NUTRIENT DISTRIBUTION AND TROPHIC STATUS ASSESSMENT IN A TROPICAL EMBAYMENT UNDER ANTHROPOGENIC STRESS

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Abstract
The spatiotemporal variations in hydrography and trophic status were investigated in an anthropogenically challenged tropical coastal embayment (Kakinada Bay) on the east coast of India. Water quality sampling was conducted from April 2016 to March 2017, and information on different physicochemical and biological parameters was gathered. Data sets suggested strong salinity gradients from south to north with significant seasonal fluctuations, ranging from 32.46 to 33.14 during the pre-monsoon, 19.31 to 31.59 in the monsoon, 20.53 to 24.98 in the post-monsoon, and 28.12 to 31.49 during the recovery period. Through multivariate analysis of water quality data, it was observed that the hydrographical characteristics of the south Bay differed from those of the north Bay during the pre-monsoon and recovery periods. In the monsoon and post-monsoon seasons, the salinity-nutrient gradients were influenced by river influx through the mangroves in the south and sea incursion through the Bay mouth in the north. Notably, elevated nutrient levels in the north Bay during the pre-monsoon and recovery periods indicated that urban and industrial discharges were significant pollution sources when the monsoonal influx was minimal. Assessing the trophic status of Kakinada Bay waters using Trophic State Index (TRIX) analysis revealed considerable spatial and seasonal variability. The north Bay, influenced by neritic conditions and monsoonal flushing across different seasons, consistently displayed lower TRIX values than the south Bay. Seasonally, TRIX values ranged from 2.19 to 7.56 (average: 5.4) in the pre-monsoon, 1.38 to 7.60 (average: 5.49) in the monsoon, 2.53 to 7.71 (average: 5.93) in the post-monsoon, and 2.37 to 7.93 (average: 5.16) in the recovery period. Most TRIX values (84% of total data points) categorized Kakinada Bay as a mesotrophic to eutrophic environment. These findings align with our previous study on macrobenthos and bottom sediment characteristics, indicating that continuous anthropogenic interventions have significantly degraded the water quality of the Bay. Consequently, the Bay environment is poised to become an environmentally and ecologically costly concern in the near future. To mitigate these issues, the government should implement measures to reduce urban discharges and increase flushing rates within the Bay.

Keywords: Kakinada Bay, water quality, chlorophyll-*a*, eutrophication, TRIX.

1. Introduction

Semi-enclosed coastal ecosystems such as bays, estuaries, and lagoons are unique water bodies mostly considered interfaces between land and sea (Wang, et al., 2008). As they are highly vulnerable to various environmental changes, information on the water quality of these areas is essential (Nixon et al., 2001). The increasing anthropogenic activities such as industrialization, urbanization, and agricultural practices have been affecting the surface hydrography of coastal waters (Qadir et al., 2008; Wang, et al., 2008) leading to, a decline in water quality and an increase in eutrophication levels, emphasizing the importance of monitoring human activities in coastal regions and implementing effective measures to minimize their impact on the marine ecosystem.

Eutrophication is an ecological process that leads to an array of cascading changes in ecosystem structure and function, such as decreased dissolved oxygen levels, the overabundance of micro and macroalgae, rise in dissolved and particulate organic matter, and the release of CO_2, the occurrence of harmful algal blooms, loss of seagrass habitat, reduced biodiversity, declining fisheries, imbalanced food webs, altered biogeochemical cycling, and weakened ecosystem services (Nixon, 1995; Kennish et al., 2008; Glibert et al., 2010; Kennish and Paerl, 2010b). These impacts generate a call for the characterization and definition of the current condition of these environments based on an ecosystem and trophic approach (Herrera-Silveira and Morales-Ojeda, 2009; Ferreira et al., 2011). Eutrophication of coastal lagoons and estuaries has been increasing worldwide (Nixon, 1995; Kennish et al., 2008). Several studies have been conducted on water quality so far to understand the eutrophication status of the coastal ecosystems all over the world such as Daya Bay (Wang, et al., 2008), Gautami-Godavari Estuarine (Sarma, et al., 2010), Sishili Bay (Wang, et al., 2012), Kuwait Bay (Al-Mutairi, et al., 2014), Oso Bay (Wetz, et al., 2016), Gokova Bay (Mustafa Dondu, et al., 2020), etc. However, understanding the ecological processes of dissolved inorganic nutrients in tropical coastal Bays is not well defined because they transform from dissolved to particulate through phytoplankton uptake and remineralization.

Identifying limiting nutrients in these systems is essential for selecting appropriate nutrient control measures to mitigate the effects of eutrophication (Magnien et al., 1992). In addition, it is necessary to apply practical tools comparable across waters of different trophic conditions to estimate the trophic status of the coastal marine system (Georgios et al., 2006). Over time, many methods and conceptual approaches have been developed to estimate the trophic state and eutrophication of aquatic water bodies to support management purposes (Carlson, 1977; Vollenweider et al., 1998; Nixon, 1995; Ferreira et al., 2011; Primpas and Karydis, 2011). As a part of it, Vollenweider et al. (1998) introduced a complex trophic index (TRIX) analysis based on biological (chlorophyll-*a* concentration) and physicochemical parameters (oxygen saturation, nitrogen, and phosphorus). In the present study, the TRIX analysis is adopted to determine the trophic status of the Kakinada Bay environment on a seasonal or spatial basis, or overall. using water quality parameters measured during the study period.

2. Study area

Kakinada (KKD) Bay is a shallow bar-built water body extending up to 146 km^2 situated on the east coast of India (16^{0}52'-17^{0}00' N and 82^{0}15'-82^{0}22' E). An important feature of KKD Bay is having a 16 km sand spit on the east side that eventually separated the Bay from the adjacent sea, covering a total area of up to 333 km^2 (Banerjee et al., 1998). The Bay is limited in the south by dense mangrove vegetation characterized by extensive mud flats intercepted by a network of tidal creeks, several estuarine gullies, and streams emanating from one of India's largest rivers, the Godavari. The river discharges freshwater up to ~17.46 x 10^{10} m^3, entering the Bay-Mangrove complex and causing considerable seasonal variations (Dash et al., 2021). Towards the north, the Bay has a wide opening (~2 km) into the sea where typically marine conditions prevail.

During the last decade, several industrial establishments have sprung up near KKD Bay and have become an important part of the Special Economic Zone called the 'Petroleum, Chemical, and Petrochemical Investment Region' (PCPIR). Subsequently, the construction of a breakwater and frequent dredging at the Bay mouth is taking place to facilitate vessel movement in the deep-water port as well as to intensify the oil and natural gas exploration activities in the Godavari basin (Rehitha et al., 2021).

