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Baseline

Impact of coastal power plant cooling system on planktonic diversity of a polluted creek system

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ABSTRACT

A tropical coastal power plant with a once-through cooling system that pumped sea water along with tiny marine phytoplankton and zooplankton for waste heat discharge recorded reduction in the population density of these organisms by 64% and 93%, respectively, at the discharge site. The depletion of organic carbon is 0.69 tons per annum with loss of 20 to 24 lakhs fish fecundity. The synergistic effect of tropical summer ambiance and waste heat discharge from the power plant considerably reduced the phytoplankton population in the coolant water discharge point during April, June, and July. This resulted in changes in the phytoplankton community structure from Bacillariophyceae > Dyanophyceae > Cyanophyceae to Bacillariophyceae > Cyanophyceae > Dyanophyceae in the Ennore creek system. A unique epibiotic assemblage of the diatoms *Licmophora juergensii* and *Licmophora flabellata* was observed on *Phormidium* sp., a mat-forming Cyanobacterium preharbored along the 4.5-km-long transport channel of the cooling tower blow out of the thermal power plant. These pedunculate fouling diatoms have a symbiotic association with *Phormidium* sp., which grows few microns high above the substrate, thus creating obstructive flow in cooling water channels of the power plant. Further, loss of fish larvae during zooplankton population reduction creates an impact on the local fishery. However, the emerging scenario of global warming predicts that the migration of fish population toward cooler regions shall further aggravate the fishery reduction near the power plant cooling operation along the tropical coasts. The marine organisms living in tropical coastal waters operated at upper limits of thermal tolerance produce a demand for the regulatory bodies in India to enforce a drop in discharge criteria for coolant water, with the pre-existing power stations permitted to discharge up to 10 °C above the ambient temperature and newer power stations permitted to discharge a maximum of 7 °C. It becomes a requisite for power stations to draw additional seawater along with the plankton. Therefore, an emerging technology of subsurface intake systems called beachwell that resolves the issue of coolant water intake without biota was advocated.

The demand for power-generating plants has been increasing regardless of several appeals in energy conservation. Factors such as urbanization and industrialization propel the need for energy production (Major Singh, 2015). Consequently, it increases the need for cooling water at various steps during energy generation procedures. In general, water bodies such as rivers and ocean were often used as key sources to meet the in-satiated demand for cooling water.

Water drawn into power plants usually contains organisms such as phytoplankton, algal propagules, zooplankton, invertebrate larvae, and fish larvae often considered as a representative of local ecological communities (York and Foster, 2005). These traversing communities can be used as a mirror reflection to determine the adverse impacts such as decreased biomass and productivity of phytoplankton and heterotrophic bacteria (Capuzzo, 1980; Choi et al., 2002; Morgan and Stross, 1969; Shiah et al., 2006; Takesue and Tsuruta, 1978), reduction in survival and diversity of zooplankton communities (Taylor, 2006), and reduction in other metazoans (Bamber and Seaby, 2004; Capuzzo, 1980; Carpenter et al., 1974; Evans et al., 1986; Hoffmeyer et al., 2005; Kartasheva et al., 2008) in the aquatic environment.

The damage in the transiting plankton cells often associates with factors such as the type of organisms, conditions of operational systems, temperature, and chlorine residues (Bamber and Seaby, 2004; Capuzzo, 1980; Poornima et al., 2005). Among these factors, thermal stress was reported as a causative factor for transiting plankton mortality (Thorhaug, 1978; Marumo et al., 1992; Taylor, 2006). In general, seasonal variation of Indian coastal water temperature widely varies (maximum of 10 °C), thereby forcing the organisms to live in upper lethal temperature limits (Krishnakumar et al., 1991). Further, mortality of planktonic communities was also strongly related to the discharge of heated waste materials in tropical coastal water (Poornima et al., 2006).

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Table 1
Impact of power plant effluent discharge on plankton reduction – an overview.

