

Phytoplankton community indices in assessing the ecological quality status (EcoQS) of a coastal ecosystem (Thane Creek, India): Mono-metric vs multi-metric approach

Revati Hardikar^{1,2}, *Haridevi Chanjaplackal Kesavan¹, Shantaj Deshbhratar²

* Corresponding author

E-mail address- haridevick@nio.org

¹ National Institute of Oceanography, Regional Centre,
Mumbai, Four Bungalows, Andheri West 400053

² Bharatiya Vidya Bhavans, Hazarimal Somani College, Mumbai

Abstract

The ecological quality status (EcoQS) of Thane Creek which is surrounded by the urbanized and industrialized sector of Mumbai was assessed by considering six phytoplankton community indices. Sampling was carried out during Premonsoon to compare the efficiency of selected indices in the tropical setting. Principal component analysis (PCA) revealed anthropogenic inputs formed a major source of nutrient load into the creek. Ecstatus proposed by selected phytoplankton indices assigned a 'moderate-good' status to phytoplankton zone (PZ)-I, 'moderate-poor' to PZ-II while 'bad' to PZ-III. Comparatively, the multi-metric phytoplankton index (MMPI) appeared to be the most efficient water quality index because of its capability in discriminating between acceptable and not acceptable EcoQS. The gradient of anthropic activities along the creek played a major role in deciding the EcoQS of Thane Creek. Limitations of all indices in evaluating environmental quality were also discussed in the present study. The investigation could provide a fillip to policymakers who are undertaking coastal water quality improvement initiatives.

Keywords: Phytoplankton assemblage, Ecological quality status (EcoQS), Multi-metric phytoplankton index, Integrated phytoplankton index, Thane Creek, India

1. Introduction

Coastal ecosystems are tactically strategic regions for human habitation as they provide livelihood resources, economic trade and transportation facilities. Recently due to the intensive social and economic headway of human settlements, the coastal zones have undergone severe undesirable influences (Gao and Chen, 2012). The creeks and rivers are treated as a sink for more than 70% of untreated industrial water and 90% of sewage waste (Creel, 2003). The anthropogenic effluent from the urban, agricultural and industrial origin modifies the chemical and biological characteristics of a coastal ecosystem which eventually over time can deepen environmental issues like eutrophication, coastal hypoxia and environmental pollution (Yin et al., 2001; Sun et al., 2019). This ultimately causes a reduction in biodiversity and adverse modification of critical habitats which overall hampers the ecosystem's health (Herrera-Silveira and Morales-Ojeda, 2009). Such adverse impacts on the ecosystem have necessitated an immediate action that diagnoses and categorizes the ecosystem under prevailing ecological quality status. Understanding and quantifying the feedback of the biological communities to anthropogenic intervention is necessary as they are one of the functional units helping ecosystem stability.

Phytoplankton are the key component of the aquatic ecosystem as they undertake an essential ecological function of primary production and being at the base of the energy pyramid directly or indirectly fuels the entire food web (Domingues et al., 2008). Additionally, due to the short generation time, phytoplankton assemblage responds quickly to environmental changes related to water quality, hydrology or climate change (Delvin et al., 2007; Domingues et al., 2008). Due to this characteristic feature, phytoplankton attributes such as biomass, abundance community structure and diversity are usually employed as an indicator for assessing the eutrophication status in coastal ecosystems (Gharib et al., 2011; Labruno et al., 2006; Spatharis and Tsirtsis, 2010).

Traditionally, chlorophyll *a* concentration is often used as a simple and collective measure of phytoplankton community response to eutrophication. However, the adverse effects of nutrient enrichment are not restricted only to chlorophyll *a* but can also affect community composition, abundance as well as frequency and intensity of bloom (Garmendia et al., 2013). Modifications in any one of these attributes can alter the energy flow and quality of food that fuels the higher trophic levels (Winder et al., 2017). In terms, this can damage the ecosystem processes such as primary production, nutrient recycling, fisheries, aquaculture and microbial processes (Houde and Rutherford, 1993; Cloern et al., 2014). Therefore, categorization of creek based on ecological status has been undertaken by applying phytoplankton community indices.

Classification encapsulates complex ecological information into a simpler form to expedite easy interpretation by stakeholders and policymakers. It has been observed that all extensively used phytoplankton water quality indices are mostly developed and tested in the temperate region (Revilla et al., 2009; Spatharis and Tsirtsis, 2010; Lugoli et al., 2012; Ni Longphuir et al., 2019). Conversely, except for the Shannon Wiener diversity index (Thillai et al., 2010; Hardikar et al., 2017), the usefulness of most relevant phytoplankton community indices in determining the ecological status of the Indian sub-continent is rare. Hence it is relevant to test the usefulness of some widely used phytoplankton community indices in assessing the ecological quality status (EcoQS) of the coastal water body of this geographical region.

The northwest coast of India is one of the most industrialized areas and encompasses highly polluted ecosystems along its long coastline (NIO, 2009). Thane Creek is a profoundly deteriorated ecosystem due to its proximity to highly urbanized Mumbai city and Asia's one of the largest Thane-Belapur industrial complexes (Jha et al., 2001; Singare et al., 2013). The dumping of pollutants into the creek has become a main concern for regulatory authorities trying to formulate remedial effective measures for restoring coastal ecosystem ecology. Therefore, the specific objective of this investigation was to assess the prevailing ecological quality status of Thane Creek and also test the comparative efficiency of selected phytoplankton community indices for evaluating the EcoQS. From the plethora of biotic indices available four mono-metric indices viz. phytoplankton chlorophyll *a* (Chl *a*) (Borja et al., 2004), abundance (Herrera-Silveira and Morales-Ojeda, 2009), Shannon Wiener diversity index (H') (Labruno et al., 2006; Hardikar et al., 2017) Menhinick diversity index (MDI) (Spatharis and Tsirtsis, 2010) and two multi-metric indices viz. integrated phytoplankton index (IPI) (Spatharis and Tsirtsis, 2010) and multi-metric phytoplankton index (MMPI) (Ni Longphuir et al., 2019) were selected based on their robustness, ease in applicability and sensitivity. The present investigation is the first attempt at a comprehensive and comparative study undertaken to evaluate the current EcoQS of Thane Creek by using attributes of the phytoplankton guild. The outcome of the present study will deliver the prevailing EcoQS of Thane Creek which can be incorporated by stakeholders or policymakers into water quality classification schemes.

2. Materials and Method

2.1. Study area

The present investigation was conducted in Thane Creek surrounded by Mumbai city, the second largest coastal city in the world and also India's premier port. Mumbai is a heavily polluted and

industrialized city situated on the west coast of India. Thane Creek (latitude 19°00' N to 19°15' N; longitude 72°55' E to 73°00' E) is a funnel shaped water body that expands at its southern end and opens into the Arabian Sea. Towards the northern end, it tapers gradually and meets the river Ulhas through a narrow channel. The creek may be considered an estuary during the southwest monsoon period. During this period, salinity drops about four units due to land drainage and river runoffs while during the rest of the season salinity is maintained in harmony with the seawater incursion. The Thane Creek experiences semi-diurnal tides with a mean tidal range of 5m in the mouth region which decreases towards upstream (Thomas et al., 2019). The creek is highly bioactive and yields about two to three thousand metric tons of fish catch per year (Shingare, 2010). Thane Creek receives effluents from wastewater treatment facilities (WWTFs) located at Bhandup (145 MLD), Ghatkopar (195 MLD), Colaba (37 MLD) and also from industrial discharge channels from Navi-Mumbai on the east bank of the creek. Excluding a few large-scale units, various medium and small-scale industries release their untreated or partially treated waste through unlined surface drains/nallah into the creek (350-375MLD) (Vijay et al., 2014; Maharashtra Pollution Control board site). Moreover, Thane Creek also receives domestic sewage from the suburbs of Mumbai. The Mumbai Port (MbPT) and Jawaharlal Nehru Port (JNPT) deal with cargo transportation of goods which is approximately >30 million tons annually, further adding up pollutants in the creek through oil leakage, spills and corrosion. Hence Thane Creek endured severe ecological stress due to a myriad of anthropogenic activities that can affect the overall environmental quality.

2.2. Sampling and analysis

Scrutiny of published literature from Thane Creek demonstrates that adverse environmental settings peak during premonsoon when there is little or no freshwater input (Vijay et al., 2015). Sivadas et al., (2016) have recommended that sampling during the decisive phase (premonsoon along the Indian west coast) was most favorable for testing the efficacy of biotic indices in the tropics. Therefore, the field sampling was conducted during the premonsoon season of April 2018 at 16 selected locations (Figure 1). For a brief understanding, the study area was divided into four zones, upper creek (UC, TC1-TC3), middle creek (MC, TC4-TC7), lower creek (LC, TC8-TC12) and coastal stations (CS, TC13-TC15). The station name, geographical coordinates, depth and type of stressors are shown in Table 1. The offshore station TC16 was considered as a reference condition.

Duplicate water samples (500 ml) were collected from the surface and near bottom at 16 selected stations (n=64) using a 5 L capacity Niskin water sampler. Samples for physico-chemical parameters such as temperature, salinity, pH, and inorganic nutrients were collected in 500 ml clean plastic bottles while samples for measurement of dissolved oxygen (DO) were collected in 125 ml glass DO

bottles. Water temperature was measured immediately by a handheld standard mercury thermometer (BRANNAN Brand, U.K.) and pH with a microprocessor controlled pH meter. DO samples were fixed immediately after collection and measured by Winkler's method and salinity by Mohr titration method, as recommended by Grasshoff, (1983). Total suspended sediments (SS) estimation was performed following the gravimetric method of APHA (2005). Samples for estimation of dissolved inorganic nutrients like nitrite (NO_2^- -N), nitrate (NO_3^- -N), ammonia (NH_4^+ -N), phosphate (PO_4^{3-} -P) and silicate (SiO_4 -Si) were filtered through Millipore filter paper (0.45 μm) and analyzed through spectrophotometric procedure within 6 h of the collection as described by Grasshoff, (1983).