3. Materials and methods

3.1. Hydrological sampling methods

To meet the objectives of the present study, attempts have been made to cover the study area in monthly intervals for physical, chemical, and biological measurements. Field observations were carried in the year April 2016 to March 2017. Subsurface (0.3-0.5 m) water samples were collected at 12 hydrographically differing GPS (Garmin III, USA) fixed locations (Fig. 1) by using a 5L Niskin sampler. *In situ,* water temperature, pH, and salinity were measured by a portable water quality analyzer (Hydrolab-quanta), Metrohm pH meter, and standard argentometric method, respectively. To analyze the dissolved nutrients, the known volume of the sample was immediately filtered through a pre-weighed 0.45 μm cellulose acetate filter paper

(Millipore), and the filtrate was collected in a 1000 ml capacity HDPE bottles and ice preserved (-4 °C) until analysis. For the estimation of TSM, the filters were dried at 105 °C for 12 h and weighed accurately before and after filtration, and the differences in the weight to the volume of water filtered were expressed as the concentration of TSM in mg L^{-1}. The dissolved oxygen of the samples was analyzed following modified Winkler's (1888) method (Carrit and Carpenter,1966). All the inorganic nutrients, such as dissolved inorganic nitrogen, phosphate, and silicate, were analyzed on filtered samples following the standard spectrophotometric procedures (Grasshoff et al., 1999). Total nitrogen and total phosphorous were measured by the wet persulfate oxidation method (Koroleff, 1983; Grasshoff et al., 1999). For chlorophyll analysis, a known volume of sample was filtered through GF/F filters, and the filter was first extracted with 90% acetone, kept at 4°C in the dark for 24 h, and then spectrophotometrically analyzed (Parsons et al., 1984).

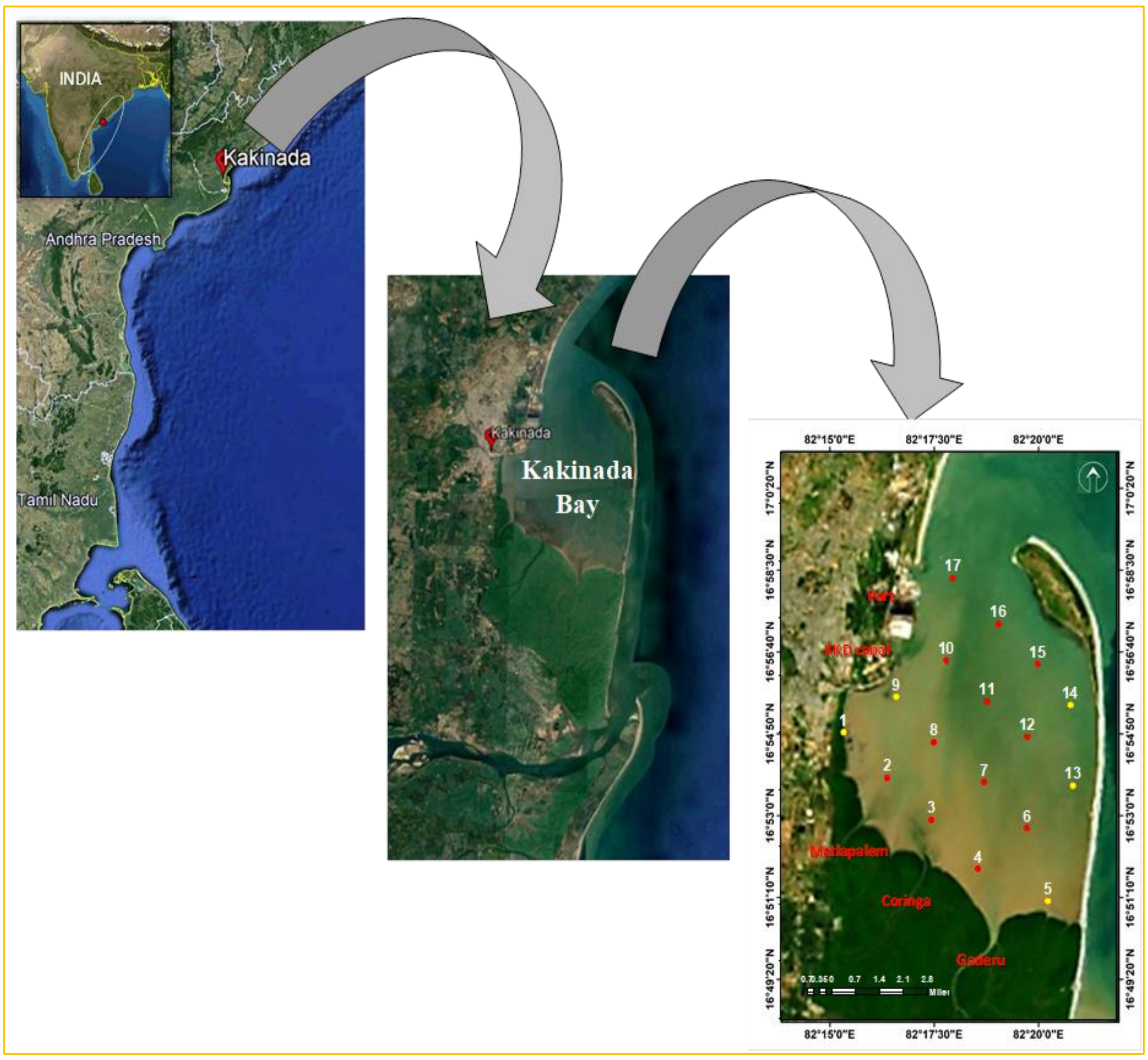

Figure 1: Map showing the Kakinada Bay sampling locations. Water sampling was restricted to the locations marked in red color. Yellow colored locations were not sampled due to inaccessibility.

3.2. TRIX – Trophic Index

To assess the trophic status of KKD Bay, a multivariate index called the Trophic State Index (TRIX) proposed by Vollenweider et al. (1998) was used. The TRIX is a combination of four state variables that directly express productivity, chlorophyll-*a* (µg L^{-1}), oxygen as absolute deviation from saturation (%), dissolved inorganic nitrogen (µg L^{-1}), and dissolved inorganic phosphate (µg L^{-1}) concentration to quantify the estuarine eutrophication. The values were converted to the logarithmic base 10. Thus, the TRIX determination for KKD Bay is proposed by the following formula:

$$TRIX = [\text{Log}\,(\text{Chl}a \times aD\%O \times DIN \times DIP) - k] / m$$

where k is the lower limits sum of the required variables for TRIX, and m is calculated by the difference between the lower and upper limits of each variable, divided by 10. Trophic scales and descriptors for water quality were adopted from Cutrim et al. (2019). Numerically, the index is scaled from 0 to 10, covering a wide range of trophic conditions from ultra-oligotrophic to hyper-eutrophic (Table 1).

Table 1: Classification of Trophic index based on the Vollenweider TRIX values (Cutrim *et al*., 2019).