S.-nos.	Power plant type	Phytoplankton reduction	Zooplankton reduction	Fin fish/larvae mortality	Primary productivity (GPP) reduction	Reference
1	Coal based, Korea	–	20–37%	–	–	Choi et al., 2012
2	Nuclear power plant, Taiwan	10–43%	–	–	–	Wen-Tseng Lo et al., 2016
3	The nuclear power plant, Chennai, India	35–70%	–	–	–	Poornima et al., 2005
4	Nuclear Power Station, USA	–	70%	–	–	Carpenter et al., 1974
5	Nuclear Plant, USA Lake Michigan	–	14–22%	–	–	Evans et al., 1986
6	The nuclear power station, South Africa	42.8–70.6%	6.3–41.9%	–	–	Huggett and Cook, 1991
7	Coal-, oil and gas-fired thermal electricity generating station, Malaysia	–	–	26%	–	Azila and Chong, 2010
8	Nuclear Power Plant, Taiwan	–	–	63%	–	Liao et al., 2004
9	Coal & oil fired thermal power station, USA	–	–	–	53%	Morgan and Stross, 1969
10	Owase-Mita Thermal Power Plant, Japan	–	–	–	11 to 32%	Takesue and Tsuruta., 1978
11	The nuclear power plant in northeastern Long Island Sound, USA	–	70%	–	–	Carpenter et al., 1974
12	Smolensk and Kursk Nuclear power plant, Russia	–	50%	–	–	Kartasheva et al., 2008
13	Tuticorin Thermal Power Station, Tuticorin, India	88%	89%	–	–	Selvin Pitchaikani et al., 2010

It is apparent that power plant intake systems pump seawater along with existing biota into a series of mechanical devices (strainers, screens, tubes, etc.) for filtration. The strainers and screens perform the function of impingement, thus restricting the entry of large marine organisms and debris as well as supplying water with microorganisms (planktonic and nektonic species) to the condenser for heating cause entrainment (Greenwood, 2008; Mayhew et al., 2000; Bamber and Seaby, 2004). This micro marine biota often releases effluents in the same environment. However, the variety of physical and chemical stresses faced by this micro marine biota may reflect on the survival of such organisms varying in biodiversity in the released environment. Our knowledge of the impact of effluents released from power plant cooling systems on planktonic biodiversity is limited (Table 1).

Studies have been conducted worldwide to address the impact of power plant effluent on plankton community (Morgan and Stross, 1969; Takesue and Tsuruta, 1978; Evans et al., 1986; Shiah et al., 2006; Lo et al., 2016). In India, few reports on the thermal impact on planktonic organisms are available from various vicinities (Saravanane et al., 1998, Rajadurai et al., 2005, Poornima et al., 2005 & 2006; Selvin-Pitchaikani et al., 2010; Palanichamy et al., 2002). For instance, reduction in benthic fauna (Kailasam and Sivakami, 2004) and zooplankton species (Easterson et al., 2000) was recorded.

Notably, no attempts were made to address the impact of a coal-based thermal power plant along the coastline of Tamil Nadu. Eccentrically, Ennore creek is the most exploited and polluted water body that is located along this coastline and receives effluent discharges from major industries including fertilizers, rubber factories, steel rolling, motor vehicles, and oil refineries surrounded by thermal power plants. Particularly, studies on understanding the change in planktonic biodiversity of the Ennore creek system after the discharge of heated effluents from the power plant into the polluted aquatic ecosystem are not available.

North Chennai Thermal Power Station (NCTPS), a coal-based thermal power plant operated by Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO), is located at the confluence point of the Ennore creek with the Bay of Bengal, South India (Fig. 1). The NCTPS Power Plant Unit shares its southern boundary with the Ennore creek (13°13′54.48″ N, 80°19′26.60″ E), northern boundary with Ennore port, eastern boundary with the Bay of Bengal coast, and western boundary with Buckingham canal (Fig. 1).

By 1995, NCTPS was commissioned with a total power production capacity of 630 MW (with three units of 210 MW each) with a cooling water suction capability of 90,000 m^3 per hour through the adjoining Ennore port *through* an open channel along the Bay of Bengal coast (WAPCOS, 2014). By 2013, additionally, two power plants of 600 MW each were installed, and this resulted in an increased cooling water suction volume of 2,00,000 m^3/h through the pre-existing cooling water intake system. A total volume of 2,90,000 m^3/h was discharged through an open precooling channel of width 130 m and length 2.5 km, followed by another warm water channel of length 2 km, which leads to the Ennore creek for discharge (Fig. 1). It measured the hot water release from the heated condenser approximately 8 °C above the ambient temperature (WAPCOS, 2014).