Water samples (500 ml) for chlorophyll *a* (Chl *a*) estimation were filled in amber color plastic bottles and kept in an icebox immediately after collection. In the laboratory, samples were filtered through Whatman GF/F filter paper (pore size 0.7 μm , 47 mm diameter) under minimal pressure. Chl *a* (mg m^{-3}) was extracted by keeping the filter paper in 90% acetone at 4°C for a minimum period of 18-24 h and measured fluorometrically using a Turner design fluorometer (Turner trilogy, model 7200) before and after acidification (10% HCL) (Parsons et al., 1984) calibrated with pure chlorophyll *a* (Sigma-Aldrich). To enumerate the phytoplankton density and community structure, 500 ml of sample was collected and fixed with 1% acidic lugol's solution. In the laboratory, samples were kept undisturbed and after settling the samples were concentrated at 10 ml. An aliquot of 1 ml from each concentrate was taken on the Sedgewick rafter chamber and counted in duplicate under an inverted microscope at 400X magnification (UNESCO 1994). Phytoplankton identification was done to the lowest possible taxonomic level following the standard taxonomic keys of Subrahmanyam, (1946); Desikachary et al., (1987); Tomas, (1997) and their total abundance was expressed as cells l^{-1} .

2.3. Assessment of ecological quality status

The thresholds with their references used for selected phytoplankton community indices are given in Table 2. During the current study, six indices were employed at all stations to evaluate the ecostatus based on phytoplankton community indices viz. chlorophyll *a*, abundance, Shannon Wiener diversity index (H'), Menhinick diversity index (MDI), integrated phytoplankton index (IPI) and multi-metric phytoplankton index (MMPI). EcoQS of the study area was then assessed using a five-point scale viz. high, good, moderate, poor and bad based on the indices mentioned above. For the abundance index, a three-point scale was adopted.

The average value of Chl *a* was used to determine the EcoQS of each station. The threshold values of Chl *a* described by Borja et al., 2004 were utilized to categorize stations under different classes. Abundance can be treated as a proxy for ecological disturbances, as community growth is correlated

with nutrient enrichment. The stations were classified under different ecological classes based on a scale proposed by Herrera-Silveira and Morales-Ojeda, 2009. Shannon's index ($H' \log_2$; Shannon and Wiener, 1949) was calculated using the PRIMER V6 software. Evenness (E2) was estimated according to the formula described by Sheldon, (1969) and Menhinick diversity index by Menhinick, (1964).

To characterize water quality based on phytoplankton biomass, abundance and diversity, the IPI is implemented by considering the above-mentioned attributes as described by Spatharis and Tsirtsis, 2010. The diversity, in this case, is expressed in terms of the Menhinick index. The MMPI encompasses all the structural components of the phytoplankton community such as Chl *a*, abundance, diversity and evenness. MMPI is calculated based on the formula developed by Ni Longphuir et al., (2019) for a single water body being sampled. The threshold adopted to classify each index under the five-level scale with the reference used is given in Table 2. Reference conditions are a prerequisite for deriving IPI and MMPI index values. An area with the least anthropogenic disturbances can be treated as a reference condition (Vincent et al., 2002). Therefore, during the present investigation, the offshore location (TC16) was treated as a reference condition, i.e. least impacted by anthropogenic activities due to its distance (20 km) from major pollution sources on land (Revilla et al., 2009).

The five ecological quality (EcoQ) classes were then divided into two categories 'acceptable' and 'not acceptable' to establish the level of agreement between the six selected indices Table 3. The EcoQ class 'high' and 'good' corresponds to acceptable status and scored as 1, while the EcoQ class such as 'moderate', 'poor' and 'bad' were included in not acceptable status and assigned 0 scores. The score allocated to each index were summed for each station (range: 0-6). Finally, this summed score was used to determine the level of agreement (full/partial) and disagreement between indices as mentioned earlier (Blanchet et al., 2008).

2.4. Data analysis

The variation in environmental parameters between sampling depths and different zones of Thane Creek was determined using one-way ANOSIM (analysis of similarity). Variables contributing majorly to the observed variation were determined using SIMPER (similarity of percentage). Spearman's rank correlation coefficient (r) was estimated between environmental parameters and phytoplankton indices at significance ≤ 0.05 using SPSS 16. The principal component analysis (PCA) was performed to log-transformed abiotic data to understand the distribution pattern of stations in terms of their environmental variables. Phytoplankton species richness (d) and Pielou's

evenness (J) were determined to understand the distribution pattern of phytoplankton assemblages. The Bray-Curtis similarity coefficient was used to construct a similarity matrix based on $\log(X+1)$ transformed phytoplankton indices data. Subsequently, the similarity matrix was processed to non-metric multidimensional scaling (nMDS) ordination to visualize the grouping of stations based on similarities in indices values. The statistical analysis was performed using PRIMER v6.

3. Results

3.1. Environmental variables and Phytoplankton assemblages

The environmental parameters (ANOSIM, $R=0.058$, $P<0.15$) did not show significant variation between sampling depths. Therefore, depth-averaged values of each parameter were used for analysis. The spatial distribution of physico-chemical parameters in Thane Creek was represented in Figure 2. ANOSIM analysis depicted significant variations in environmental parameters between different zones of the creek ($R=0.543$ $P<0.001$). The inorganic nutrients contributed majorly to the observed variation. The physico-chemical variables such as temperature, salinity, pH and DO did not vary considerably in the study region (Table 4). The PCA analysis (Figure 3) of environmental variables generated two primary components (PC1 and PC2), together explain 85.5% of the total variability. All inorganic nutrients displayed negative loading to PC1 while salinity, pH and DO displayed positive loading. The spatial distribution pattern revealed a high concentration of inorganic nutrients in the upper and middle creek while the coastal station displayed high DO and salinity with lower nutrient concentration (Figure 3). The SS displayed significant positive loading to PC2 with a high SS load from the upper creek.

Altogether 86 phytoplankton species belonging to five functional groups such as diatoms (53 spp.), dinoflagellates (29 spp.), chlorophytes (01 sp.), cryptophytes (02 sp.) and euglenophytes (01 sp.) were identified in the present study. The phytoplankton community structure in the upper creek and coastal waters was predominantly contributed by diatoms, dinoflagellates and chlorophytes. Whereas, the remaining stretch (middle and lower creek) was dominated only by diatoms (>90%) (Figure 4). The study revealed an elevated count of phytoplankton species ($>10^5$ cells l^{-1}) such as *Skeletonema costatum*, *Guillardia delicatula*, *Chaetoceros* spp., *Thalassiosira* spp., *Pseudo-nitzschia* spp. and *Asterionellopsis* sp. in the middle and lower creek zone. While in the upper creek and coastal zone the density of these species got reduced however, the total density was more or less equally distributed among all species (Figure 4). The phytoplankton species richness and evenness displayed high species evenness at the upper creek and coastal stations, while, low evenness was

observed from the lower creek zone. The stations belonging to the middle creek displayed high species richness but encountered comparatively low species evenness Figure 5.

3.2. Assessment of ecological quality status

The EcoQS and index value at each station by six phytoplankton community indices are mentioned in Table 5 and Figure 6. Chl *a* ranged from 1.40 to 16.78 mg m⁻³ in the study region. Zone wise, the lowest Chl *a* concentration was observed at the coastal station (TC14) and the highest at the lower creek (TC9). The EcoQS derived by Chl *a* index as per the thresholds mentioned in Table 2 indicated that the upper, middle and lower creek fell predominantly in the 'moderate' category while coastal stations were under the 'good' to 'high' category. Two stations (TC3 and TC8) qualified under 'poor' status while the only station tagged with 'bad' status was TC9 of the lower creek zone. Phytoplankton abundance as an index of EcoQS assessment ranged from 1.51 x 10⁵ to 68.65 x 10⁵ cells l⁻¹ and the ecological status varied between 'moderate' to 'poor'. Following the defined thresholds (Table 2) upper creek and coastal stations were classified predominantly under the 'moderate' category. Towards the middle to lower creek zone, the EcoQS worsened to the 'poor' category.

Shannon Wiener's diversity index (*H'*) ranged from 0.93 to 3.70. The lowest diversity value was observed at lower creek classifying this zone under 'moderate' (TC8, TC9 and TC12) and 'bad' (TC10 and TC11) category while middle creek reflected 'moderate' EcoQS. The upper creek reflected 'good' status while the coastal stations demonstrated 'good' (TC13) and 'moderate' status to TC14, TC15. MDI values ranged from 0.02 to 0.07 with upper and coastal zone displaying 'moderate' EcoQS. The middle and lower creek displayed 'poor' and 'bad' status respectively except at TC4 (Moderate) and TC12 (Poor).

Out of 16 stations sampled, the IPI index (min-max 0.0-0.90) assigned 'poor' status to 10 stations and 'bad' to one location showing heavily disturbed ecological quality in the major stretch of the creek. In contrast, stations TC1 and TC13 were categorized under 'good' while TC14 and TC15 under 'moderate' ecological status. MMPI which integrates Chl *a*, abundance, evenness and diversity to assess the EcoQS of the creek, ranged from 0.04 (TC9) to 0.76 (TC13). The derived MMPI values reflected 'moderate' to 'poor' status to the upper creek and 'poor' to 'bad' status to the middle and lower creek. The coastal zone displayed EcoQS in the range of 'moderate' to 'good' where, TC13 exhibited 'good', while TC14 and TC15 showed 'moderate' status. The offshore location (TC16) was assigned with 'good-high' EcoQS by six phytoplankton indices (Figure 6).

3.3. Comparison between indices

The ecostatus of each location based on six phytoplankton community indices was not always consistent as shown in Figure 6. Chl *a* index classified 80% stations as 'not acceptable' and 20% stations under 'acceptable' EcoQS. The more severe categorization was done by abundance and MDI index where 100% of stations were tagged with 'not acceptable' status. H' and MMPI index recorded 26.67% stations with 'acceptable' and 73.33% stations with 'not acceptable' status. Whereas, the IPI index documented 13.33% and 86.66% stations under 'acceptable' and 'not acceptable' respectively (Figure 7). It was observed that only Chl *a* index classifies stations in all five classes while MMPI and IPI are under four categories. Abundance and MDI index did not assign 'high' and 'good' ecological status to any of these stations.

