Application of TRIX-based indices and ASSETS model to assess the degradation of aquatic ecosystems with varying climatic conditions

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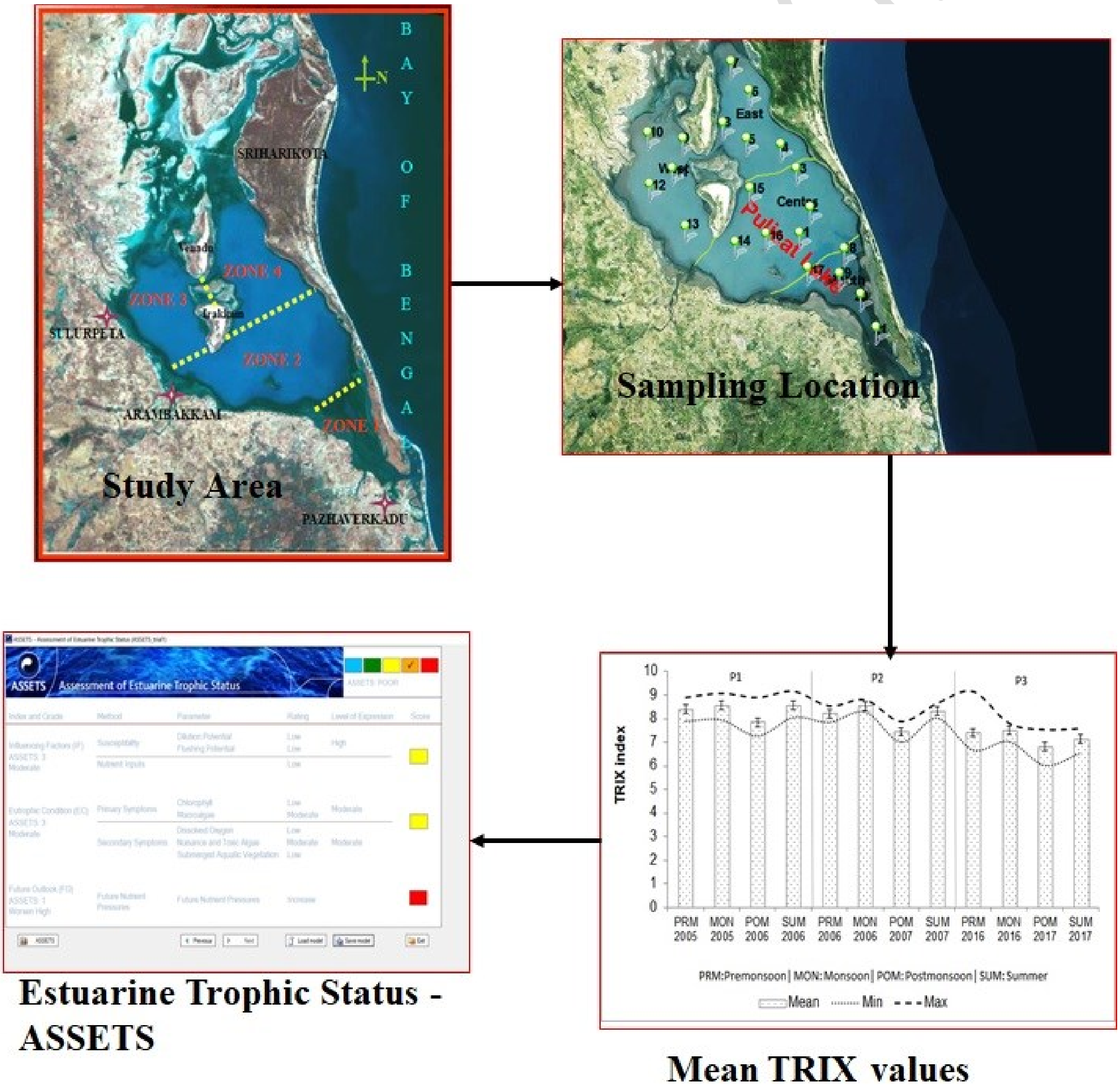
Graphical Abstract



Abstract

The applications of TRIX-based indices are more effective methods to understand the source, transport of contamination and its effect on the ecosystem. In the present study, the changes to the trophic status of Pulicat lagoon over a decadal scale using multiple annual and seasonal datasets for the years 2005-2006, 2006-2007, and 2016-2017 has been carried out to understand the application of TRIX in the aquatic ecosystem. We derived TRIX-based indices using the globally recognised Vollenweider's indexing methodology for the lagoon, for which previously classical indices using Carlson's Trophic State methods had been derived. Using the new methodology to understand the trophic status, we illustrate the eutrophic status of the whole lagoon ecosystem, comparing the decadal datasets represented by a spatial interpolation model. Further, we combined the US EPA-based ASSETS model results to confirm the trophic status given lagoon-specific parameters over a decadal scale. The study provides data on the trophic conditions of the ecosystem, confirming the increasing eutrophic status over the past decade and providing significant information to the coastal managers for further action.