The ecological and economic significance of the Ennore creek system adjoining coastal waters of the Bay of Bengal have been reported (Shanthi and Gajendran, 2009). The glorious past of the creek had flourishing mangrove swamps that later degraded to patches and fringes because of the anthropogenic activities (Chaves and Lakshumanan, 2008). The north–south trending channels of the creek connect with the Pulicat Lake bioreserve in the north to the distributaries of the Kosasthalaiyar River in the south.

The creek situated in the direction of west to east opens into the Bay of Bengal. It receives a large quantity of wastewater from various sources present along the adjoining industrial belt located at Manali (Sreenivasan and Franklin, 1975; Purvaja and Ramesh, 2000; Jayaprakash et al., 2005; Prince Prakash jebakumar et al., 2014; Sachithanandam et al., 2017). Buvaneshwari et al. (2014) studied the thermal dispersion of power plant effluent discharge at the Ennore creek and recorded serious environmental concerns. Thus, the present study conceived to unravel the impact of effluents released from NCTPS on plankton population diversity in the creek waters.

The plankton standing crop assessment is done by collecting monthly samples for a period of one year from July 2014 to June 2015 in the vicinity of NCTPS. The power plant operating conditions were constant throughout the sampling period. Water samples for physico-chemical analysis were collected from various places such as intake point, discharge point, and possible thermal plume dispersion areas inside the Ennore creek. The population density of the residing planktonic communities was analyzed once in a month throughout the study tenure.

The sampling stations were designated as EHE1 to EHE5: EHE1 for intake water collection area at the Bay of Bengal near the approach channel of the Ennore port; EHE2 for hot water discharge point at the Ennore Creek bank; EHE3 for an area that is 300 m away from the

Fig. 1. Depicting study area Ennore creek and its environment.

discharge point; EHE4 for an area 1 km away from the discharge point; and EHE5 for the Ennore creek mouth 500 m away from the discharge point. The study participants were well informed about the study sites because sampling was done monthly by the same crew (Fig. 1).

Surface water samples were collected using a clean plastic bucket, and planktons were collected using plankton nets with a mechanical flow meter (64-micron net by vertical haul). Parameters such as temperature, salinity, dissolved oxygen (DO), and conductivity were measured using the YSI-85 DO meter. The concentrated phytoplankton was preserved by the addition of formaldehyde (2%) and Lugol's iodine (1%) solution. Phytoplankton number was counted by following the Utermohl sedimentation method (Utermohl, 1931; Utermöhl, 1958) under an inverted compound microscope (Carl Zeiss); the total number of organisms per liter of seawater was calculated.

A sampling of zooplankton was carried out using vertical hauls of a 300-μm net with a flow meter (Hydro-Bios) at all designated points. The samples collected were preserved in formaldehyde (4% buffered) and zooplankton number was counted under a stereo zoom microscope (NIKON) during daylight under flood tide to avoid navigational difficulties inside the creek. Shannon species diversity index was calculated to understand the species diversity pattern among the samples.

The estimate of breeding female fishes whose fecundity was potentially lost was obtained using the formula

$$FH = \frac{1}{F_T}\sum_{i=1}^{m}\frac{E_{T_i}}{S_i}$$

where F_T is the average total lifetime fecundity for female fishes, equivalent to the average number of eggs spawned per female over their reproductive years, m is the number of months the larvae are vulnerable to mortality due to elevated temperatures of the power plant, E_{Ti} is the estimated total loss for the ith monthly survey period ($i = 1, \ldots, m$), and S_i is the survival rate from the fertilized eggs to larvae of the stage present in the ith monthly survey period (Ehrler et al., 2002). Details on lifetime fecundity, reproductive viability, and quantum of eggs produced were collected from available literature (Nair et al., 2016; Murugan et al., 2014; Deshmukh et al., 2010; Das, 1977). The survival rate of eggs to larvae was derived from the average of the egg and larval ratio obtained on the one-year data set. The fecundity hindcast (FH) model calculation was applied to estimate the amount of potential female reproductive gonads eliminated due to high temperature and other reaction inside the cooling tower of the power plant per annum. Approximately 11 species of fish and larvae were reported at this vicinity (WAPCOS, 2014), and the input parameters required for the FH model availability were restricted to two dominant and commercially important species (*Mugil cephalus* and *Sardinella longiceps*). According to our survey, it was assumed that 90% of eggs belong to *M. cephalus*, 9% of *S. longiceps,* and the remaining 1% of eggs belong to other species.