According to the sum of score method of Blanchet et al. 2008 (Table 3), 60% of stations (middle to lower creek zone) displayed full agreement on the 'not acceptable' status. Partial agreement on 'not acceptable' status (5 out of 6 indices agreed on 'acceptable' or 'not acceptable' status) occurred in 13.33% of stations (TC3, TC15) while 26.66% of stations (TC1-TC2, TC13-TC14) disagreed on status derived by six indices. Spearman rank correlation between environmental variables and phytoplankton community indices is given in Table 6. Abundance displayed a positive correlation with pH and DO while negative with $\text{PO}_4^{3-}\text{-P}$ and $\text{SiO}_3^{2-}\text{-Si}$. Whereas, in the case of MDI, H', IPI and MMPI the inverse correlation was evidenced. Spearman rank correlation was also carried out between all indices and displayed a significant correlation with each other (Table 7). MDI, H', IPI and MMPI were positively correlated with each other while negatively with chl *a* and abundance. Among diversity indices (MDI and H'), H' exhibited a significant correlation with most of the physico-chemical parameters other than $\text{NH}_4^+\text{-N}$ while MDI displayed a strong correlation with multi-metric indices (IPI and MMPI).

3.4. Zone formation based on selected indices

Three phytoplankton zones (PZ) were identified based on selected phytoplankton community indices (Figure 8). These zones partially overlapped with the zones formed based on the station location of the creek (upper, middle, lower and coastal zones). Based on the phytoplankton community indices, phytoplankton zone I (PZ-I) includes stations TC1-TC2, and TC13-TC15 which were predominantly characterized as 'moderate' to 'good' ecological conditions. In this zone 56.67% indices accepted on 'moderate', 33.33% on 'good' and 6.67% on 'high' ecological status. The PZ-II comprised stations TC3-TC7 and TC12 which displayed mostly 'poor' (58.33%), 'moderate' (33.33%) and 'bad' (5.56%) ecological status. The PZ-III (TC8-TC11) was categorized mostly under 'bad' (50%) and 'poor'

(33.33%) status. Overall, the upper creek (except TC3) and coastal area displayed 'moderate' to 'good' while the middle and lower creek zone displayed poor to bad ecological quality status.

4. Discussion

Different zones of Thane Creek were affected to a varying degree by numerous stressors as discussed in Table 1. Phytoplankton indices include biomass, abundance, diversity and evenness which are considered indicators of an ecosystem's health condition. High phytoplankton abundance can decrease the amount and quality of light reaching the water column. Likewise, evenness and diversity can be useful descriptors of change in coastal hydrodynamics and water quality (Herrera-Silveira and Morales-Ojeda, 2009). PCA analysis revealed the upper and middle creek exhibited comparatively high nutrient concentration with the inverse relationship with salinity, pH and DO which explained anthropogenic inputs of inorganic nutrients in the study region (Kathiravan et al., 2017). Whereas along with low nutrient concentration increased DO, salinity and pH in coastal stations revealed comparatively improved water conditions. Based on anthropogenic activities listed in Table 1, the distribution of environmental parameters (Figure 2 & 3) and phytoplankton assemblage (Figure 4 & 5) inferred that the upper creek holds high nutrients, high species richness, evenness and diversity which ultimately showed less impact on phytoplankton assemblage. Middle and lower creek zones with escalated anthropogenic activities displayed a reduction in species diversity and evenness. Additionally, opportunistic species who are efficient in exploiting the resources from the surrounding for example *Skeletonema costatum*, *Gunardia delicatula* and *Chaetoceros spp.* dominated the above zone depicting impoverished phytoplankton assemblage. The entire creek zone displayed the presence of anthropogenic stressors but the main sources of biological integrity such as species richness, evenness and diversity were reported high from the upper creek and coastal waters revealing rich phytoplankton assemblage.

4.1. EcoQS assessment of phytoplankton zone

The community attributes of an efficient EcoQS assessment include the ease of measurements along with sensitivity in the determination of environmental status and also it should convey relevant information to decision makers for efficient management initiatives (Borja and Dauer, 2008). In the current observations Chl *a*, abundance, H', MDI, IPI and MMPI were compared to evaluate their efficiency in establishing the EcoQS of the Thane Creek.

The PZ-I is comprised of stations TC1 and TC2 in the upper creek and TC13 to TC15 in the mouth of Thane Creek. The upper creek area did not receive direct wastewater from major discharge points however; domestic and sewage discharges entered the creek through drains (non-point sources) on

either side. Due to the shallow depth and limited exchange with seawater, the pollutant gets accumulated in this area exerting pressure on the phytoplankton community structure. As a result, the phytoplankton indices assigned chiefly 'moderate' EcoQS to these stations. On the other hand, stations at the mouth of the Thane Creek (TC13-TC15) received minimal anthropogenic pressure. Naidu and Sharma, 2001 characterized this area with comparatively strong currents and a highly mixed water column. Even though it received minor disturbance through anthropogenic activities such as transportation, recreational and harbor related dredging, the pollutants got dispersed and diluted with the ebb and flood currents. The dilution of water helped in maintaining the water quality of this zone and assigned 'moderate' to 'good' EcoQS. The current observations were in agreement with the previous study conducted by Vijay et al., 2014; Vijay et al., 2015 and Thomas et al., 2019 who also observed that the tidal amplitude reduces towards the upper creek which led to the accumulation of pollutants while towards the lower stretch of the creek, prevalence of tidal water for dilution helps in improving the water quality.

The stations of PZ-II and PZ-III received a considerable amount of waste from Asia's biggest Thane-Belapur industrial complex through Panvel Creek, Dharamtar Creek, Colaba outfall and also from a few drains opening into the creek. Along with industrial and domestic waste, these zones were also affected by shipping related dredging, port, fishing and recreational activities. India's two premier ports MbPT and JNPT are also located in this area. The anthropogenic disturbances caused due to these activities exerted a detrimental effect on the phytoplankton community structure classifying the PZ-II and PZ-III under 'poor' to 'bad' EcoQS. Moreover, the study conducted by Sasamal et al., 2007 in Thane Creek also demonstrated the high load of industrial and domestic waste in the middle and lower creek zone.

There was no location in the entire Thane Creek which was completely free from anthropogenic interference. In general, it can be stated that the gradient of anthropic activities along the creek played a major role in deciding the EcoQS of Thane Creek.

4.2. Comparative approach: Mono-metric vs multi-metric indices

Phytoplankton Chl *a* concentration is considered an excellent trophic state indicator. There is also a good link between phytoplankton biomass, primary production and eutrophication (Boyer et al. 2009). In the present study, Chl *a* index overestimated the ecological status. It categorized the entire creek mostly under 'moderate' to 'high' status despite single-species dominance of opportunistic species such as *Guinardia delicatula* at locations TC4-TC6 and *Skeletonema costatum* at TC6, TC7, TC10, TC11, TC12, TC14, TC15 (Figure 4 & 5). Moreover, Gao et al., 2012 also categorized these

species as opportunistic mixers from an urbanized estuarine complex. The elevated count of 10^6 cells l^{-1} (Revilla et al., 2009) or 250000 cells l^{-1} (Ni Longphuir et al., 2019) of any single species was considered a bloom that can affect the ecosystem's health. The possible reasons for overestimation of status could be the variability in cellular Chl *a* content (0.1-9.7% of fresh weight) depending on species (Boyer et al., 2009). Secondly, even though Chl *a* is a photosynthetic pigment and is found in all phytoplankton cells, it only symbolizes a portion of total biomass. The biomass of heterotrophic species is not considered in Chl *a* estimation (Domingues et al., 2008). These conditions explained the disparity in EcoQS assessment between Chl *a* and abundance index. Ni Longphuir et al., 2019 also observed the discrepancy in Chl *a* and abundance due to size differences in different cells. Therefore, the EcoQS based only on Chl *a* index is considered inappropriate. The highest values of Chl *a* at station TC3, TC8 and TC9 were probably due to the influence of anthropogenically generated waste coming from Panvel and Dharamtar Creek. These stations were located near the mouth of Panvel and Dharamtar Creek, which receives a direct influence from domestic and industrial waste. The study was in agreement with the findings of Revilla et al., 2009 made on the Basque coast, Spain, where the elevated Chl *a* was observed at the station located near the estuarine mouth.

Phytoplankton abundance can be treated as a proxy for ecological disturbances since their growth rate is directly correlated with nutrient inputs. Due to the aforesaid weaknesses of Chl *a* index, the categorization of ecological status based on phytoplankton abundance appeared to be more conservative when weighted against Chl *a* index. The usefulness of the abundance as a suitable bio-indicator was also endorsed by many researchers for estuarine and coastal water (Delvin et al., 2007; Revilla et al., 2009; Herrera-Silveira and Morales-Ojeda, 2009). During the present investigation, only 3 levels of classification were adopted for the abundance index. The abundance well differentiated the zones into the 'moderate' and 'poor' categories according to the intensity of disturbances each station received (Table 1). Elevated phytoplankton abundance ($>10^6$ cells l^{-1}) was observed from the lower stretch of the creek associated with the increased anthropogenic stressors such as domestic and industrial waste along with fishing, transportation and port related activities.

Shannon Wiener (H') and Menhinick (MDI) were two diversity indices tested in the present study for their suitability in the ecological status assessment. H' has been an extensively used measure of diversity in community ecology (Digby and Kempton, 1987; Heumann, Hackett & Monfils, 2015). In the present investigation, H' overestimated ecological status, except at stations TC10, TC11 and TC14. Besides, H' has given almost the same diversity values and thereby the same ecological status (moderate) to the majority of stations (TC4-TC9, TC12, TC14 and TC15), even though there was a

wide range of variation in species richness (27-49 nos.) and total abundance (2.4×10^5 - 6.9×10^6 cells l^{-1}). Moreover, in the present study, H' was found to be inefficient in differentiating between stations with species-poor phytoplankton assemblage with no dominance and species-rich assemblage with the dominance of one or a few species. The current observation was in accordance with the findings of Spatharis et al., 2011, from the coastal area of the Aegean Sea, Greece. Consequently, during the present investigation, it was concluded that the Shannon diversity index (H') on phytoplankton assemblage was not suitable for water quality assessment (Spatharis and Tsirtsis, 2010). This index was also criticized by many researchers saying its response mainly depends on species richness rather than the relative abundance of each species (Boyle et al., 1990; Karydis and Tsirtsis, 1996; Simboura et al., 2005).

On the other hand, the Menhinick diversity index (MDI) exhibits linear and monotonic behavior with eutrophication (Spatharis and Tsirtsis, 2010). It also well discriminates the stations between 'moderate', 'poor' and 'bad category. Its measurement is a function of total abundance and species richness; both these attributes are efficiently used in characterizing the EcoQS (Karydis and Tsirtsis, 1996). Additionally, MDI also exhibited a stronger relationship than H' with multi-metric indices (Table 7). Thus, in comparison with H' , MDI was found to be more efficient as a diagnostic tool in EcoQS assessment. This observation was consistent with the previous studies that investigated the suitability of MDI in ecological status assessment (Spatharis et al., 2011; Nincevic-Gladan et al., 2015; Ni Longphuir et al., 2019).