Keywords: TRIX, Vollenweider index, ASSETS model, coastal lagoon, eutrophic, Pulicat lagoon.

1 Introduction

It has been illustrated that in coastal ecosystems, changes to environmental parameters such as salinity, even in very small magnitudes (for example, a two ‰), can completely alter the population structures of the fauna (e.g. Khlebovich, 1968; Telesh and Khlebovich, 2010). It is quite challenging to accurately determine the trophic state of a coastal ecosystem owing to factors such as system complexity, dynamicity of the biogeochemical processes, data insufficiency or absence and the inherent capacity of the trophic state index to adequately explain the stable and alternate states (e.g. Xu and Xu, 2015). A comprehensive discussion on the merits and demerits of popular indexing approaches for depicting the trophic status has been given in Vollenweider et al. (1998). Taking this important discussion forward to a coastal lagoon ecosystem, the differential spatiotemporal scale of exchanges with adjacent ecosystems such as estuaries, rivers and the sea further makes it difficult to study the trophic changes at appropriate spatiotemporal and seasonal resolutions. Differential precipitation rates and freshwater influx into such coastal lagoons are often highly dynamic variables that can control short-term ecosystem changes.

The problems of applying classical trophic state indices such as Carlson's Index or empirical models to transitional coastal systems have been reported earlier (e.g. Zalvidar et al., 2008; Santhanam et al., 2010). However, with advancements in the field, new indices have been used with suitable modifications that make them functional to indicate the trophic states. One such Index is the Vollenweider's or the TRIX model, whose functionality has been illustrated for many global ecosystems (Giovanardi & Vollenweider, 2004; Pettine et al., 2007). Concurrently, the growth of a suite of models as packages such as, for example, the ASSETS model has also become quite popular for ecological investigations of estuarine and brackishwater ecosystems (http://www.eutro.org). These models offer simplicity and ease in determining the trophic states for quick assessments of the ecological statuses at different periods. The purpose of the present investigation is to illustrate the trophic status of the ecosystem using the TRIX model proposed by Vollenweider et al. (1998). In past investigations of the Pulicat ecosystem, the functionalities of classical models and a new logic-based model had been explored with different levels of complexity and accuracy (Santhanam et al., 2009; Santhanam and Amalraj, 2010; Mageshkumar et al., 2013). In the present investigation, the trophic statuses over multiple years over a decadal scale have been assessed based on the advanced Vollenweider's model (Vollenweider et al., 1998), which is exclusively for marine ecosystems.

The major hypothesis of the investigation was that the decadal-level changes in the trophic changes undergone by the Pulicat ecosystem would be highlighted by adopting a sequential, numerical scale model which can focus on the exclusivity of the nutrient exchanges within marine and coastal systems. Thus TRIX model (Vollenweider et al., 1998) and the ASSETS model for brackishwater systems can be expected to provide an effective means to illustrate and reflect such changes in detail. The decadal changes in trophic changes are hypothesised to be noticeably large in tandem with the changes in the land-use patterns and the large-scale urbanisation surrounding the ecosystems in the past decade. Thus, it is necessary to study how these changes in land use may be reflected as changes to the nutrient ratios and ecosystem trophic states as a function of the changes in the precipitation, run-off and salinity changes in the lagoon ecosystem.

2 Study area

Pulicat Lagoon ecosystem is situated near the village of Pulicat Town, located about 60 km from Chennai city (Figure 1). It is a coastal inland water embayment in the form of a lagoon, known as the Pulicat lagoon, which is the second largest brackish water lagoon in India, geographically situated between 13° 25′– 13° 55′ N and 80° 03′ – 80°19′ E (Azariah, 1988). The water spread area has a total area of 650 km^2 with a high tide water spread area of about 178 km^2 (Rao and Rao, 1975). The lake is about 60 km long and 0.2 to 17.5 km wide. The total area of about 72,000 ha includes about 20,000 ha (27.7%) of swamps to the north of the lake. It has a high water spread area of 460 km^2 and a low water spread area of 250 km^2. Seawater enters the lagoon through two bar mouths at the north and south ends (W.W.F., 1993) through the flooding tide of the Bay of Bengal by two gateways, namely, Pamanjeri and Vepenjeri.