TRIX	Conditions	Water Quality	Trophic State
0 – 2	Water very poorly productive and very low trophic status	Excellent	Ultra-Oligotrophic
2 – 4	Water poorly productive and low trophic status	High	Oligotrophic
4 – 5	Water moderately productive and medium trophic status	Good	Mesotrophic
5 – 6	Water moderate to very productive and high trophic status	Moderate	Mesotrophic to Eutrophic
6 – 8	Water very productive and high trophic status	Poor	Eutrophic
8 – 10	Water highly productive and highest trophic status	Very Poor	Hypereutrophic

3.3. Statistical analysis

Two-way analysis of variance (ANOVA) has been performed to evaluate the spatial-temporal variations among the environmental variables. To derive the significant and dynamic relationships between the TRIX and select environmental variables, the correlation coefficient (r) has been derived. Also, hierarchical cluster analyses were performed to establish the similarities among the stations. All the mathematical and statistical computations were performed using various statistical packages viz., Excel 2010 (Microsoft Office), GraphPad prism-5, and PRIMER 6.

4. Results and discussion

The entire study period has been categorized based on the mean salinity distribution of the Bay into four seasons, i.e., pre-monsoon (April-June), monsoon (July-September), post-monsoon (October-December), and recovery period (January-March) (Dash et al., 2021). The spatiotemporal descriptive statistics of the environmental variables for the entire study period are given in Table 2.

Agglomerative hierarchical cluster analysis (AHCA) was performed on the normalized environmental physicochemical data to measure the similarities between the stations, using Euclidean distances as a measure of similarity (Fig. 2). The results of the dendrogram and MDS plots divided the Bay into two groups during pre-monsoon (ANOSIM: Global R=0.64; P=0.3%) and recovery period (ANOSIM: Global R=0.88; P=0.1%), whereas, three groups during monsoon (ANOSIM: Global R=0.61; P=0.1%) and post-monsoon (ANOSIM: Global R=0.72; P=0.1%) (Fig. 2). This shows the dynamic nature of the KKD Bay in hydrological variability concerning the seasons.

4.1. Hydrological Settings in the Bay

The two-way ANOVA revealed that the entire study period showed significant spatiotemporal variations for all the environmental variables except DO saturation, NH_4^+-N, NO_2-N, and TRIX (Table 3). The sea surface temperature (SST) varied from 24.95 °C to 33.58 °C (Table 2). At the same time, the highest SST was encountered during the pre-monsoon, and the lowest was noticed in the recovery period (Fig. 3a). These variations could be due to the air-sea exchange of temperatures with the influence of various seasons (Muduli et al., 2012; Kanuri et al., 2013). The highest mean TSM was observed during the pre-monsoon (67.26 ± 34.18 mg l^{-1}) followed by monsoon (65.61 ± 21.98 mg l^{-1}) (Table 2). Irrespective of the season, lower TSM values were observed towards the high salinity regime, i.e., towards the mouth of the Bay (Fig. 3b). The entire Bay showed distinguished variations among different seasons. This indicates that TSM in the Bay might be controlled either due to the influence of river-borne sediments or vertical churning of water masses in the Bay due to wind and shallowness (Muduli et al., 2012, Patra et al., 2016). pH and dissolved oxygen (DO) play a vital role in understanding the sustainability of marine aquatic life. pH ranged from 7.68 to 8.24, with the highest value observed during monsoon and post-monsoon and the minimum value during pre-monsoon (Table 2 and Fig. 3c). Generally, these fluctuations in pH during different seasons are attributed to productivity, community respiration, and freshwater influx (Rajasegar, 2003; Muduli et al., 2013). Salinity varied from 10.76 to 35 in the Bay, with higher values observed in the northern Bay. The highest mean salinity was found during pre-monsoon (32.86 ± 2.77). In contrast, during the other seasons, it was <30 (Table 2 and Fig. 3d). The lower salinity in the south Bay could be attributed to the influence of freshwater from the riverine systems/creeks and higher values in the north Bay are due to the influence of saline water intrusion from the Bay of Bengal (Lovaraju et al., 2022). The dissolved oxygen (DO) varied from 2.97 to 10.22 mg L^{-1}. The mean concentration of DO was found to be high during post-monsoon (7.5 ± 0.78 mg L^{-1}) and low during pre-monsoon (6.47 ± 1.09 mg L^{-1}) (Table 2). Higher values of DO in post-monsoon might be due to the primary production associated with sufficient nutrient runoff from the freshwater discharge into the Bay. In contrast, the lower values during pre-monsoon might be related to the warm waters and lower nutrients (Wu et al., 2009b) (Fig. 3e). Similar trend was also observed in DO saturation with a maximum saturation of ∼103%.

Table 2: Bay-wide range, mean and standard deviation of environmental variables during pre-monsoon, monsoon, post-monsoon, and recovery periods.

parameter	pre-monsoon	monsoon	post-monsoon	recovery period
WT (^{0}C)	27.01-33.58 (31.01±1.76)	27.85-31.2 (29.51±0.95)	24.96-29.57 (27.42±1.3)	24.95-30.46 (27.31±1.46)
TSM (mg L^{-1})	25-157 (67.26±34.18)	30-100 (65.61±21.98)	12.25-64.5 (34.3±14.68)	18.89-64 (36.61±10.82)
pH	7.68-8.2 (7.97±0.12)	7.77-8.24 (8.06±0.13)	7.82-8.22 (8.06±0.14)	7.84-8.09 (7.99±0.08)
Salinity	21.78-34.97 (32.86±2.77)	10.76-34.72 (26.84±7.35)	15.5-26.52 (22.39±2.77)	22.55-35 (29.53±3.37)
DO (mg L^{-1})	3.63-9.47 (6.47±1.09)	3.9-10.22 (6.49±1.29)	6.14-9.29 (7.5±0.78)	2.97-9.59 (6.69±1.52)
DO%	55.93-155.69 (104.42±19.27)	54.94-162.76 (99.09±22.18)	88.13-136.27 (107.39±11.21)	43.84-143.59 (99.55±22.72)
Ammonia (µM)	0.48-10.38 (2.29±2.66)	0.42-7.5 (2.21±1.6)	0.37-3.83 (1.61±1.02)	0.13-12.2 (2.75±2.76)
Nitrite (µM)	0.09-4.07 (0.99±0.94)	0-3.29 (0.79±0.82)	0.07-4.67 (1.04±0.9)	0.05-4.47 (0.78±1)
Nitrate (µM)	1.3-11.84 (4.68±2.15)	0.69-18.31 (7.22±4.65)	0.93-10.28 (4.14±2.22)	0.37-12.79 (5.08±3.69)
DIN (µM)	2.11-22.77 (7.95±4.29)	1.38-25.03 (10.21±5.9)	2.19-15.51 (6.78±3.23)	1.36-23.26 (8.61±5.33)
Phosphate (µM)	0.38-4.31 (1.46±0.87)	0.65-9.28 (3.38±2.02)	0.88-5.32 (2.08±0.97)	0.35-28.83 (4.7±7.15)
Silicate (µM)	9.93-93.73 (30.56±15.94)	5.86-126.48 (44.5±31.64)	12.33-102.29 (48.99±24.54)	4.13-84.04 (35.07±25.61)
TN (µM)	43.46-136.06 (90.82±25.12)	40.23-185 (93.4±38.66)	7.8-94.67 (50.21±22.43)	25.4-200.48 (66.3±36.95)
TP (µM)	0.58-4.74 (1.78±0.95)	0.9-11.28 (3.94±2.25)	1.24-6.07 (2.58±1.09)	0.85-32.32 (5.66±8.09)
N/P	0.92-30.11 (6.95±4.98)	0.71-11.3 (3.73±2.68)	0.75-10.58 (3.74±2.08)	0.4-25.25 (5.33±6.45)
Chlorophyll-*a* (mg m^{-3})	1.75-38.9 (11.63±8.95)	1.78-45.01 (14.48±10.89)	1.73-17.94 (6.95±4.4)	0.85-28.55 (7.8±7.59)
TRIX	2.19-7.56 (5.40±1.31)	1.38-7.60 (5.49±1.53)	2.53-7.71 (5.93±1.24)	2.37-7.93 (5.16±1.55)