With the ongoing discussion, it was concluded that although there is inconsistency, each index carries its specific information. Therefore, the use of multi-metric indices combining various attributes into a single index is more appropriate for water quality assessment. Multi-metric indices are widely employed in the ecological assessment of water bodies due to their robustness more than the component metrics (Lacouture et al., 2006; Wu et al., 2011). Moreover, multi-metric indices synthesize information from more than one ecological quality element, thereby reducing the possibility of error and also misleading of results. For this reason, during the present investigation, IPI and MMPI were the two multi-metric indices used to assess the ecological quality status of the creek. In the present investigation, both these indices exhibited a similar correlation with environmental variables (Table 7). The EcoQS assessment based on IPI assigned 'poor' status to the majority of the stations even though with a wide range of IPI values (0.05-0.49). This suggested a low discriminating power between the 'poor' and 'bad' categories. Due to this inconsistency, both indices explained only 26.66% agreement on the status allocated to each station. On the other hand, MMPI gives equal weight to all quality classes and in the present investigation well discriminated

stations into 'good', 'moderate', 'poor' and 'bad' categories. With these results, MMPI can be considered more efficient in assessing EcoQS.

Furthermore, the intrinsic ability to differentiate between acceptable and not acceptable EcoQS is critical in selecting suitable biotic indices. According to the classification given by Blanchet et al. 2008, Chl *a*, H', IPI and MMPI possess the substantial capacity to differentiate between 'acceptable' and 'not acceptable' EcoQS. Whereas, other indices agreed that the entire Thane Creek had not acceptable status (Figure 7). Chl *a* index assigned an acceptable status to the entire coastal zone, H' to the TC1-TC3 (upper creek) and TC13 (coastal zone) whereas the IPI and MMPI index to stations TC13. Since stations of the upper creek as well as TC14 and TC15 received anthropogenic disturbances, station TC13 was the only station with minimum anthropogenic activities (Table 1). Consequently, EcoQS assigned by IPI and MMPI was found to be more appropriate. Furthermore, considering the above mentioned limitations of Chl *a*, H' and IPI, the MMPI was regarded as more sensitive for EcoQS assessment.

During the present study, the significant correlation of phytoplankton indices with environmental parameters (Table 6) such as pH, DO and nutrients prove its usefulness in assessing the water quality. Regardless of the significant correlation amongst phytoplankton indices (Table 7), there were inconsistencies in EcoQS produced by each index. The observed correlation between indices was anticipated since the phytoplankton attributes used to calculate the index values were correlated with each other. An inconsistency that arises in ecological quality assessment by these indices can be due to the different methods and threshold values adopted by each index to calculate the index values. However, the classification must be based on a robust tool and it should be able to synthesize information from more than one quality element. Therefore, with the present investigation, the use of mono-metric indices on phytoplankton assemblage is not found to be appropriate for water quality assessment. In contrast, a multi-metric index (MMPI) was found more suitable for this purpose.

5. Conclusion

The present investigation was the first venture to study the efficiency of various attributes of the phytoplankton guild in evaluating EcoQS of Thane Creek. The Chl *a* and H' index derived the most optimistic quality status but due to the functional limitation, the EcoQS exclusively based on these indices appeared inappropriate. On the other hand, the multi-metric index-MMPI encompassed all the structural attributes of phytoplankton assemblages and appeared most effective in assessing ecostatus. This reinforced the idea that instead of a single element, all features of phytoplankton assemblage should also be considered when studying the impact of anthropogenic forcing. The

present investigation could also be a model for researchers to perform a similar kind of work in coastal ecosystems along the Indian coast. However, further study may be required to incorporate bloom intensity, species richness as well as density of harmful species in evaluating the ecological quality status of the tropical region. Since there is no historical data available to represent reference conditions, further studies including long term monitoring of water quality from less impacted sites along tropical coastal environments need to be initiated.

Acknowledgment

The authors are grateful to Dr. Sunil Kumar Singh, Director, CSIR-National Institute of oceanography and Dr. Mohandas C., Scientist-in-Charge CSIR-NIO, Mumbai for facilitating the study. We also acknowledge Mr. Jubin Thomas for plotting sampling locations. We also express our sincere gratitude to Dr. AnirudhRam and Dr. Rakesh P.S for their immense support to carry out the sampling. The financial support from OLP2009 is acknowledged.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Financial support from OLP 2009 and MLP 1802 (Council for Scientific and Industrial Research, Govt. India) is gratefully acknowledged.

Authors' contributions

RH- Conceptualization, formal analysis and drafting of the manuscript. **HCK**- Involved in the investigation, data curation and validation of research output. **SD**- Involved in the review and editing of the manuscript.

References

- APHA, 2005. Standard Methods for the Examination of Water and Waste Water, 21st edition. American public Health Association, Washington, DC.
- Blanchet, H., Lavesque, N., Ruellet, T., Dauvin, J. C., Sauriau, P. G., Desroy, N., ... & Bessineton, C. (2008). Use of biotic indices in semi-enclosed coastal ecosystems and transitional waters habitats-implications for the implementation of the European Water Framework Directive. *Ecological indicators*, 8(4), 360-372.
- Borja, A., & Dauer, D. M. (2008). Assessing the environmental quality status in estuarine and coastal systems: comparing methodologies and indices. *Ecological indicators*, 8(4), 331-337.
- Borja, Á., Franco, J., Valencia, V., Bald, J., Muxika, I., Belzunce, M. J., & Solaun, O. (2004). Implementation of the European water framework directive from the Basque country (northern Spain): a methodological approach. *Marine pollution bulletin*, 48(3-4), 209-218.
- Boyer, J. N., Kelble, C. R., Ortner, P. B., & Rudnick, D. T. (2009). Phytoplankton bloom status: Chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. *Ecological indicators*, 9(6), S56-S67.
- Boyle, T. P., Smillie, G. M., Anderson, J. C., & Beeson, D. R. (1990). A sensitivity analysis of nine diversity and seven similarity indices. *Research Journal of the Water Pollution Control Federation*, 749-762.
- Cloern, J. E., Foster, S. Q., & Kleckner, A. E. (2014). Phytoplankton primary production in the world's estuarine-coastal ecosystems. *Biogeosciences*, 11(9), 2477.
- Creel, L. (2003). Ripple effects: population and coastal regions (pp. 1-7). Washington, DC: Population Reference Bureau.
- Desikachary, T. V. (1987). Diatoms from the Bay of Bengal. *Atlas of diatoms*, 3, 222-400A.
- Devlin, M., Best, M., Coates, D., Bresnan, E., O'Boyle, S., Park, R., ... & Skeats, J. (2007). Establishing boundary classes for the classification of UK marine waters using phytoplankton communities. *Marine pollution bulletin*, 55(1-6), 91-103.
- Digby, P.G.N., Kempton, R.A., 1987. *Multivariate Analysis of Ecological Communities*. Chapman and Hall, London.
- Domingues, R. B., Barbosa, A., & Galvão, H. (2008). Constraints on the use of phytoplankton as a biological quality element within the Water Framework Directive in Portuguese waters. *Marine Pollution Bulletin*, 56(8), 1389-1395.
- Gao, X., & Chen, C. T. A. (2012). Heavy metal pollution status in surface sediments of the coastal Bohai Bay. *Water research*, 46(6), 1901-1911.
- Garmendia, M., Borja, Á., Franco, J., & Revilla, M. (2013). Phytoplankton composition indicators for the assessment of eutrophication in marine waters: present state and challenges within the European directives. *Marine Pollution Bulletin*, 66(1-2), 7-16.

- Gharib, S. M., El-Sherif, Z. M., Abdel-Halim, A. M., & Radwan, A. A. (2011). Phytoplankton and environmental variables as a water quality indicator for the beaches at Matrouh, south-eastern Mediterranean Sea, Egypt: an assessment. *Oceanologia*, 53(3), 819-836.
- Grasshoff, K., Ehrhardt, M., Kremling, K., 1983. *Methods of Seawater Analysis*. Second revised and extended. Weinheim' Verlag Chemie.
- Hardikar, R., Haridevi, C. K., Chowdhury, M., Shinde, N., Ram, A., Rokade, M. A., & Rakesh, P. S. (2017). Seasonal distribution of phytoplankton and its association with physico-chemical parameters in coastal waters of Malvan, west coast of India. *Environmental monitoring and assessment*, 189(4), 151.
- Herrera-Silveira, J. A., & Morales-Ojeda, S. M. (2009). Evaluation of the health status of a coastal ecosystem in southeast Mexico: Assessment of water quality, phytoplankton and submerged aquatic vegetation. *Marine Pollution Bulletin*, 59(1-3), 72-86.
- Heumann, B. W., Hackett, R. A., & Monfils, A. K. (2015). Testing the spectral diversity hypothesis using spectroscopy data in a simulated wetland community. *Ecological Informatics*, 25, 29-34.
- Houde, E. D., & Rutherford, E. S. (1993). Recent trends in estuarine fisheries: predictions of fish production and yield. *Estuaries*, 16(2), 161-176.
- Jha, S. K., Chavan, S. B., Pandit, G. G., Negi, B. S., & Sadasivan, S. (2002). Behaviour and fluxes of trace and toxic elements in creek sediment near Mumbai, India. *Environmental Monitoring and Assessment*, 76(2), 249-262.
- Karydis, M., & Tsirtsis, G. (1996). Ecological indices: a biometric approach for assessing eutrophication levels in the marine environment. *Science of the Total Environment*, 186(3), 209-219.
- Kathiravan, K., Natesan, U., & Vishnunath, R. (2017). Spatio-temporal variability of hydro-chemical characteristics of coastal waters of Gulf of Mannar Marine Biosphere Reserve (GoMMBR), South India. *Applied Water Science*, 7(1), 361-373.
- Labrune, C., Amouroux, J. M., Sarda, R., Dutrieux, E., Thorin, S., Rosenberg, R., & Grémare, A. (2006). Characterization of the ecological quality of the coastal Gulf of Lions (NW Mediterranean). A comparative approach based on three biotic indices. *Marine Pollution Bulletin*, 52(1), 34-47.
- Lacouture, R. V., Johnson, J. M., Buchanan, C., & Marshall, H. G. (2006). Phytoplankton index of biotic integrity for Chesapeake Bay and its tidal tributaries. *Estuaries and Coasts*, 29(4), 598-616.
- Lugoli, F., Garmendia, M., Lehtinen, S., Kauppila, P., Moncheva, S., Revilla, M., ... & Basset, A. (2012). Application of a new multi-metric phytoplankton index to the assessment of ecological status in marine and transitional waters. *Ecological Indicators*, 23, 338-355.
- Menhinick, E. F. (1964). A comparison of some species-individuals diversity indices applied to samples of field insects. *Ecology*, 45(4), 859-861.