The lagoon is shallow, with an average depth of about 1.5 m (Santhanam PhD Thesis, Anna University, 2009); the maximum depth is 9.0 m at the entrance to the sea on its southeastern side. The lake is separated from the Bay of Bengal by an inland spit called Sriharikota Island. The main source of fresh water to the lake is due to the run-off from three seasonal rivers, which open into the lake. Of these rivers, river Arani flows at its southern side and Kalangi (Chacko et al., 1953; Rao and Rao, 1975) at its mid-western region, while Swarnamukhi scarcely joins the northern end of the lagoon, in addition to some smaller streams. The tidal inlets that open into the lagoon are Tupillipalem, Rayadoravu and Pulicat. Irakkam, Venadu and several smaller islands are located inside the lagoon. The settlement areas around the lagoon are Sriharikota, the village of Pulicat, Dugarajupatnam, and Sullurpeta. The lagoon water flows into the Bay of Bengal through its "mouths", with each one on either side of a sand spit. Due to the closing of the mouth during the summer months, the tidal exchange between the lagoon and the sea becomes affected. These changes in the water quality, especially its salinity, have numerous implications for conserving the biodiversity of the ecosystem (e.g. Ramesh et al., 2002; Purvaja et al., 2008; Shalini et al., 2012; Santhanam and Natarajan, 2018; Santhanam et al., 2018). The lagoon is impacted by pollution from various sources such as industries, agriculture, and domestic sewage. There has been significant encroachment on the lagoon's shores, leading to habitat loss and disruption of ecological processes. Overfishing and unsustainable fishing practices can deplete fish stocks and disrupt the lagoon's ecosystem. Climate change impacts, such as sea-level rise, changes in temperature and precipitation patterns, and increased frequency of extreme weather events, pose additional challenges to Pulicat Lagoon. These impacts can exacerbate existing environmental problems and further degrade the lagoon's ecosystem. (Harini et al., 2022). Modelling the trophic status of this ecosystem has been attempted in the past (e.g. Santhanam and Amalraj, 2010; Mageshkumar et al., 2013); however, a few limitations for each of these approaches necessitate the use of more constrained models using numerical scaling, which can overcome the inherent disadvantages. Hence, we use an improved TRIX-based approach, which we detail in the following sections.

3 Methodology

For the present work, water samples were collected from different locations within Pulicat Lagoon for 2005-2006, 2006-2007 and 2016-2017. The Pulicat Lagoon is shown in Figure 1. The sampling station positions were accurately located using a hand-held Global Positioning System (G.P.S.). The lagoon water samples were collected at 1.5 meters below the water surface through a water sampler and transferred in polyethene bottles, which were pre-cleaned by soaking in 5 M HCl for more than three days and washing with distilled-deionised water thoroughly before use. The atmospheric and water temperatures were measured using a thermometer on the spot and recorded (Velsamy et al., 2013). Salinity pH, T.D.S., and E.C. was determined using a Multiparameter probe on the spot (Model: W.T.W. field probes). Dissolved oxygen (D.O.) was measured using a D.O. meter on the spot in the study area. The other parameters were measured using standard laboratory methods (Grasshoff et al., 1999).

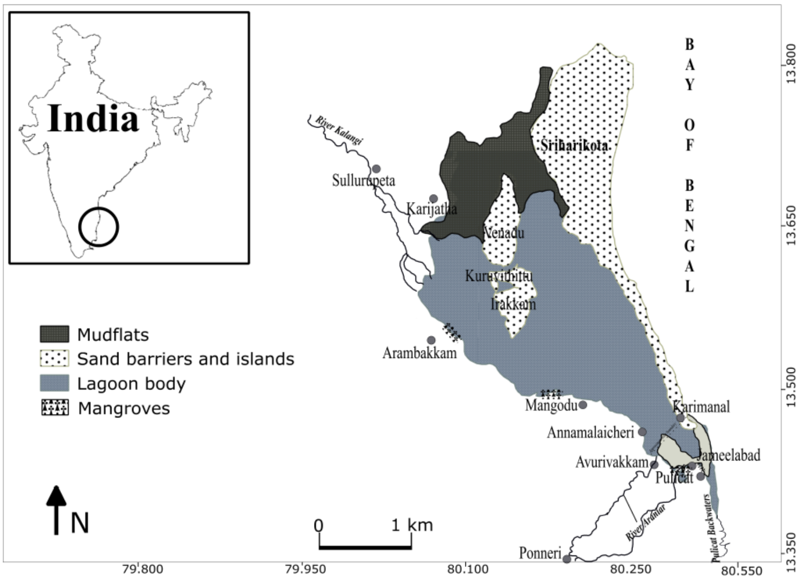


Figure1. The Pulicat lagoon

Calculation of TRIX indices

We adopted the TRIX modelling approaches Vollenweider et al. (1998) used to estimate the indices. The first step was the identification of the index components and limiting their validity within specific numerical boundary values. We used the results from the modelling studies at Pulicat lagoon (Santhanam and Amalraj, 2010; Santhanam et al., 2011 and Mageshkumar et al., 2013) to identify the significant index components and their numerical boundary ranges for Pulicat lagoon. These studies have consistently indicated the statistically significant correlations between the following environmental parameters using multiple regression analyses with the primary production (measured as chlorophyll-a): pH, water temperature, transparency of the water column (Secchi depth), salinity, D.O, Total nitrogen and total phosphorus. In the case of D.O., we calculated the deviation of oxygen saturation from 100% (aD%O) and used the same to interpret the production intensity of the system. We used consistent, log-transformed, mean seasonal data on chlorophyll-a concentrations reported for the ecosystem for the analyses (Santhanam et al., 2011; Mageshkumar et al., 2013). The indexing parameters were log-transformed and incorporated into the basic structure of the TRIX model to quantify the trophic status using the following equation:

$$TS = \frac{LOG[(chl * aD\%O)O * N * P] - [-1.5]}{1.2}$$

Where,

T.S. = Trophic status as TRIX indices

Chl = concentrations of Chlorophyll-a (in mg/m^3)

aD%O = percent deviation of oxygen saturation

O = concentrations of dissolved oxygen (in ppm)

N = concentrations of total nitrogen (in ppm)

P = concentrations of total phosphorus (in ppm)

The Index obtained from the above equation is numerically scaled between 0 and 10, indicating the different trophic conditions from oligotrophy (low) to eutrophy (high), as explained in Vollenweider et al. (1998). Intermediate values represent the changing states from oligotrophy to mesotrophy to eutrophy; the higher the values, the greater the indication of eutrophication. TRIX values greater than 6.5 can indicate the conditions of high nutrient supply, low salinity and higher water depth. TRIX values below 4.5 indicate highly turbid conditions and could correspond to low nutrient availability. If the TRIX values lie outside the range of 4.5 and 6.5, it indicates the high domination of external forcing functions over the ecosystem status. Further, the ratios of the concentrations of N and P were used to calculate the TN: T.P. ratios for the different sites within the lagoon ecosystem.

4. 0 Results and discussion

4.1 Annual and seasonal trends in the trophic status by TRIX model

The mean TRIX values showed interesting trends over different seasons and years. In general, all the TRIX values (no. of observations = 146) for Pulicat lagoon were >7, indicating the mesotrophic to eutrophic waters with low water quality (Vollenweider et al., 1998; Giovanardi & Vollenweider, 2004). The level of eutrophication is also quite high from the decadal datasets compared to global datasets (e.g. Pettine et al. 2007).

Decadal trends in the trophic status of the lagoon based on TRIX values for periods P1(years 2005-2006), P2 (2006-2007) are quite comparable to the recent period P3 (2016-2017). TRIX values are usually found to be homogenous with stable standard deviations for coastal zones, with values <3 Representing consistent marine conditions (Giovanardi and Vollenweider, 2004). In the present study, the average S.D. for all the years was found to be ±0.3 while they ranged between ±0.2 and 0.6 across the different seasons. These results show the consistency of the variations in the TRIX values across years and seasons. Hence, it is clear that Pulicat Lagoon, although a brackishwater ecosystem during periods of freshwater inflow, on the whole, represents a predominantly marine condition.

The order of seasonal changes considered in this study is as follows: pre-monsoon monsoon post-monsoon summer. For all the periods, as we move from pre-monsoon to post-monsoon, the TRIX values indicate a slow rise during monsoon and then a decrease in the post-monsoon, followed by an increase in the summer, although there are differences in the magnitudes of the changes over the decadal scale.

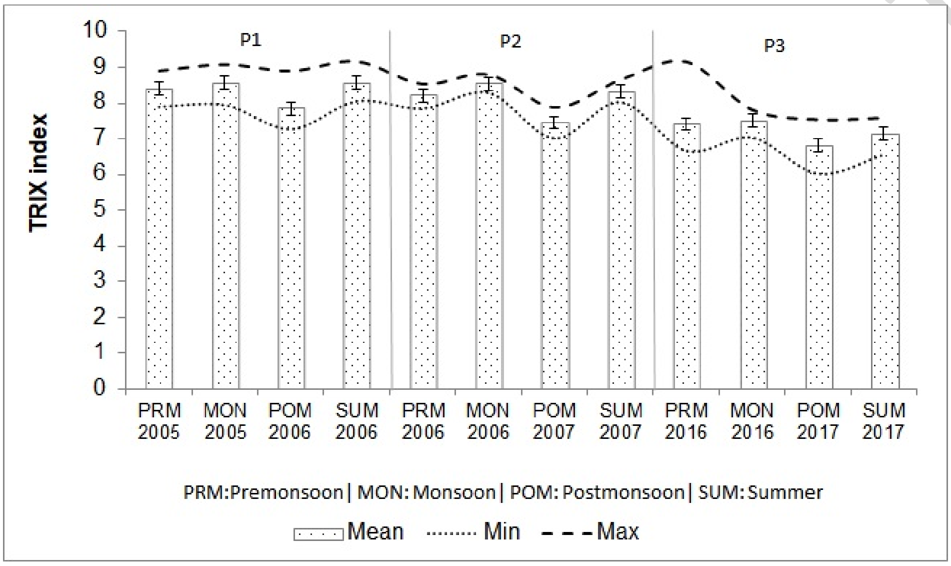


Figure 2 Mean TRIX values for different seasons and years for Pulicat Lagoon Mean

