; PC-4, Nutrient; PC5, Dissolved oxygen; PC-6, PHc.

The water in Kandla creek is dynamic as is evident from the existing strong tidal currents. The current measurements in the creek[7] indicated that during spring, the current speed varies from 0.08 to 1.7 m/s, whereas during ebb, the current speed varies from 0.09 to 2.0 m/s. This indicated strong ebb tidal flow towards the GoK, transporting water from Kandla creek to the inner GoK with greater force, facilitating good flushing of the creek, which helps transfer the contaminants from Kandla creek to the inner gulf.

This study when compared with the Mormugao port located in the estuarine region of Zuari river in Goa along the west coast of India indicated that the Mormugao port water is much cleaner with low TSS and turbidity as the currents are not as strong as in Kandla creek and the tidal height also is low (2.5 m). However, the water is influenced by microbes (total vibrio coliforms, total coliforms and total vibrios) due to the effect of sewage discharges from Mormugao Sewage Treatment Plant (STP) located little away from the port towards the Zuari estuarine mouth. Besides this, the contaminations observed from nitrogenous substances are mostly from domestic waste and not from the industrial wastes; whereas the PHc result mainly from boat traffic, with lower concentrations compared to those in Kandla creek. Similarly, there are no exceeding levels of phenols in Mormugao port water such as those seen in the Kandla creek water. The water quality shows increasing values of OIP at low tide during the post-monsoon relative to pre-monsoon season, suggesting 'slightly polluted' water at most of the locations, while 'polluted water' at selected few locations in the harbour region, which could be a localized and temporary effect. Despite this, the seasonal Chl *a* and PP remain fairly good, with higher values during all the seasons.

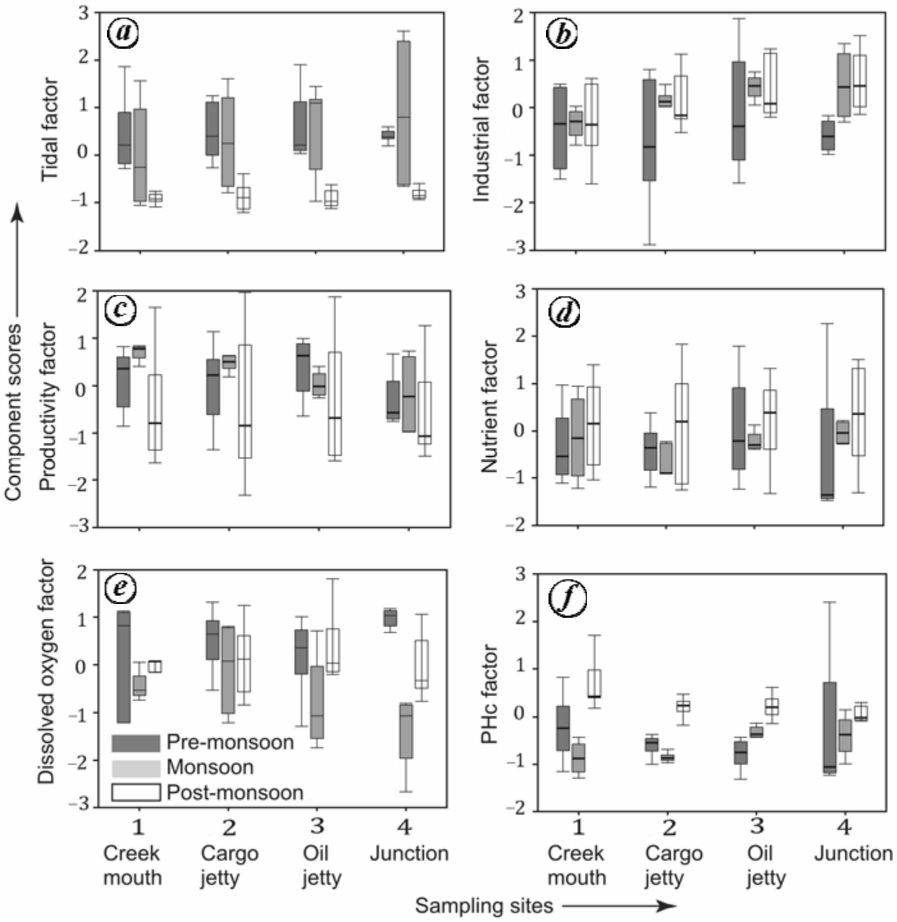

Figure 4. ***a–f***, Seasonal variations of annual PCs at various sampling locations along Kandla creek through box–whisker plot.