- Moser, GAO., Ciotti, A. M., Giannini, M. F. C., Tonini, R. T., & Harari, J. (2012). Changes in phytoplankton composition in response to tides, wind-induced mixing conditions, and freshwater outflows in an urbanized estuarine complex. *Brazilian Journal of Biology*, 72(1), 97-111.
- Naidu, V. S., & Sarma, R. V. (2001). Numerical modeling of tide-induced currents in Thane Creek, west coast of India. *Journal of waterway, port, coastal, and ocean engineering*, 127(4), 241-244.
- NIO, 2009. Monitoring of Coastal Marine and Estuarine Ecology of Maharashtra - Phase I. Part A: (Main Report).
- NIO, 2018. Assessment of impact of release of effluents on ecology of inshore and coastal areas of Maharashtra and their management
- Ni Longphuir, S., McDermott, G., O'Boyle, S., Wilkes, R., & Stengel, D. B. (2019). Decoupling abundance and biomass of phytoplankton communities under different environmental controls: a new multi-metric Index. *Frontiers in Marine Science*, 6, 312.
- Ninčević-Gladan, Ž., Bužančić, M., Kušpilić, G., Grbec, B., Matijević, S., Skejić, S., ... & Morović, M. (2015). The response of phytoplankton community to anthropogenic pressure gradient in the coastal waters of the eastern Adriatic Sea. *Ecological Indicators*, 56, 106-115.
- Parsons, T.R., Maita, Y. and Lalli, C.M (1984) *A Manual of Chemical and Biological Methods for Seawater Analysis*. Pergamon Press, Oxford, England, pp. 173.
- Revilla, M., Franco, J., Bald, J., Borja, Á., Laza, A., Seoane, S., & Valencia, V. (2009). Assessment of the phytoplankton ecological status in the Basque coast (northern Spain) according to the European Water Framework Directive. *Journal of Sea Research*, 61(1-2), 60-67.
- Sasamal, S. K., Rao, K. H., & Suryavansi, U. M. (2007). Sewage and industrial pollution in and around Thane Creek, Mumbai using high resolution IRS data. *International Journal of Remote Sensing*, 28(19), 4391-4395.
- Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. University of Illinois Press, Urbana. 117 p.
- Sheldon, A. L. (1969). Equitability indices: dependence on the species count. *Ecology*, 50(3), 466-467.
- Simboura, N., Panayotidis, P., & Papathanassiou, E. (2005). A synthesis of the biological quality elements for the implementation of the European Water Framework Directive in the Mediterranean ecoregion: the case of Saronikos Gulf. *Ecological indicators*, 5(3), 253-266.
- Singare, P. U., Lokhande, R. S., & Pathak, P. P. (2010). Study on physico-chemical properties and heavy metal content of the soil samples from Thane Creek of Maharashtra, India. *Interdisciplinary Environmental Review*, 11(1), 38-56.
- Singare, P. U., Bhattacharjee, S. S., & Lokhande, R. S. (2013). Analysis of the heavy metal pollutants in sediment samples collected from Thane Creek of Maharashtra, India. *International Journal of Sustainable Society*, 5(3), 296-308.

- Sivadas, S. K., Nagesh, R., Gupta, G. V. M., Gaonkar, U., Mukherjee, I., Ramteke, D., & Ingole, B. S. (2016). Testing the efficiency of temperate benthic biotic indices in assessing the ecological status of a tropical ecosystem. *Marine pollution bulletin*, 106(1-2), 62-76.
- Spatharis, S., & Tsirtsis, G. (2010). Ecological quality scales based on phytoplankton for the implementation of Water Framework Directive in the Eastern Mediterranean. *Ecological Indicators*, 10(4), 840-847.
- Spatharis, S., Roelke, D. L., Dimitrakopoulos, P. G., & Kokkoris, G. D. (2011). Analyzing the (mis) behavior of Shannon index in eutrophication studies using field and simulated phytoplankton assemblages. *Ecological indicators*, 11(2), 697-703.
- Subrahmanyam, R. (1946). A systematic account of the marine plankton diatoms of the Madras coast. In *Proceedings of the Indian Academy of Sciences-Section B* (Vol. 24, No. 4, pp. 85-197). Springer India.
- Sun, Q., Gao, F., Chen, Z., Wang, Y., & Li, D. (2019, February). The content and pollution evaluation of heavy metals in surface seawater in Dalian Bay. In *IOP Conference Series: Earth and Environmental Science* (Vol. 227, No. 6, p. 062021). IOP Publishing.
- Thillai, R. K., Rajkumar, M., Sun, J., Ashok, P. V., & Perumal, P. (2010). Seasonal variations of phytoplankton diversity in the Coleroon coastal waters, southeast coast of India. *Acta Oceanologica Sinica*, 29(5), 97-108.
- Thomas, J., Velamala, S. N., & Prasad, K. V. S. R. (2019). Numerical Simulation of Tidal Constituents in Thane Creek and the Ulhas Estuary, West Coast of India. *Journal of Coastal Research*, 35(2), 376-388.
- Tomas, C. R. (Ed.). (1997). *Identifying marine phytoplankton*, Elsevier. UNESCO, (1994). *Protocols for joint global ocean flux study*, UNESCO.
- Vijay, R., Khobragade, P. J., Dhage, S. S., Gupta, A., & Wate, S. R. (2015). Tidal and seasonal variations in water quality of Thane creek, Mumbai, India: a statistical analysis. *Indian Journal of Geo-Marine Sciences*, 44(06), 808-817.
- Vijay, R., Khobragade, P. J., Sohony, R. A., Kumar, R., & Wate, S. R. (2014). Hydrodynamic and water quality simulation of Thane creek, Mumbai: an impact of sewage discharges.
- Vincent, C., Heinrich, H., Edwards, A., Nygaard, K., & Haythornthwaite, J. (2002). Guidance on typology, reference conditions and classification systems for transitional and coastal waters. *CIS working group*, 2, 119.
- Winder, M., Carstensen, J., Galloway, A. W., Jakobsen, H. H., & Cloern, J. E. (2017). The land–sea interface: A source of high-quality phytoplankton to support secondary production. *Limnology and Oceanography*, 62(S1), S258-S271.
- Wu, N., Schmalz, B., & Fohrer, N. (2012). Development and testing of a phytoplankton index of biotic integrity (P-IBI) for a German lowland river. *Ecological Indicators*, 13(1), 158-167.
- Yin, K., Qian, P. Y., Wu, M. C., Chen, J. C., Huang, L., Song, X., & Jian, W. (2001). Shift from P to N limitation of phytoplankton growth across the Pearl River estuarine plume during summer. *Marine Ecology Progress Series*, 221, 17-28.

Table 1

Description of the study area along with their primary disturbance sources

Station code	Study site	Geographical coordinates	Depth (m)	Source of disturbance
TC1	Vashi	19° 2'45.00"N 72°58'43.00"E	9	Domestic and industrial waste
TC2	Trombay	18°59'53.00"N 72°57'50.00"E	12	Domestic and industrial waste
TC3	Panvel creek	18°59'21.00"N 73° 0'20.00"E	11	Domestic and industrial waste
TC4	Elephanta caves	18°58'40.51"N 72°56'43.22"E	7	Transportation, Domestic and industrial waste
TC5	Jawahar Dweep	18°58'5.00"N 72°53'10.00"E	7	Transportation and fishing activities, Dredging
TC6	Mora	18°55'22.00"N 72°53'58.00"E	12	Domestic waste and fishing activity
TC7	Fort	18°54'3.16"N 72°52'23.11"E	12	Harbour, transportation and fishing activities
TC8	Bori	18°51'50.00"N 72°53'49.00"E	9	Domestic, recreational and fishing activities
TC9	Dharamtar creek	18°49'58.98"N 72°56'39.48"E	13	Industrial and domestic waste
TC10	Colaba	18°52'48.00"N 72°48'59.00"E	14	Industrial and domestic waste, Harbour
TC11	Mumbai harbor	18°51'26.62"N 72°50'10.10"E	15	Industrial and domestic waste, Harbour
TC12	Revas	18°48'59.00"N 72°52'11.00"E	14	recreational, Industrial and domestic waste
TC13	Colaba	18°54'4.00"N 72°46'16.00"E	19	Minimum anthropogenic activities
TC14	Mumbai harbor	18°49'37.00"N 72°47'34.00"E	17	Harbour/transportation activities
TC15	Sasavane	18°47'20.00"N 72°49'37.00"E	18	recreational and domestic waste
TC16	Off-shore	18°53'52.00"N 72°35'44.00"E	24	Minimum anthropogenic activities

Source: NIO, 2008 & 2018; Expert judgment

Table 2

Thresholds used for each index. Superscript letters indicate the references for each index (see footnote). Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI-Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index

Index	Classification				
	High	Good	Moderate	Poor	Bad
Chl <i>a</i> (mg m ⁻³) ^a	<2	2-5	6-10	11-15	>15
Abundance (Cells l ⁻¹) ^b	-	<129000	129000-349000	>349000	-
H' ^{c,d}	>4.0	3-4	2-3	1-2	≤1.0
MDI ^e	>0.15	0.15-0.09	0.09-0.05	0.05-0.03	0.03-0.01
IPI ^e	IPI>0.9	0.9>IPI≥0.72	0.72>IPI≥0.53	0.53>IPI≥0.0	0
MMPI ^f	MMPI≥0.8	0.8>MMPI≥0.6	0.6>MMPI≥0.4	0.4>MMPI≥0.2	MMPI<0.2

^a Borja et al., 2004

^b Herrera-Silveira & Morales-Ojeda, 2009

^c Labruno et al., 2006

^d Hardikar et al., 2017

^e Spatharis and Tsirtsis, 2010

^f Longphuir et al., 2019

Table 3

Criteria used for measurement of agreement/disagreement between indices for each station. Full agreement was measured as [a]+[g], partial as [b]+[f] and disagreement as [c]+[d]+[e] (Blanchet et al., 2008)