4.2. Nutrient dynamics and Chlorophyll-*a*

Nutrients (viz., nitrogen, phosphorous, and silicon) are the crucial elements that govern biological productivity in coastal and marine environments (Smith, 2007). The major sources of these nutrients are human-derived domestic runoff, atmospheric inputs, and other autochthonous inputs, and they become a growing threat to coastal ecosystems (Vidal et al., 1999; Rabalais and Nixon, 2002; Smith, 2007). Dissolved inorganic nitrogen (i.e., Ammonia+Nitrite+Nitrate) is the one among them that alters the coastal eutrophication status. The spatial and seasonal distributions of dissolved inorganic nitrogen (DIN) in the KKD Bay showed a strong variability in terms of various nitrogen species (ammonia, nitrite, nitrate), which are given in Tables 2, 3.

The seasonal mean DIN concentration was high during monsoon (10.21 ± 5.9 µM) followed by the recovery, pre-monsoon, and post-monsoon seasons (Table 2). Whereas, the DIN levels gradually decreased towards the high salinity regime, i.e., regions near the Bay of Bengal, during monsoon and post-monsoon seasons (Fig. 4a). The annual mean DIN concentration (8.39 ± 4.91 µM) in the Bay is corroborated with the values reported by Tripathy et al., 2005. Also found to be well below the reported values by elsewhere Godavari estuary (Sarma et al., 2010); Sishili Bay (Wang et al., 2012); Bay of Annaba (Ounissi et al., 2014) and Oso Bay (Wetz et al., 2016). The high concentration of DIN during monsoon is associated with the monsoon freshwater influx into the Bay. The percentage of ammonia, nitrite, and nitrate concentration in DIN was 27%, 13%, and 60%, respectively. Whereas, irrespective of the season the mean concentrations of NO^{3-}-N were high among all the nitrogen species. This result indicates that the KKD Bay is enriched with nitrate species followed by ammonia. Whereas, the high mean concentrations of ammonia were observed during the recovery period (2.75 ± 2.76 µM), emphasizing the importance of localized anthropogenic influence and the in-situ remineralization of organic matter rather than the riverine inputs. Also, the low NH_4^+-N concentration in the post-monsoon (1.61 ± 1.02 µM) might be due to the prominent dilution of low-concentrated coastal waters of the Bay of Bengal with the KKD Bay.

Table 3: Analysis of variance (ANOVA) for the environmental variables between the seasons.

Parameters	Source of Variation	Sum of Squares	df	Mean square	F	sig.
WT (^{0}C)	Between Seasons	343	3	114	58.8	0.000**
	Within Season	272	140	1.94		
TSM (mg L^{-1})	Between Seasons	34700	3	11600	23.3	0.000**
	Within Season	69400	140	496		
pH	Between Seasons	0.211	3	0.0702	5.17	0.002**
	Within Season	1.9	140	0.0136		
Salinity	Between Seasons	2110	3	704	35	0.000**
	Within Season	2820	140	20.1		
DO (mg L^{-1})	Between Seasons	25.42	3	8.475	5.907	0.000**
	Within Season	200.9	140	1.435		
DO%	Between Seasons	1725	3	574.9	1.529	ns
	Within Season	52660	140	376.1		
Ammonia (µM)	Between Seasons	23.59	3	7.864	1.729	ns
	Within Season	636.9	140	4.549		
Nitrite (µM)	Between Seasons	1.92	3	0.639	0.766	ns
	Within Season	117	140	0.835		
Nitrate (µM)	Between Seasons	196	3	65.4	5.85	0.000**
	Within Season	1570	140	11.2		
DIN (µM)	Between Seasons	221.4	3	73.81	3.216	0.025*
	Within Season	3213	140	22.95		
Phosphate (µM)	Between Seasons	223	3	74.4	5.24	0.002**
	Within Season	1990	140	14.2		
Silicate (µM)	Between Seasons	7710	3	2570	4.09	0.008**
	Within Season	87900	140	628		
TN (µM)	Between Seasons	46000	3	15300	15.4	0.000**
	Within Season	140000	140	998		
TP (µM)	Between Seasons	310	3	103	5.71	0.001**
	Within Season	2540	140	18.1		
N/P	Between Seasons	256	3	85.34	4.391	0.005**
	Within Season	2721	140	19.44		
Chl-*a* (mg m^{-3})	Between Seasons	1323	3	441	6.404	0.000**
	Within Season	9640	140	68.86		
TRIX	Between Seasons	11.04	3	3.679	1.838	ns
	Within Season	280.3	140	2.002		