However, the minimum and maximum values over the decade 2005-2017 illustrate higher fluctuations. The maximum mean values for the TRIX index seem higher in the latter years than in the former. Similarly, the minimum values for the decade's recent years are lower than those of the early period. Among the seasons, higher TRIX values are consistently observed for pre-monsoon and monsoon seasons over all the datasets. This can be attributed to the changes in the water depth and increase in the turbidity of the water column, which is most evident during these seasons at Pulicat.

Figure 3 shows the spatial distribution of the TRIX index for Pulicat Lagoon for three periods: P1 (2005-2006), P2(2006-2007) and P3(2016-2017). The spatial patterns for indices are similar for P1 and P2. Compared to these two periods, the spatial patterns for P3 show differences across all the seasons. During P1 and P2, the TRIX indices were closer to the ranges of 9.4 compared to P3, when the index values did not increase beyond 7.5. In general, the southern sectors of the lagoon showed a higher TRIX value than the northern and central regions.

Annual differences (between P1, P2 and P3) are more pronounced during the monsoon and summer seasons. For example, notable transitions in the indices for P1 and P2 occurred during the shift from monsoon to post-monsoon seasons and subsequently between post-monsoon and summer seasons. Dramatic spatial and seasonal changes are evident throughout P3 and more prominent during the shift from monsoon to post-monsoon. Unlike the earlier periods, very few differences were observed in the spatial trends between post-monsoon and summer for P3. In general, a sudden shift in the ecosystem status becomes evident at the cross-over from monsoon to post-monsoon and from post-monsoon to summer across all the periods.

Summer being the period of least freshwater influx, high evaporation and the drastic reduction in water depths and the crystallisation of salts, the lagoon becomes hypersaline and exhibits marine conditions; the TRIX model for summer illustrates this scenario quite clearly. However, it is interesting that the TRIX indices that emerged from 2016-2017 clearly show increased marine dominance over the years. Since TRIX is the multi-criteria model, which is inclusive of the changes to the lagoon's T.N., T.P. and N:P ratios, it is necessary to understand the changes to the N:P concentrations for the different years on a decadal scale.

The post-monsoon season is an important indicator of the change in the trophic status, illustrating the least index value compared to the other seasons over all the periods. While a level of uniformity is noticeable in the spatial patterns of the indices for P1 and P2 across all four seasons, the indices of the data from P3 show distinct differences with the lowest indices among all the years.