Primary productivity measurements were carried out using the 300-ml light–dark bottle incubation method, and samples containing natural phytoplankton assemblage were irradiated at 40 $\mu E m^{-2} s^{-1}$ for 4 h (Strickland and Parsons, 1975). The change in oxygen content was determined by Winkler titration as described previously (Strickland and Parsons, 1975). The values of oxygen evolved were converted to carbon equivalent using a photosynthetic quotient of 1.20 (Strickland and Parsons, 1975). The following formula was used to calculate the biogenic carbon estimation:

$$BC = \sum_{i=1}^{m}\{(Ic_i \times I_i) - (Oc_i \times O_i)\}$$

where *Ic* is the estimate of possible carbon produced by the aquatic environment, *I* is the quantum of water utilized by the power plant for the ith month, *m* is the number of months the biogenic carbon is

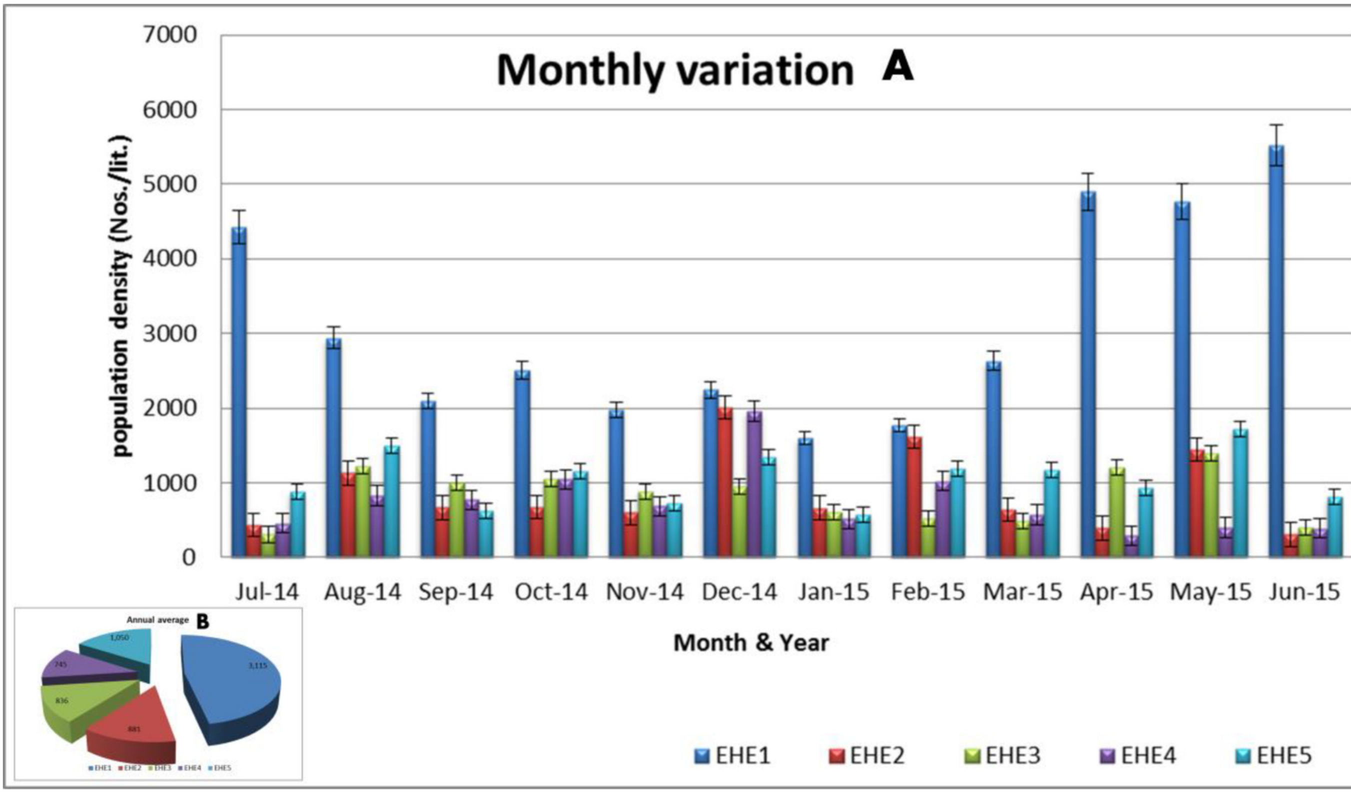

Fig. 2. Spatial & temporal variation of phytoplankton population density along the study area.