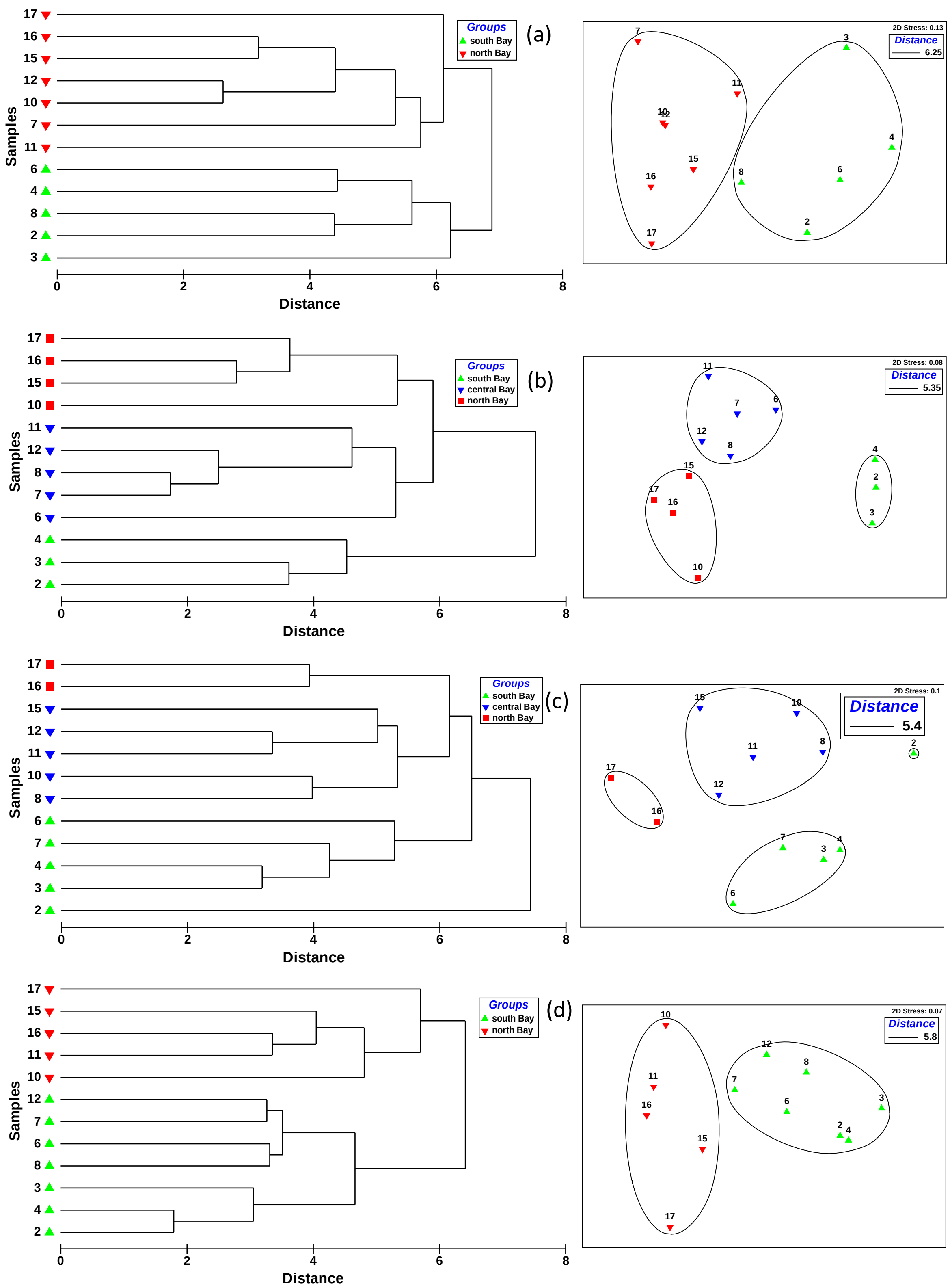

Figure 2: Normalised Euclidean distance-based classification showingdifferent regions Dendrogram and MDS (a) pre-monsoon, (b) monsoon, (c) post-monsoon, and (d) recovery period.

The NO_2^--N concentration was high in post-monsoon (1.04 ± 0.9 μM), whereas it was lowest during the recovery period (0.78 ± 1.0 μM) (Table 2). NO_2^--N always indicates the fresh input of organic load into the water system. The high concentration of NO_2^--N in post-monsoon is due to the freshwater runoff from rivers and creeks, and the lowest values observed in the recovery period may be due to the restriction of fresh water into the Bay. NO_3^--N concentration varied significantly ($p < 0.01$) between 0.37 and 18.3 μM (Fig. 3h). NO_3^--N shows a higher concentration in monsoon (7.22 ± 4.65 μM) and lowest in post-monsoon (4.14 ± 2.22 μM) (Table 2). The most important source of NO_3^--N is the biological oxidation of organic nitrogenous substances, which originates through sewage and industrial wastes through terrestrial runoff. This phenomenon was also observed in the Mahanadi estuary (Sundaray et al., 2006). A lower concentration of NO_3^--N in post-monsoon due to higher primary productivity causes more nutrient utilization (Sarma et al., 2009); as a consequence, this high concentration of

DO values is observed (Table 2). Spatially NO_3^--N shows higher values in north Bay, due to the proximity of anthropogenic sources like domestic sewage, agricultural wash-offs, and other waste effluents from the KKD canal. High concentrations of DIN in the north Bay, especially in the recovery period, are probably related to the massive input of organic matter and nutrients from anthropogenic sources through the KKD canal. We, therefore, contend that mangroves may not be a significant source of inorganic nitrogen in KKD Bay (Rakhesh et al., 2008).