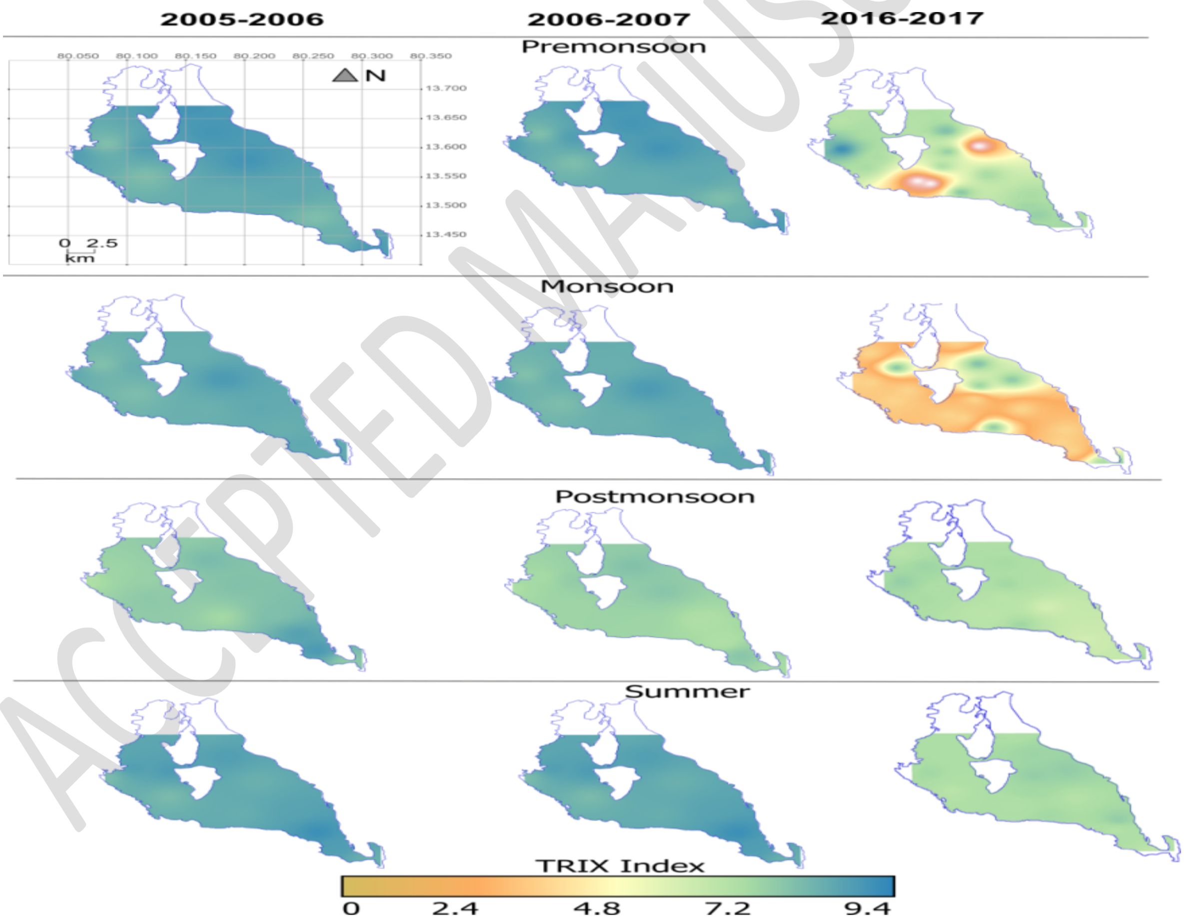


Figure 3 Spatial representation of decadal datasets of TRIX indices for Pulicat lagoon concerning seasonal changes in the water quality parameters.

The spatial representation shows that TRIX values for the season for the southern portions of the lagoon (with open exchange with the Bay of Bengal) and the northeast (stagnant, hypersaline) illustrate a typical marine condition across all seasons (Giovanardi and Vollenwieder, 2004). However, the northwest and the central portions show sudden changes in the post-monsoon season, probably due to differences in the recirculation of the dissolved nutrients.

4.2 TN: T.P. ratios

The TN: T.P. ratios for Pulicat for the periods P1, P2 and P3 showed interesting trends (Figure 4). It is evident that the ratios are different for different periods, illustrating differences in nutrient recirculation and assimilation over the seasons. The lowest ratios were recorded during P2. The highest ratios, obtained in P3, are approximately ten times those from earlier periods, illustrating severe T.P. limitations in the lagoon in the latter years. Such trends have been reported earlier for the lagoon ecosystem (Santhanam and Amalraj, 2016).

Seasonally, the ratios are higher for the post-monsoon season for P1 and P2 (Figures 4a and b), except for P3 (Figure 4c). The lowest ratios for all periods were recorded in the monsoon season. Comparable ratios are observed for both the pre-monsoon and the summer seasons with low S.D. values (error bars in Figure 4). The highest S.D. is observed for the post-monsoon season across all the periods.

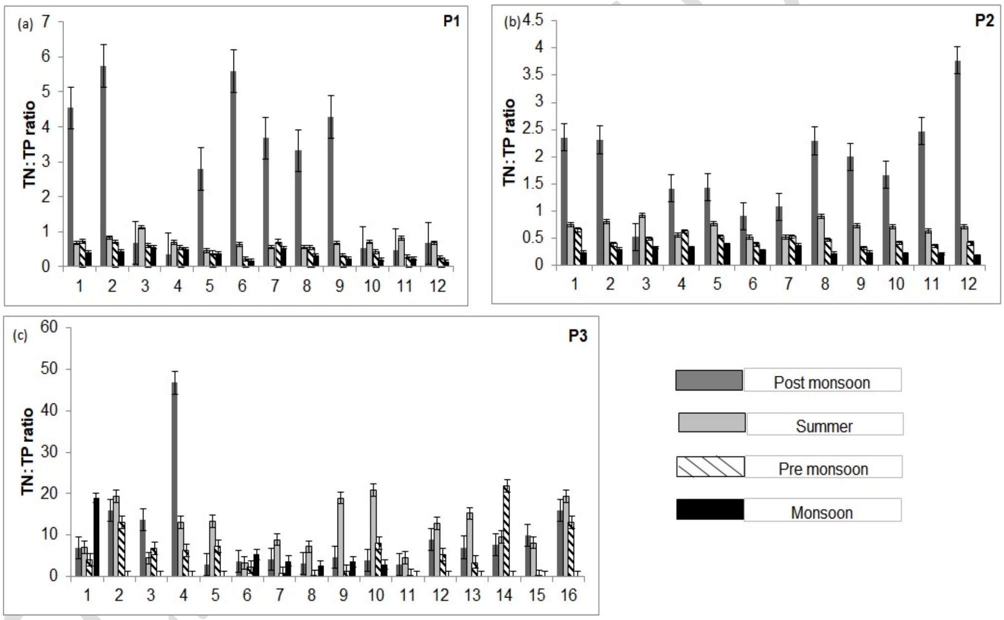


Figure 4. Annual and Seasonal TN: T.P. ratios for Pulicat lagoon for the periods 2005-2006 (P1), 2006-2007 (P2) and 2016-17 (P3) from different locations within the lagoon.