Sum of the score	Interpretation	
0	Full agreement of the six biotic indices on moderate or worse ecological quality status ('not acceptable')	[a]
1	Partial agreement (five out of six) on moderate or worse ecological quality status ('not acceptable')	[b]
2	A disagreement between the six indices	[c]
3	A disagreement between the six indices	[d]
4	A disagreement between the six indices	[e]
5	Partial agreement (five out of six) on good or higher ecological quality status ('acceptable')	[f]
6	Full agreement of the six biotic indices on good or higher ecological quality status ('acceptable')	[g]

Table 4

Results of ANOSIM (analysis of similarity) and SIMPER (similarity of percentage) analysis on environmental variables (UC- Upper creek, MC- Middle creek, LC- Lower creek and CS- Coastal stations)

Group	ANOSIM					SIMPER (Cutoff 50%)
	Global test		Pairwise Tests			Major contributing variables
	R	P	Groups	R	P	
Sector	0.543	<0.001	UC, MC	0.253	0.006	nitrate, phosphate, silicate
			UC, LC	0.979	0.001	nitrite, phosphate, silicate
			UC, CS	0.997	0.001	nitrate, nitrite
			MC, LC	0.423	0.001	nitrate, nitrite
			MC, CS	0.394	0.002	nitrate, nitrite
			LC, CS	0.327	0.001	phosphate, ammonia
Depth	0.058	<0.15				

Table 5

Ecological quality status derived from six phytoplankton community indices with their values in parentheses for the area sampled (Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI-Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index)

Stations	Chl <i>a</i>	Abundance	MDI	H'	IPI	MMPI
TC1	Moderate (5.40)	Moderate (151300)	Moderate (0.07)	Good (3.68)	Good (0.73)	Good (0.64)
TC2	Moderate (8.95)	Moderate (166600)	Moderate (0.05)	Good (3.43)	Poor (0.49)	Good (0.61)
TC3	Poor (11.16)	Poor (511300)	Moderate (0.05)	Good (3.70)	Poor (0.28)	Poor (0.32)
TC4	Moderate (6.57)	Poor (345800)	Moderate (0.05)	Moderate (2.88)	Poor (0.35)	Poor (0.31)
TC5	Moderate (6.03)	Poor (620000)	Poor (0.04)	Moderate (2.89)	Poor (0.28)	Poor (0.22)
TC6	Moderate (6.82)	Poor (640300)	Poor (0.04)	Moderate (2.75)	Poor (0.25)	Poor (0.20)
TC7	Moderate (5.48)	Poor (895900)	Poor (0.04)	Moderate (2.45)	Poor (0.24)	Bad (0.17)
TC8	Poor (14.91)	Poor (3389100)	Bad (0.02)	Moderate (2.48)	Poor (0.05)	Bad (0.06)
TC9	Bad (16.78)	Poor (6864900)	Bad (0.02)	Moderate (2.31)	Bad (0.00)	Bad (0.04)
TC10	Moderate (6.89)	Poor (4348400)	Bad (0.02)	Bad (0.93)	Poor (0.05)	Bad (0.06)
TC11	Moderate (5.25)	Poor (3487600)	Bad (0.02)	Bad (0.98)	Poor (0.09)	Bad (0.09)
TC12	Moderate (5.11)	Poor (1119800)	Poor (0.04)	Moderate (2.44)	Poor (0.23)	Bad (0.16)
TC13	High (1.56)	Moderate (176400)	Moderate (0.07)	Good (3.39)	Good (0.90)	Good (0.76)
TC14	High (1.40)	Poor (239500)	Moderate (0.05)	Moderate (2.66)	Moderate (0.71)	Good (0.65)
TC15	Good (2.17)	Poor (240700)	Moderate (0.06)	Moderate (2.91)	Moderate (0.68)	Moderate (0.52)
TC16	High (0.97)	Good (64600)	Good (0.11)	Good (3.06)	High (1.00)	High (1.00)

Table 6

Spearman's Rank correlations between environmental variables and phytoplankton indices (Temp.- Temperature, DO- Dissolved oxygen, SS- Total suspended solids, Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI-Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index)

	Temp.	pH	Salinity	DO	Nitrite	Nitrate	Ammonia	Phosphate	Silicate	SS
Chl a			-.561*							
Abundance		.657**		.596*				-.804**	-.629*	
MDI		-.598*						.711**	.524*	
H'	.720*	-	-.568*	-	.664*	.620*		.796**	.821**	.561*
IPI		.757**		.729**	*			.746**		
MMPI		-.593*		-.522*				.797**		
		-.614*		-.543*						

** $p < 0.01$

* $p < 0.05$

Table 7

Spearman's Rank correlations between six phytoplankton indices. Only significant values are presented

(Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI- Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index)

	Chl a	Abundance	MDI	H'	IPI
MDI		-.939**			
H'		-.854**	.836**		
IPI	-.597*	-.964**	.957**	.784**	
MMPI	-.559*	-.962**	.940**	.795**	.987**

** $p < 0.01$

* $p < 0.05$

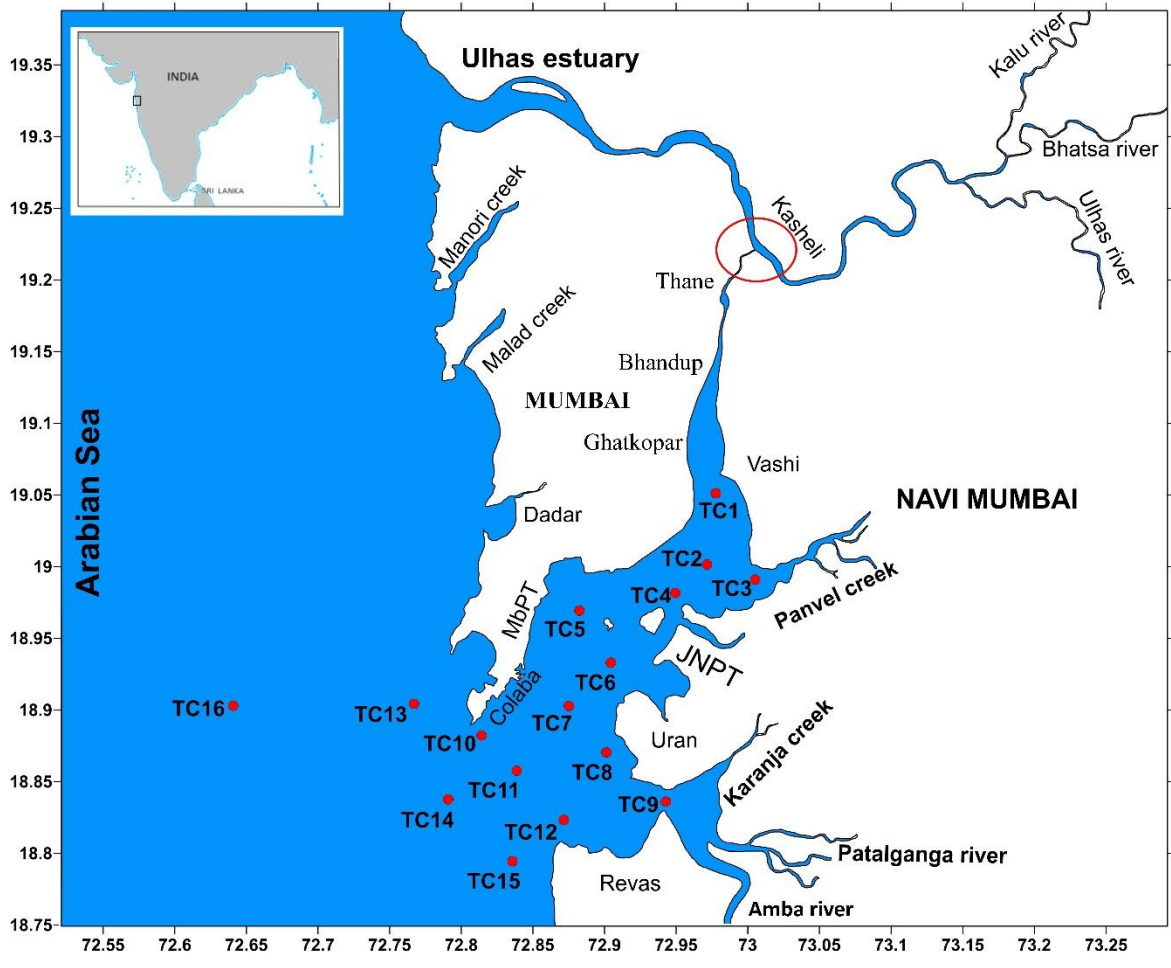


Figure 1. Map of the study area (Thane Creek) showing the position of sampling locations and reference site. The red circle showed the joining of Ulhas estuary into Thane Creek