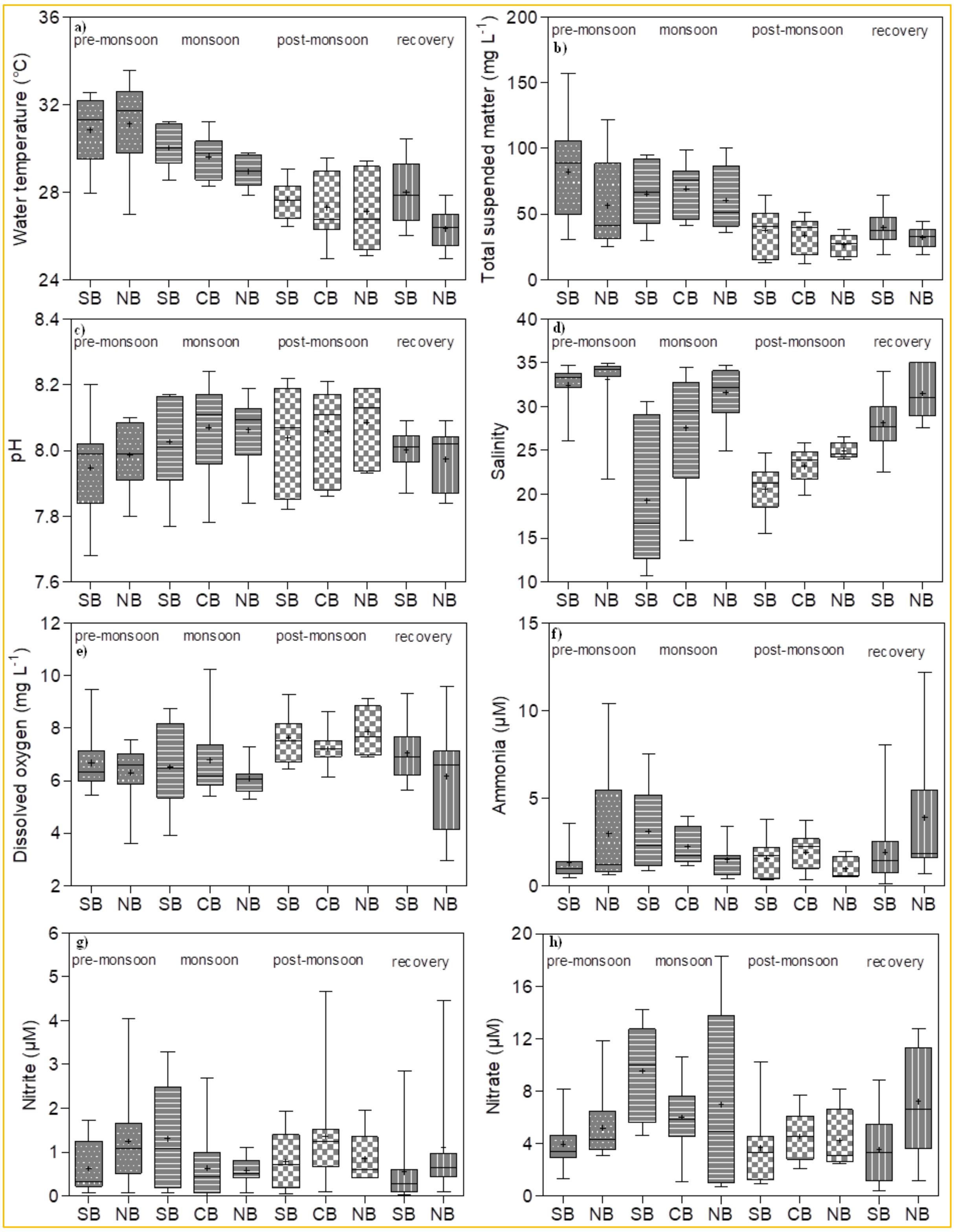

Figure 3: Seasonal variations of physico-chemical parameters in Kakinada Bay. (a) water temperature, (b) total suspended matter, (c) pH, (d) salinity, (e) dissolved oxygen, (f) ammonia, (g) nitrite, (h) nitrate (Box represents quartile deviation, whiskers minimum and maximum values, symbol inside the box represent mean values and horizontal line

Remarkable seasonal variations were observed in dissolved inorganic phosphate (DIP). To a temporal extent, DIP was high during the recovery period (4.7 ± 7.15 µM) compared to monsoon, post-monsoon, and pre-monsoon (Table 2). The average DIP concentration in the Bay was 2.9 ± 3.93 µM; these results are consistent with a previous study (Tripathy et al., 2005), which were found to be well below those of the Mahanadhi estuarine system (Sundaray et al., 2006); Bay of Annaba (Ounissi et al., 2014) and Oso Bay (Wetz et al., 2016). The spatiotemporal variation patterns of DIP in the KKD Bay are shown in Fig. 4b. The lower concentration of DIP during pre-monsoon can be attributed to lack of rainfall, land water runoff, and rapid utilization of phosphate by phytoplankton and other primary producers. Maximum DIP during the recovery period, particularly in north Bay, might be due to high organic load, brought during the monsoon and post-monsoon may be accumulated in the Bay sediment, which gets re-mineralized and leached into the water column during the recovery period (Hyung et al., 2003; Linge and Oldham, 2004). Another possible source might be the regeneration and release of phosphorus from the bottom mud into the water column due to mixing and turbulence (Velsamy et al., 2013). Elevated NH_4^+-N and DIP concentrations are good indicators of inputs from sewage discharge.

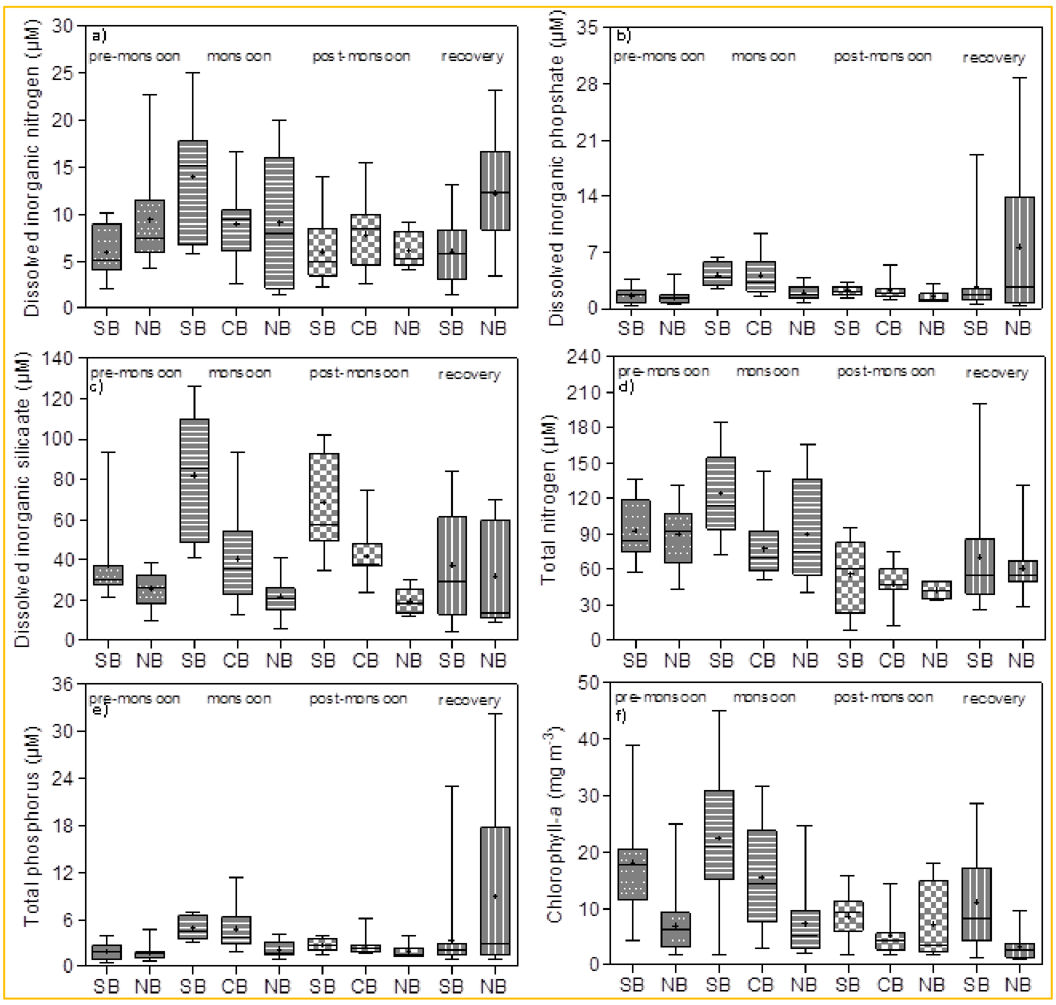

Figure 4: Seasonal variations of physico-chemical parameters in Kakinada Bay. (a) dissolved inorganic nitrogen, (b) dissolved inorganic phosphate, (c) dissolved inorganic silicate, (d) total nitrogen, (e) total phosphorus, (f) chlorophyll-*a* (Box represents quartile deviation, whiskers minimum and maximum values, symbol inside the box represent mean values and horizontal line median).