4.3 ASSETS Model

The Assessment of Estuarine Trophic Status (ASSETS) model (http://www.eutro.org) provided a holistic assessment of the trophic status based on the weights assigned to the various parameters linked to the lagoon properties, as shown in Table 2 below.

Table 2: Values assigned to lagoon environmental properties in the ASSETS model for Pulicat lagoon

Tidal freshwater zone			
Primary symptoms	Value	Spatial	Temporal
Chlorophyll	5	6	5
Macroalgae	1		3
Secondary symptoms			
Dissolved oxygen	6	5	4
Nuisance and toxic blooms	1	1	0
Submerged Aquatic Vegetation	2	0	
Mixing zone			
Primary symptoms	Value	Spatial	Temporal
Chlorophyll	4	6	5
Macroalgae	1		0
Secondary symptoms			
Dissolved oxygen	5.3	5	4
Nuisance and toxic blooms	1	1	0
Submerged Aquatic Vegetation	2	0	
Seawater zone			
Primary symptoms	Value	Spatial	Temporal
Chlorophyll	3	6	5
Macroalgae	2		3
Secondary symptoms			
Dissolved oxygen	4	0	1
Nuisance and toxic blooms	1	1	1
Submerged Aquatic Vegetation	2	0	

Based on the parameters and the weights, the ASSETS score for Pulicat lagoon is quite high, corresponding to the category "POOR", as shown in a screenshot in Figure 5. The rating for the different parameters indicates the "moderate" impact of algae and macroalgae due to the eutrophic conditions existing in the lagoon. This result directly supports the observations from the TRIX model discussed in section 4.1, which placed the lagoon ecosystem under the category "Eutrophic" (index value > 7) for most parts of the year.

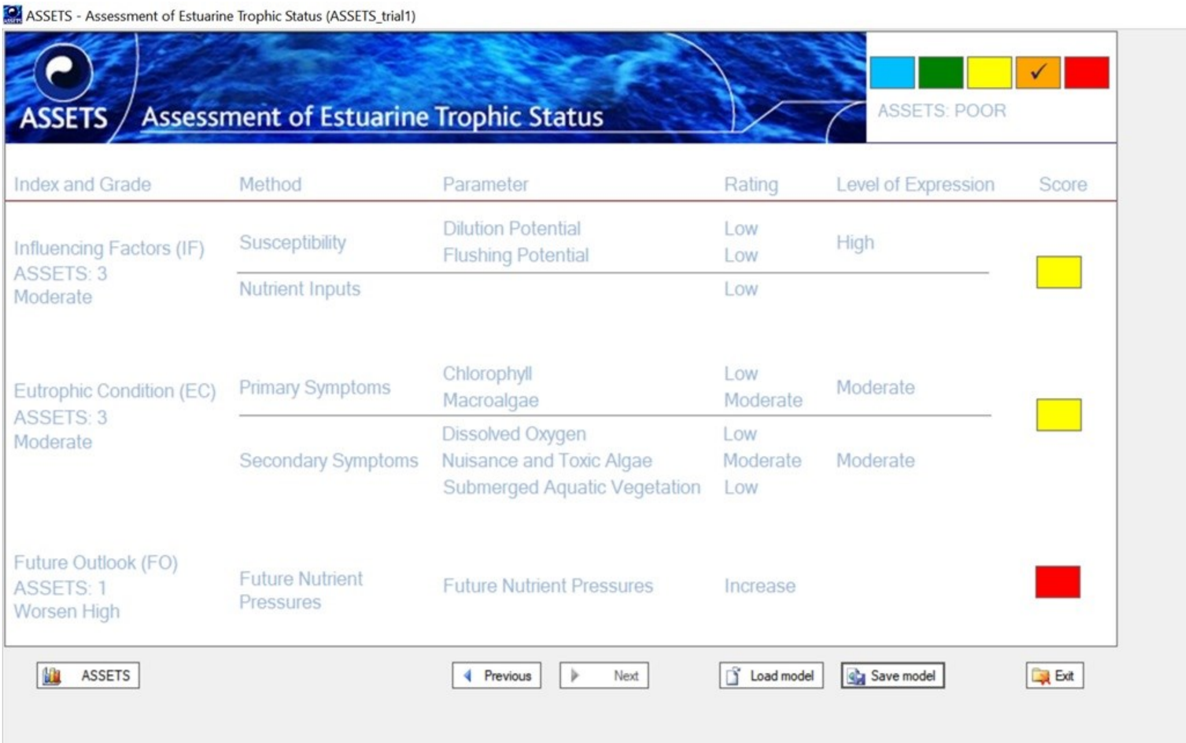


Fig 5 Results of the ASSETS (Assessment of Estuarine Trophic Status; http://www.eutro.org) model for Pulicat lagoon