vulnerable for elimination because of elevated temperatures of the power plant, Oc_i is the estimated total loss for the ith monthly survey period ($i = 1, \ldots, m$), and O_i is the quantum water discharged from the power plant in the ith month of the survey period. The derived *BC* represents the planktonic biogenic carbon loss per annum due to power plant operations. These estimations utilized were for determining biodiversity changes due to the impact of coolant water discharge.

The present study observed the phytoplankton population (represented by 76 species) grouped under three classes such as Bacillariophyceae, Dinophyceae, and Cyanophyceae. The size, structures, and the taxonomic composition of the plankton communities were determined on the basis of the physical and chemical environments (Bouman et al., 2003; Badosa et al., 2007; McKinnon et al., 2007). Notably, seasonal variations in phytoplankton population (maximum density: 4770 to 5520 cells L^{-1}) were observed from July 2014 to June 2015 from the EHE1 station at the Bay of Bengal coast (Fig. 2). The present observation of seasonal variation in phytoplankton population was in agreement with previous findings reported along the Chennai coast (Sahu et al., 2012; Ashok Prabu et al., 2015).

It was observed that the reduction in phytoplankton population was very high at the site EHE2 and crossed more than 90% during July 2014, April 2015, and June 2015 (Fig. 3). The possible explanation for such scenario was the synergistic action of tropical summer ambiance and hot effluents discharged from power plants aggravated by the reduction in phytoplankton density.

Although a similar environmental condition prevailed during May 2015, the phytoplankton population reduced by only 21% (Fig. 3), whereas two pedunculate fouling diatoms *Licmophora flabellata* and *Licmophora juergensii* proliferated at the site EHE2 during this period. Similarly, these two pedunculate fouling diatoms also contributed substantially (1470 of 1643 cells L^{-1}) to lessen the total phytoplanktonic density reduction at the effluent water discharge site (EHE2) during February 2015 (Fig. 3). The less reduction in total phytoplankton population (August 2014, December 2014, February 2015, and May 2015) was observed because of the increase in population density of the two pedunculate fouling diatoms *L. flabellata* and *L. juergensii* (Fig. 3).

These two pedunculate fouling diatoms are epibiotic and epilithic (Pangu, 1993; Patil, 2003; Romagnoli et al., 2014; Al-Harbi, 2017) and are found on crab carapace, seaweed blades, etc. At NCTPS, these diatoms were found to be on the *Phormidium* sp., a mat-forming cyanobacteria that occupy the 4.5-km long coolant water discharge canal (Fig. 4).

The pedunculate fouling diatoms *Licmophora* sp. has a stalk production capability of elevating the cells above the substratum, thereby avoiding competition for light and nutrients in the dense biofilm on the walls of the coolant water channel of the power plant (Matilde and Gustaaf, 2015). This evolved characters evading intra-specific competition of this epiphytic diatom provides implications such as increased friction during water flow as well as reduced flow rate in coolant water intake and discharge channels of hydroelectricity industries at Tasmania (Ravizza, 2015). Thus, current flow conditions of the NCTPS discharge channel warrant in-depth studies. Further, the reported epiphytic diatom *L. flabellata* C. Agardh by Bailey (1913) listed as diatom species presumed to be native to the Canadian coastal waters (Mather et al., 2010). Hence, the ecological status of classifying it as non-native species warrant detailed studies.

The biofilm formation studies at MAPS coolant water discharge point also recorded that *Phormidium* sp. and *Licmophora abbreviata* in the test panels were exposed for 120 h to the waste heat effluent (Rao, 2010). A study on the cyanobacterial abundance on coastal wetlands along Kanyakumari district also reported the presence of *Phormidium fragile* along the Tamil Nadu coast (Sivakumar et al., 2012).