Table 4: Pearson correlation coefficients of TRIX values and select environmental variables.

	DO%	DIN	DIP	Chl-*a*
$TRIX_{PRM}$	0.140	0.172	0.564**	0.444**
$TRIX_{MN}$	0.167	0.496**	0.476**	0.390**
$TRIX_{PM}$	0.328*	0.143	-0.012	0.530**
$TRIX_{RE}$	-0.196	0.505**	0.550**	0.247

Correlation is significant at **P<0.01; *P<0.05

The concentration of DISi was higher in post-monsoon (48.99 ± 24.54 µM) than in the rest of the seasons (Table 2). The recorded highest values of DISi in monsoon and post-monsoon were due to heavy inflow of freshwater runoff derived from land drainage carrying silicate leached out from rocks from the upstream regions (Gouda and Panigrahy, 1992; Bhattacharya et al., 2002) and exchange between bottom sediment with overlying water (Rajasegar, 2003). The gradual lowering of DISi concentrations in pre-monsoon and recovery periods was attributed to the low freshwater influx. The DISi concentrations are decreasing towards the north Bay from the south Bay in all the seasons (Fig. 4c), which could be explained by the proximity of the south Bay to the river creeks, which receive fresh water.

The seasonal mean concentration of TN was high during the monsoon (93.4 ± 38.66 μM). In contrast, it was lowest in the post-monsoon (50.21 ± 22.43 μM) (Table 2, Fig. 4d). Spatially high concentrations of TN were high in south Bay may be due to the freshwater influx through Coring, Gaderu, and Matlapalem creeks, which can contribute high concentrations of nutrients into this area. TP followed the same trend as DIP, and it was highest during the recovery period and varied from 0.85 – 32.32 μM (Table 2, Fig. 4e). The lower concentration of TP during pre-monsoon can be attributed to the limited flow of freshwater, high salinity gradient, and utilization of phosphate by phytoplankton. High concentrations of TP in the north Bay during the recovery period are probably related to the regeneration and release of phosphorus from the bottom mud into the water column due to mixing and turbulence, and organic load through the KKD canal.

The N:P ratio observed during the study period showed a significant seasonal variation in the Bay. The mean N:P ratios were observed to be 6.95 ± 4.98, 3.73 ± 2.68, 3.74 ± 2.08, and 5.33 ± 6.45 during the pre-monsoon, monsoon, post-monsoon, and recovery periods, respectively (Table 2) and observed that the levels are less than16 in all the seasons and seemed to be consistent throughout the Bay. In the present study, the concentrations of nutrients in the Bay are high, and the ratio of N:P (4.9:1) was very low and could be attributed to the enrichment of these nutrients (DIP compared to DIN) through external inputs (Redfield et al., 1963). Similar values were also reported by Tripathy et al., 2005. The low N:P ratio in KKD Bay may be due to the slow regeneration of DIN compared to DIP. Biswas et al. (2010) also reported lower N:P ratios, presumably because of higher rates of DIP loading relative to DIN combined with higher consumption rates of DIN. Ray et al. (2014) analyzed the biogeochemical cycle of nitrogen in a tropical mangrove ecosystem, and the author concluded that nitrogen could be largely limiting in the mangrove-dominated aquatic system. The deficiency in nitrogen to phosphate ratio in many inshore areas (De Souza et al., 1981; Ounissi et al., 2014) may suggest that nitrogen is the limiting nutrient for photosynthesis.

Chlorophyll is the most important photosynthesis pigment, and an important index for eutrophic levels in the waters (Demirak, 2003). Chl-*a* distribution depends on water temperature, salinity, light and nutrient availability, and water dynamics (George et al., 2012), and it is the primary indicator of nutrient enrichment (Chau, 2005; Süleyman and İsmail, 2019). During the study period, the Chl-*a* showed wide variations from 0.85 to 45.01 mg m^{-3} (Fig. 4f). The concentrations of Chl-*a* were the highest in monsoon (14.48 ± 10.89 mg m^{-3}) and the lowest in post-monsoon (6.95 ± 4.4 mg m^{-3}) (Table 2). In the present study, a marginal variation of Chl-*a* levels was observed between pre-monsoon and monsoon. In monsoons, the increased freshwater discharge decreases the salinity and increases stratification, favoring phytoplankton biomass accumulation (Xu et al., 2010). The gradual increase in Chl-*a* levels during pre-monsoon could be subjected to increasing salinity, making the systems more conducive to primary productivity. The spatial variation of Chl-*a* levels revealed that the south Bay, i.e., the mangrove area contained comparatively higher levels of Chl-*a*. Similar Chl-*a* values were also reported by Tripathy et al., 2005.

4.3. Trophic Index

The trophic state of a system depends on the availability of nitrogen and phosphorus for primary production, the determination of phytoplankton biomass (Chl-*a*), and the saturation of dissolved oxygen. The distributions of the TRIX values for KKD Bay are given in Fig. 5. TRIX values ranged between 2.19 to 7.56 (5.4) in pre-monsoon, 1.38 to 7.60 (5.49) in monsoon, 2.53 to 7.71 (5.93) in post-monsoon and 2.37 to 7.93 (5.16) in the recovery period. Seasonally, the TRIX index covered various trophic conditions and may be explained by several factors. This variation depends on the elevated nutrient amount and Chl-*a* concentration. High amounts of dissolved oxygen and Chl-*a* in pre-monsoon and high amounts of inorganic nutrients and Chl-*a* in monsoon and post-monsoon seasons reflect higher TRIX values. In the recovery period, high amounts of inorganic nutrients and organic load through the KKD canal, regeneration, and phosphorus release from the bottom mud into the water column reflect higher TRIX values in the north Bay. The comprehensive TRIX-based classification (Cutrim et al., 2019) for coastal water bodies indicated that during the pre-monsoon and recovery period, the Bay behaves oligotrophic to the eutrophic environment. In contrast, during the monsoon, the south Bay, central Bay, and north Bay behave like eutrophic, mesotrophic to eutrophic, and ultra-oligotrophic to mesotrophic to eutrophic conditions due to considerable inputs of freshwater in the form of rainfall and increased river flow (Fig. 5). In the post-monsoon south Bay exhibit mesotrophic to eutrophic condition and central and north Bay behaves like oligotrophic to the eutrophic environment.