4.4 Discussion

During the pre-monsoon season, the dry climatic conditions, in addition to the absence of flow from the rivers, cause a reduction in the water column causing high evaporation, sediment resuspension and an increase in turbidity (Purvaja et al., 2008; Santhanam and Amalraj, 2016). In the summer season, though high rates of evaporation are noticed, the probability of active southwest monsoonal precipitation is also high, which may contribute to very low amounts of freshwater flow into the lagoon without increasing the turbidity. Both in pre-monsoon and summer, the TN: T.P. ratios indicate a low recirculation at all locations without altering the ratios. The reverse is the case in post-monsoon and monsoon seasons, where large differences in recirculation cause different magnitudes of changes to the TN: T.P. ratios.

The changes in the TRIX values for summer are critical to indicate the changes to the trophic statuses corresponding to non-significant increases in the TN: T.P. ratios and reflect the intermediate ecosystem status prevalent during the period. A recent study showed a spatial relationship of TRIX with oxygen and chlorophyll concentrations, significantly correlating with the phosphorus concentrations moving from the open ocean to the coastal sites (Krivokapić et al., 2016). This indicates the sensitivity of the TRIX to small changes in nutrient concentrations. During the monsoon season, a huge influx of monsoonal discharges from north-east monsoonal rainfall as well as due to the active exchange with the sea, increases the rates of siltation and recycling significantly of the bottom substratum (e.g. Sanjeevaraj, 2011), contributing to the turbidity and alter the TN: T.P. ratios significantly. Both summer and monsoon seasons are, in some ways, the general lean periods for phytoplanktonic growth and low eutrophication levels are expected at these times. However, it is also possible to expect the low dependencies of trophic status with the amount of precipitation (Monroy and Troccoli-Ghinaglia, 2018) in contrast to the high increases in the rates of nutrient recirculation since bioavailability for new production may not be necessarily enhanced. The ASSETS model further provides support to this observation. The model indicated that the lagoon ecosystem is quite vulnerable to the stress from pressures of nutrient circulation (Figure 5) during inter-seasonal periods rather than within a given season, a trend which is quite reflected in the recent data on TN: T.P. ratios as elaborated in section 4.2.

5 Conclusions

The present investigation of the trophic status of Pulicat Lagoon has illustrated the decadal and seasonal changes. Overall the periods investigated, the lagoon ecosystem remained eutrophic, and the magnitude is observed to have increased during the recent period at the end of a decade.

- Poor Lateral Circulation: Nutrient inputs from adjacent land areas (such as agricultural runoff) often accumulate in the lagoon due to inadequate lateral water movement. Addressing this requires better land-use practices and efficient drainage management.
- Systematic Nutrient Recirculation: The lagoon's nutrient recirculation system needs improvement. Implementing measures to enhance nutrient cycling within the ecosystem is crucial. This could involve restoring wetlands, promoting natural filtration processes, and controlling nutrient inputs.
- Decadal Changes: The study analyzed data from different periods (P1, P2, and P3) spanning several years. Notably, the lagoon ecosystem remained eutrophic throughout these decades. However, the magnitude of eutrophication increased significantly during the most recent period (P3).
- TRIX Indices: The TRIX indices, which quantify trophic state, showed a pronounced change between P2 and P3. This suggests that the lagoon's nutrient enrichment intensified over the last ten years.
- ASSETS Model: The ASSETS model corroborated these findings. It revealed that the surge in eutrophication occurred specifically in the past decade (P3), contrasting with the relatively stable trends observed in earlier years (P1 and P2).

Futuristic Management Strategies

Under the constraints of low data availability on the nutrient statuses of the lagoon, the present investigation combined the available datasets on seasonal and annual nutrient concentrations to study the decadal changes in the trophic status of the lagoon. Such a study is important for planning the futuristic management measures to manage nutrient recirculation within the lagoon system such as:

- Monitoring Programs: Regular monitoring of nutrient levels, algal blooms, and dissolved oxygen is crucial. This will help track changes and guide management decisions.
- Integrated Approaches: Collaborative efforts involving scientists, policymakers, and local communities can lead to integrated management approaches. These may include nutrient reduction programs, habitat restoration, and sustainable fishing practices.
- Public Awareness: Educating local communities about the importance of nutrient management and sustainable practices is vital. Community involvement can drive positive change.

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