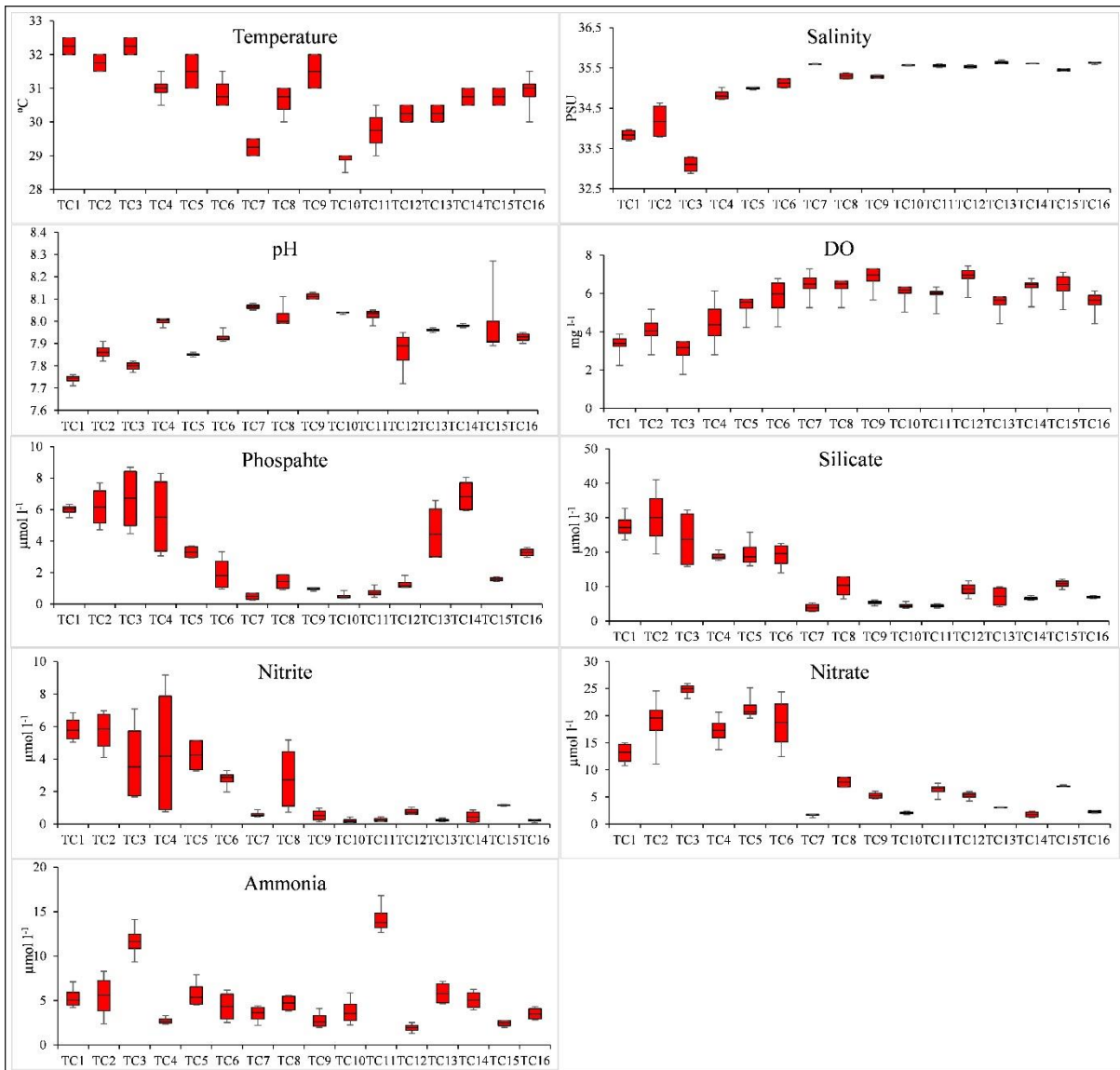


Figure 2. Spatial distribution of physico-chemical parameters of Thane Creek

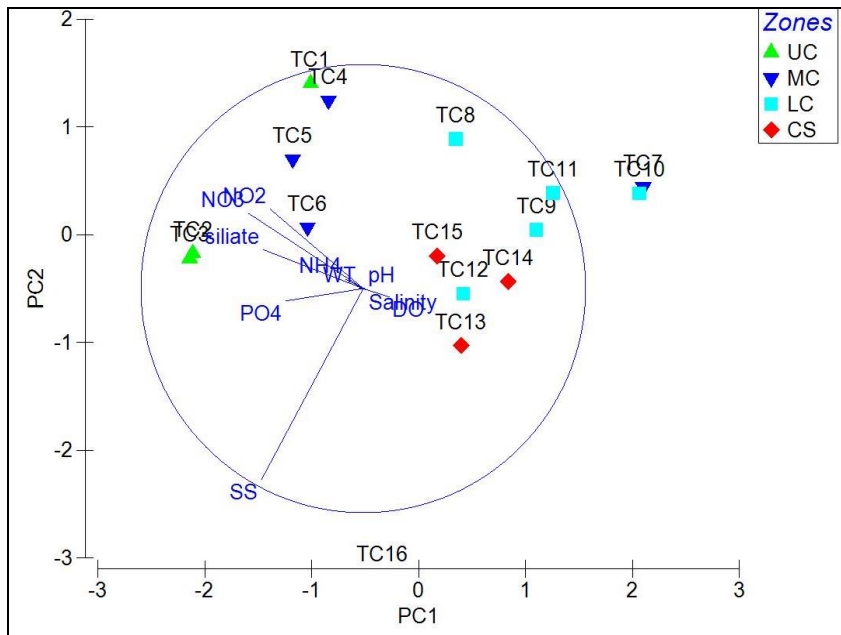


Figure 3. Principal component analysis (PCA) on physico-chemical parameters of Thane Creek (UC- Upper creek, MC- Middle creek, LC- Lower creek and CS- Coastal stations)

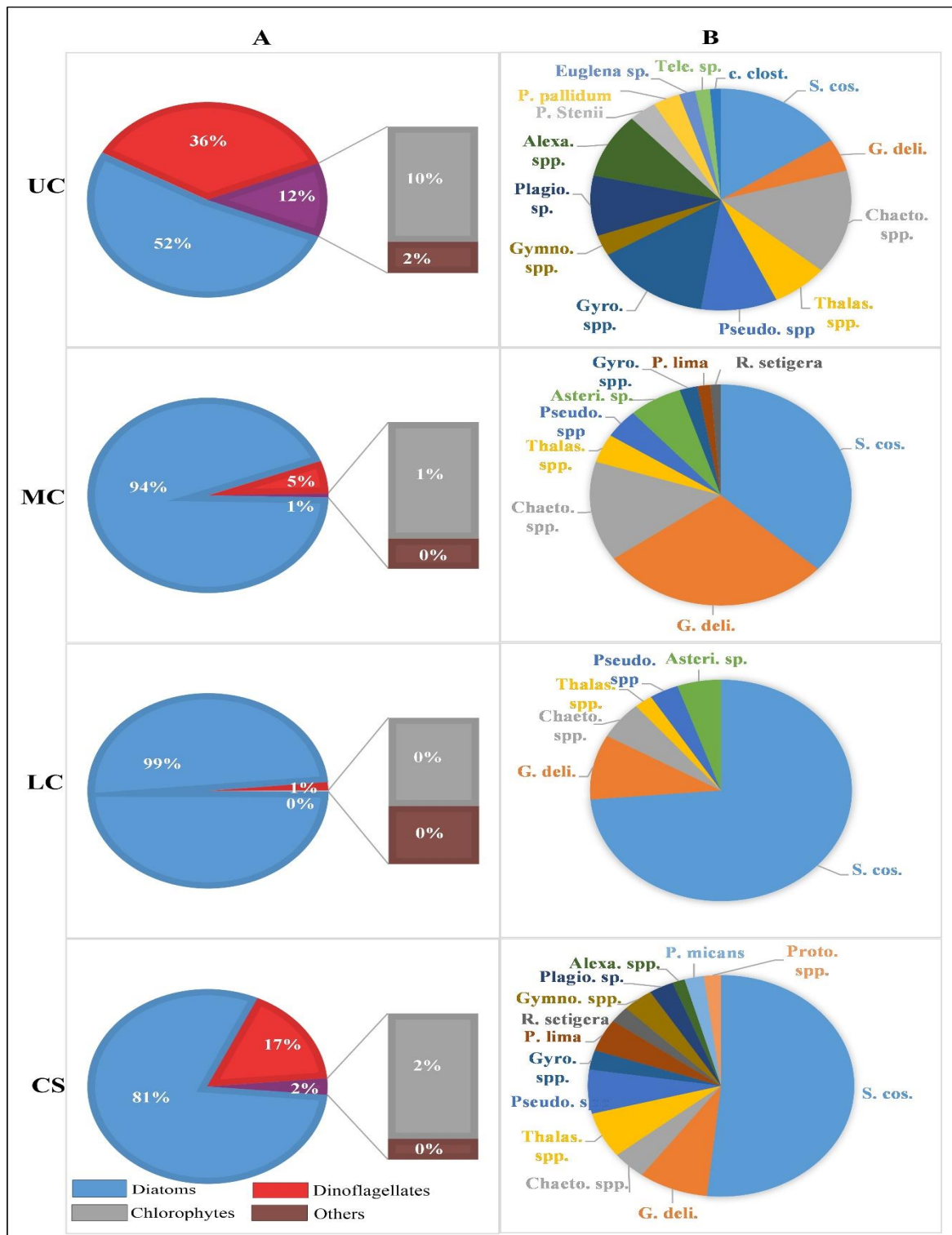


Figure 4. Spatial distribution of A) phytoplankton function groups and B) major phytoplankton species at different zones of Thane Creek. (*S. cos.*-*Skeletonema Costatum*, *G. deli.*- *Guinardia delicatula*, *Chaeto. Spp.*- *Chaetoceros spp.*, *Thalas. spp.*- *Thalassiosira spp.*, *Pseudo. spp.*- *Pseudo-nitzschia spp.*, *C. clost.*- *Cylindrotheca closterium*, *Asteri. sp.*- *Asterionellopsis sp.*, *R. setigera*- *Rhizosolenia setigera*, *Gyro. spp.*- *Gyrodinium spp.*, *P. lima*- *Prorocentrum lima*, *Gymno. spp.*- *Gymnodinium spp.*, *Alexa. spp.*- *Alexandrium spp.*, *P. micans*- *Prorocentrum micans*, *Proto. spp.*- *Protopteridinium spp.*, *P. stenii*- *Protopteridinium stenii*, *P. pallidum*- *Protopteridinium pallidum*, *Tele. sp.*- *Teleaulax sp.*, *Plagio. spp.*- *Plagioselmis spp.*, UC- Upper creek, MC- Middle creek, LC- Lower creek and CS- Coastal stations)

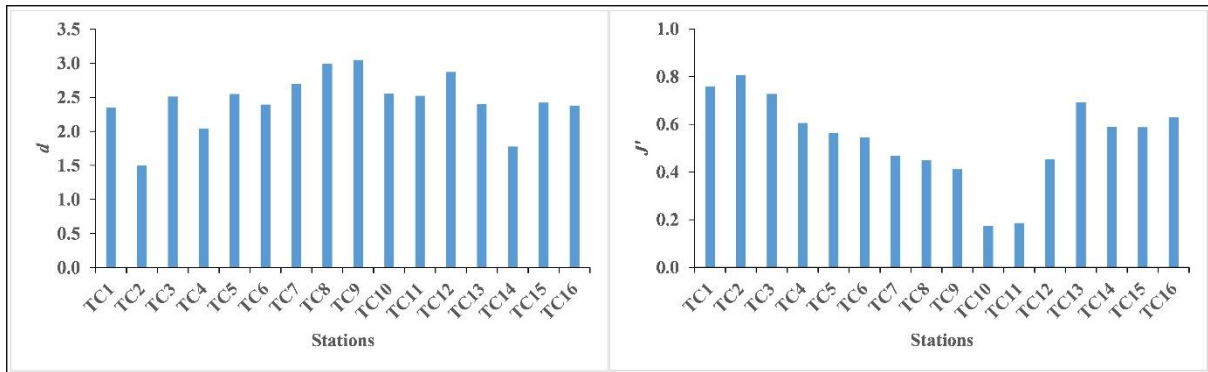


Figure 5. Spatial distribution of phytoplankton Margalef's richness index (d) and Pielou's evenness index (J') in Thane Creek