Throughout the year, among the 144 samples analyzed, 35% of the samples were Ultra-Oligotrophic to mesotrophic (TRIX values less than 5), and 65% were Meso-Eutrophic to Eutrophic (TRIX values between 5 and 8). Seasonally, in the pre-monsoon, 39% of the samples were Ultra-Oligotrophic to mesotrophic (TRIX values less than 5), and 61% were Meso-Eutrophic to Eutrophic (TRIX values between 5 and 8). In the monsoon, 31% of the samples were Ultra-Oligotrophic to mesotrophic (TRIX values less than 5), and 69% were Meso-Eutrophic to Eutrophic (TRIX values between 5 and 8). In the post-monsoon, 25% of the samples were Ultra-Oligotrophic to mesotrophic (TRIX values less than 5), and 75% were Meso-Eutrophic to Eutrophic (TRIX values between 5 and 8). In the recovery period, 47% of the samples were Ultra-Oligotrophic to mesotrophic (TRIX values less than 5), and 53% were Meso-Eutrophic to Eutrophic (TRIX values between 5 and 8). This clearly showed that freshwater in monsoon and post-monsoon was trigging the TRIX values.

On a spatial scale, during the pre-monsoon, the highest mean TRIX value of 5.61 ± 1.7 was recorded in the south Bay, and the lowest mean TRIX value of 5.26 ± 0.97 was recorded in the north Bay. During the monsoon, the mean concentration of TRIX in south Bay was high (7.05 ± 0.39) and decreased significantly in central Bay, followed by north Bay. During the post-monsoon, it was in the order of the south Bay, north Bay, and central Bay. On the other hand, during the recovery period, TRIX variation in the order of 5.28 ± 2.04 and 5.09 ± 1.13 in the north, and south Bay, respectively (Fig. 5).

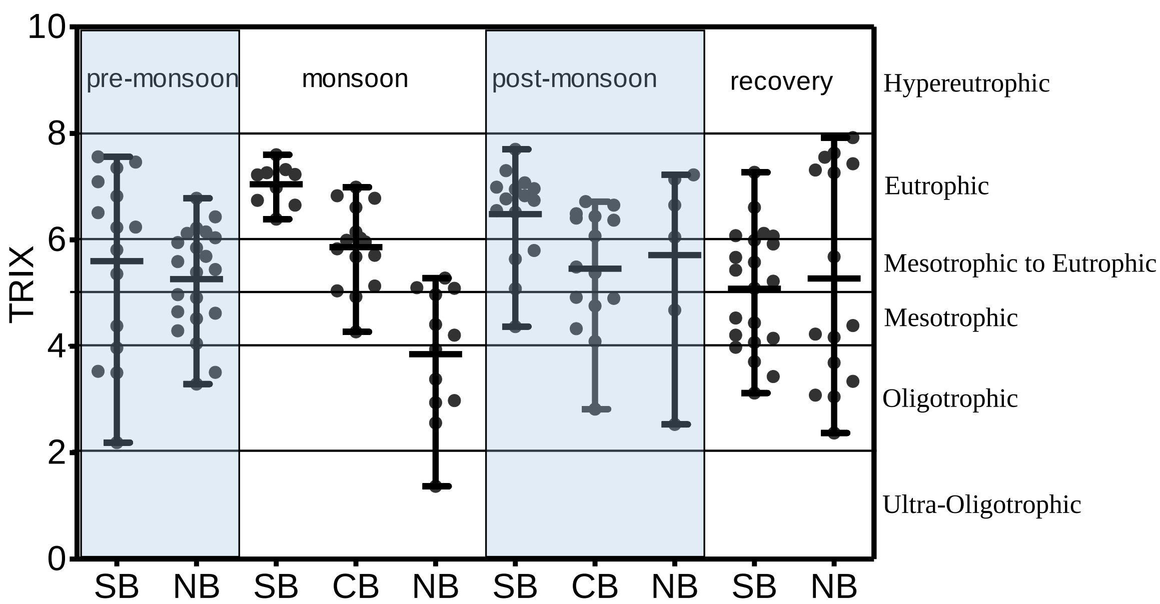

Figure 5: TRIX classification of Kakinada Bay during the study

According to the TRIX values, the KKD Bay waters changed from excellent water quality to very poorly productive water and very low trophic status (TRIX: <2 Ultra-oligotrophic) to poor water quality with very productive water and high trophic status (TRIX: 6-8 Eutrophic) (Table 2, Fig. 5), due to Nitrogen rich river inflows and direct discharges of urban wastewaters (Dogan-Saglamtimur and Tugrul, 2004; Tugrul et al., 2011) in these semi-enclosed water bodies. The seasonal average values of the TRIX Index characterize KKD Bay as a mesotrophic to the eutrophic environment with levels between 5 and 6, indicating moderate water quality with moderate to very productive and high trophic levels. The trophic state in the KKD Bay is found to be better than that of other systems like the Foz de Almargem coastal lagoon (Coelho et al., 2007), Boka Kotorska Bay (Krivokapić et al., 2011), Bizerte Lagoon (Béjaoui et al., 2016), Jansen Lagoon (Cutrim et al., 2019) and similar to the Lesina lagoon (Roselli et al., 2009). The presence of close correlations between TRIX values and all the eutrophication indicators (DIN, DIP, Chl-*a*) indicates deterioration of water quality and development of eutrophication in the KKD Bay (Table 4).

5. Conclusion

The spatiotemporal hydrographical differences within KKD Bay indicate that various factors influence water quality, including human activities and seasonal variations. The fact that pollutants were predominantly anthropogenic shows how human activities, as the most critical factor, stress the Bay environment. Despite being closer to the Bay mouth, where salinity is high, the high nutrient concentrations in this area underscore its significance as a source of anthropogenic nutrient inputs into the Bay. Conversely, the low salinity conditions in the south Bay suggest how riverine influx through rivulets and mangrove channels modify the south-north environmental gradients within the Bay, especially under monsoon and post-monsoon conditions. The wide variability in TRIX values, elevated ammonia levels, and dissolved inorganic phosphorus in the north Bay during the recovery period indicate eutrophication caused by point sources. However, the enhanced nutrient levels have not resulted in oxygen depletion, possibly due to tidal exchange. The mean seasonal values of the TRIX characterized KKD Bay as a mesotrophic to eutrophic environment. The close correlations between TRIX values and various eutrophication indicators suggest a deterioration in water quality and the development of pronounced eutrophication within the Bay. It is recommended that the government enforce strict management practices to reduce the indiscriminate discharge of domestic and industrial waste into the Bay. This can be achieved through implementing municipal solid waste landfills, proper treatment of municipal and industrial wastewater before its release into the environment, relocation or extension of existing sewage discharge points outside the Bay, and improvements in agricultural practices. These measures will help in decreasing the accumulation of pollutants in the water column and bottom sediment, thereby minimizing environmental degradation and promoting the overall health of KKD Bay.

CRediT authorship contribution statement

The manuscript and figures were prepared by AL and BCK; water quality analysis was done by AL, Review of literature and manuscript editing by BCK, KVV, and DR; supervision & editing by TSR and GNR.

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