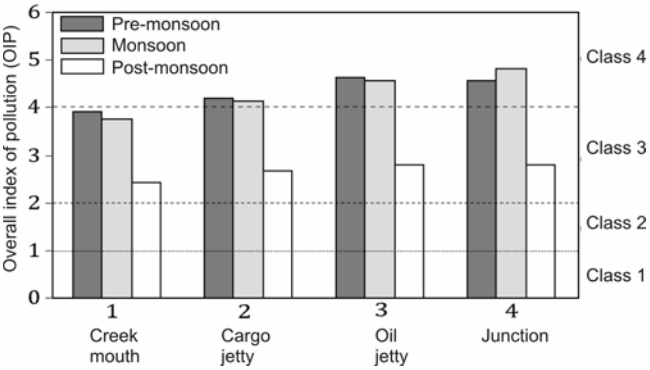

Figure 5. Overall index of pollution (OIP) at different sampling locations during the three seasons. OIP values: 0–1 (class 1; excellent water); 1–2 (class-2; acceptable water); 2–4 (class 3; slightly polluted water); and 4–8 (class 4; polluted water).

The hydrodynamics of the Mormugao port area reveals that in Zuari estuary, the water enters the estuary from the north and flows out of the estuary primarily towards south. At the mouth of the estuary, the northward flow takes a cyclonic reversal and flows again southwards without entering the estuary. The circulation inside the estuary is such that the contaminants are siphoned off into the sea, posing no threat to the quality of Mormugao port water[28], whereas, the strong ebb currents throw the contaminants out of the Kandla creek. However, the main difference between the two is that the contaminants from Mormugao port are thrown out into the coastal water from where they go to the sea, while the contaminants from the Kandla creek are thrown out into the inner GoK, which can affect the Marine Sanctuary and the Marine National Park.

Conclusions

The Kandla creek, a macrotidal region in the eastern GoK is significantly influenced by anthropogenic activities of Kandla port located along its western bank. The regular seasonal studies over a five-year period indicate high turbidity, suspended solids and salinity during the pre-monsoon. Their further increase during the monsoon season affects the DO solubility and hampers Chl *a* and PP generation in the creek water. The strong tidal currents and the water flow from the creek system (Little Rann) rich in soft marine clays of the mud flats contribute to these increases in turbidity and TSS. While the dissolved salts formed from intense evaporation during summer and brought by tributarine water increase the salinity of creek water during pre-monsoon, the seepage of brines from the nearby salt pans during monsoonal drainage increase salinity during the monsoon. The normal and well-oxygenated conditions, with low turbidity and TSS helping in good Chl *a* and PP generation of the creek water are maintained during the post-monsoon. The BOD remains low in Kandla creek water throughout the year.

The nutrients (phosphates, nitrites, nitrates and ammonia), PHc and phenols in the creek water remain high during the pre- and post-monsoon seasons, relative to monsoon season, due to the fallout from industrial and the loading–unloading activities at IFFCO jetty and at oil jetty. Besides this, their further increase during the monsoon and post-monsoon is due to monsoonal runoff and land drainage.

The PCA act as excellent tools to identify the dominant parameters in the creek during different seasons. The influences of various contaminants and other parameters on Chl *a* generation and its deactivation indicate low productivity during monsoon and its recovery during the post-monsoon. The RDA plots revealed the status of existing environmental conditions at different locations in Kandla creek, supporting the identification of sources of contaminants in the creek. It indicated that the tidal and industrial factors play an important role and result in elevated levels of suspended solids and increasing turbidity in the creek. The spatial variability indicated the tidal factor to be more prominent near the mouth region, influencing up to cargo jetty. During post-monsoon, the nutrient factor and turbidity play an important role, suggesting effective nutrient load in the creek system supporting creek productivity. Nutrient factor varies widely from the junction towards the mouth of the creek, supporting the addition of nutrients to the creek system from upstream. Productivity ranged high at cargo jetty due to the availability of nutrients, spilled over during loading and unloading activities at the jetties, with an increase towards the mouth region. During monsoon, the dissolved oxygen factor in association with pH indicates considerable oxygenation of water with increasing alkaline condition in the creek. The spatial variability shows good oxygenation of water at all the four locations, with lesser variation at the mouth during the monsoon season. Petroleum hydrocarbon factor shows high values of PHc during monsoon, with a narrow range of variation during other seasons, which exerts influence all through the creek due to large boat traffic. The existing high nutrients do not indicate excellent productivity in Kandla creek, due to inhibiting effect of turbidity, TSS, PHc and phenols on Chl *a* generation. The transfer of contaminants and suspended load from Kandla creek to the inner GoK by strong ebb tidal currents keeps the creek away from eutrophication. This study is significant as it shows the transport of large amounts of suspended solids, leading to siltation in the approach channel from the GoK to the Kandla creek as well as the transport of anthropogenic contaminants such as nutrients, PHc and phenols into the Gulf, which can affect the Marine Sanctuary and the Marine National Park and this needs to be investigated further.

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