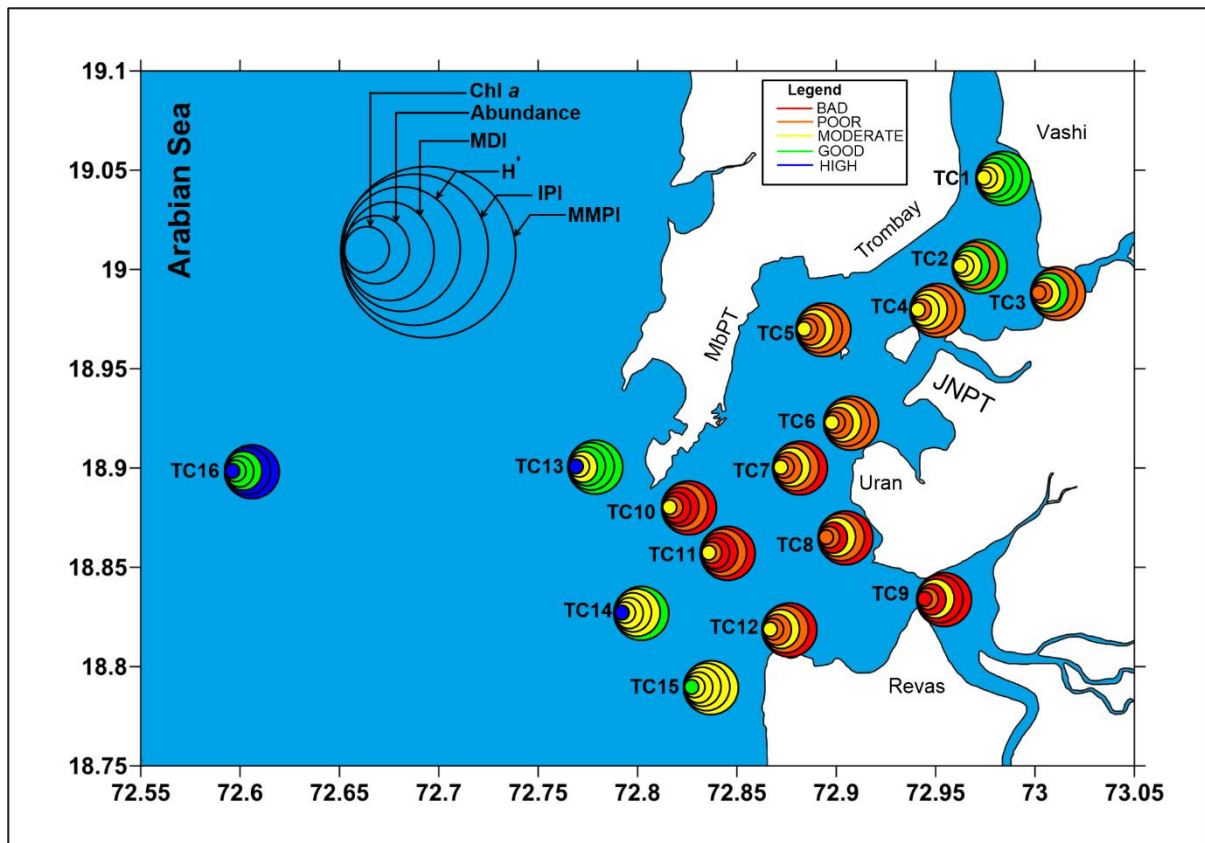


Figure 6. Graphical representation of EcoQS assign by six phytoplankton indices to each station (Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI- Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index)

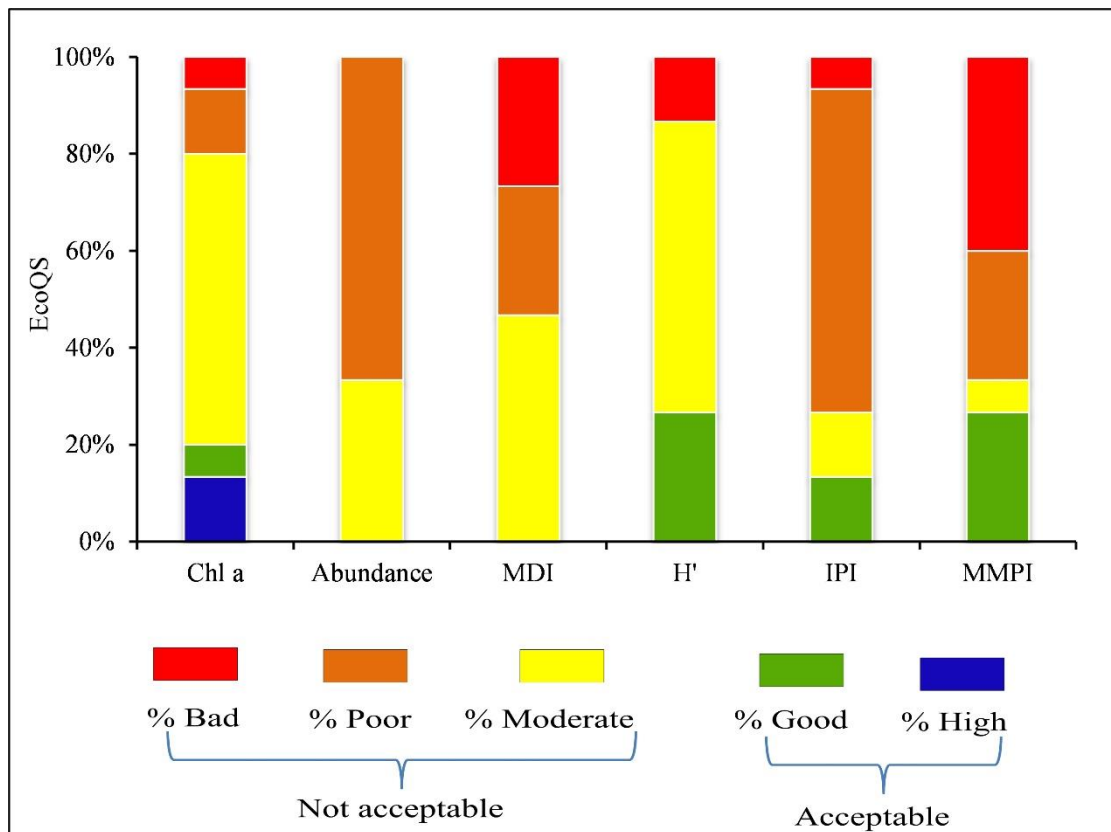


Figure 7. Integrated ecological quality status (EcoQS) of Thane Creek using six phytoplankton indices (Chl *a*- Chlorophyll *a*, H'- Shannon wiener diversity index, MDI- Menhinick diversity index, IPI-Integrated phytoplankton index, MMPI- Multi-metric phytoplankton index)

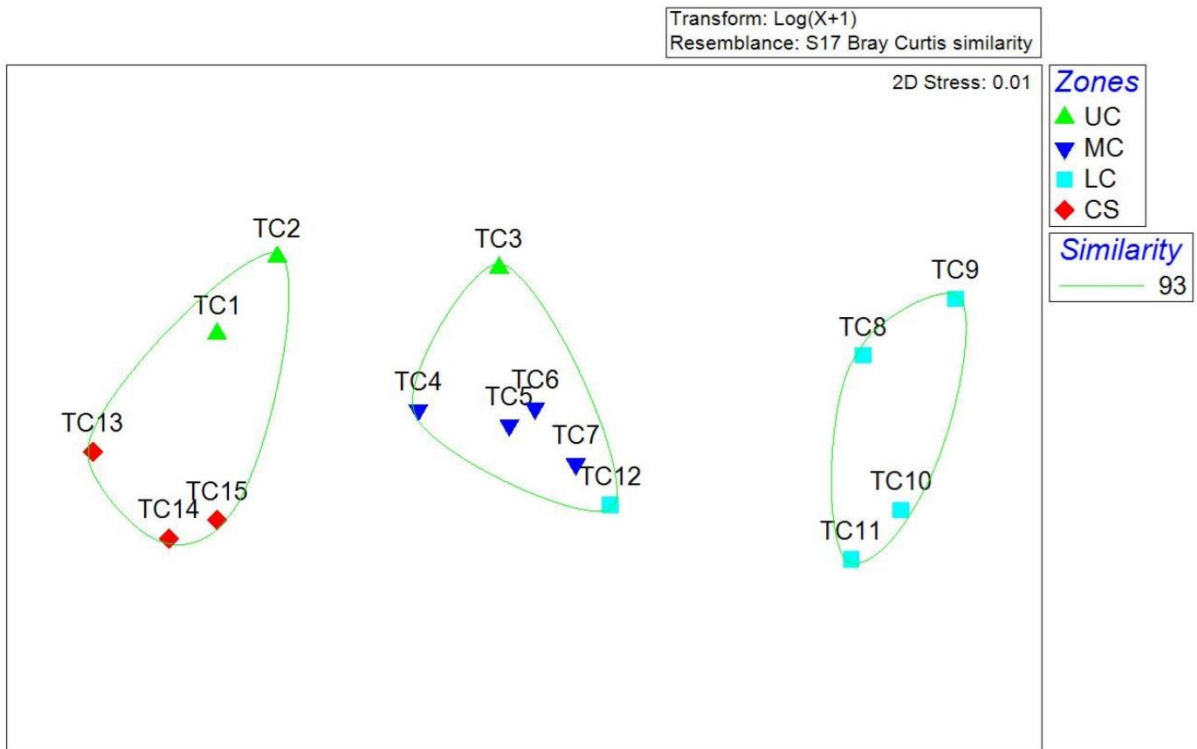


Figure 8. Multidimensional scaling (nMDS) plot of phytoplankton indices data at all sampling stations in Thane Creek (UC- Upper creek, MC- Middle creek, LC- Lower creek and CS- Coastal stations)