In general, Cyanophyceae serves as symbionts to epibiotic diatoms, as it fixes nitrogen from the air and transfers to diatoms (Foster et al., 2011). Historical studies by Hofmann and Todgham (2010) reported that cyanobacterial population is capable of surviving in the tropical ecosystem as infra-littoral mat formers or symbiotic associates adapted

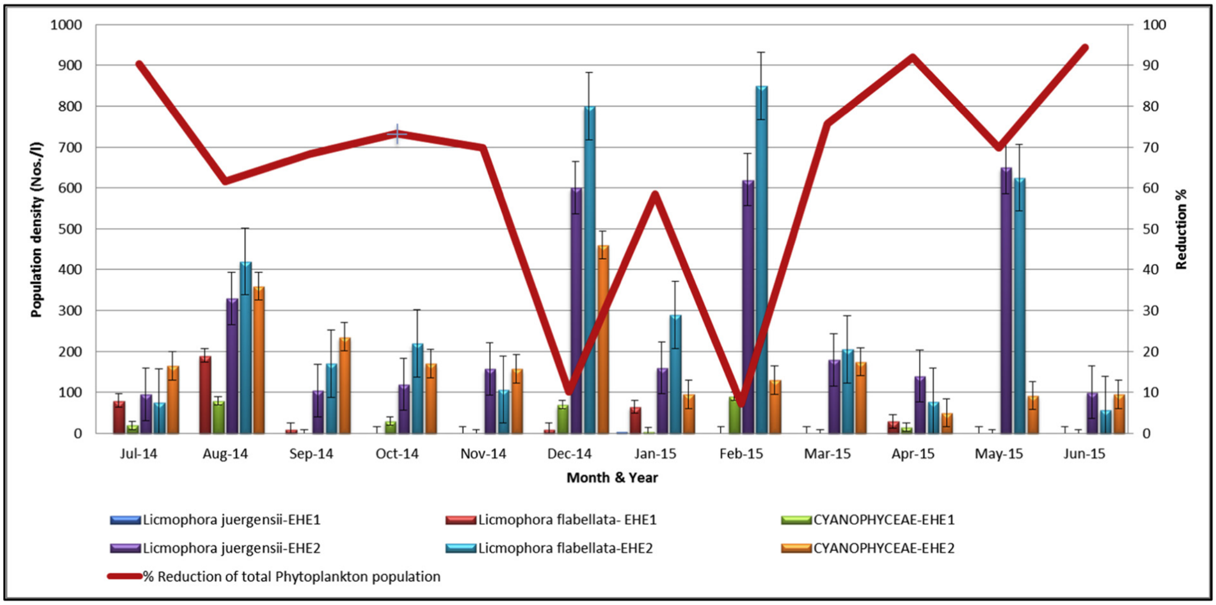

Fig. 3. Depicting phytoplankton population reduction due to power plant discharge and species succession.

to survive in elevated temperatures and intertidal areas. Hence, the typical association of the pedunculated diatom with *Phormidium* sp. at NCTPS might be a reflection of sustainability of the ecosystem.

The intake point (EHE1) was observed to have relatively low values for the Cyanophyceae group compared with the remaining two groups of algae Bacillariophyceae and Dynophyceae (Fig. 5). The Cyanophyceae group in the present study was represented by *Trichodesmium* sp., *Oscillatoria* sp., *Anabaena* sp., *Merismopedia* sp. as reported by earlier studies conducted along the Bay of Bengal coast (Mani, 1992; Kannan and Vasantha, 1992).

Notably, a substantial increment in the density of Cyanophyceae was recorded to occur in the coolant effluent discharge site (EHE2) compared to the intake point EHE1 (Fig. 5). It is established that cyanobacteria thrive in sudden increase in temperature and increase in population density under experimental conditions (Schabhu¨tt et al., 2013). Indeed, the hottest summers in Europe (2003) also recorded cyanobacterial blooms promoted by the heat waves (Joehnk et al., 2008). Hence, our study substantiates the fact that Cyanophyceae holds the capability to survive at higher ambient temperature.

The present study observes predominant changes in the phytoplankton community at various sites. Here, the order of dominance of phytoplankton at the site EHE1 was Bacillariophyceae > Dinophyceae > Cyanophyceae, whereas at the sites EHE2 to EHE5, the order was Bacillariophyceae > Cyanophyceae > Dinophyceae. The alteration in community structure, as

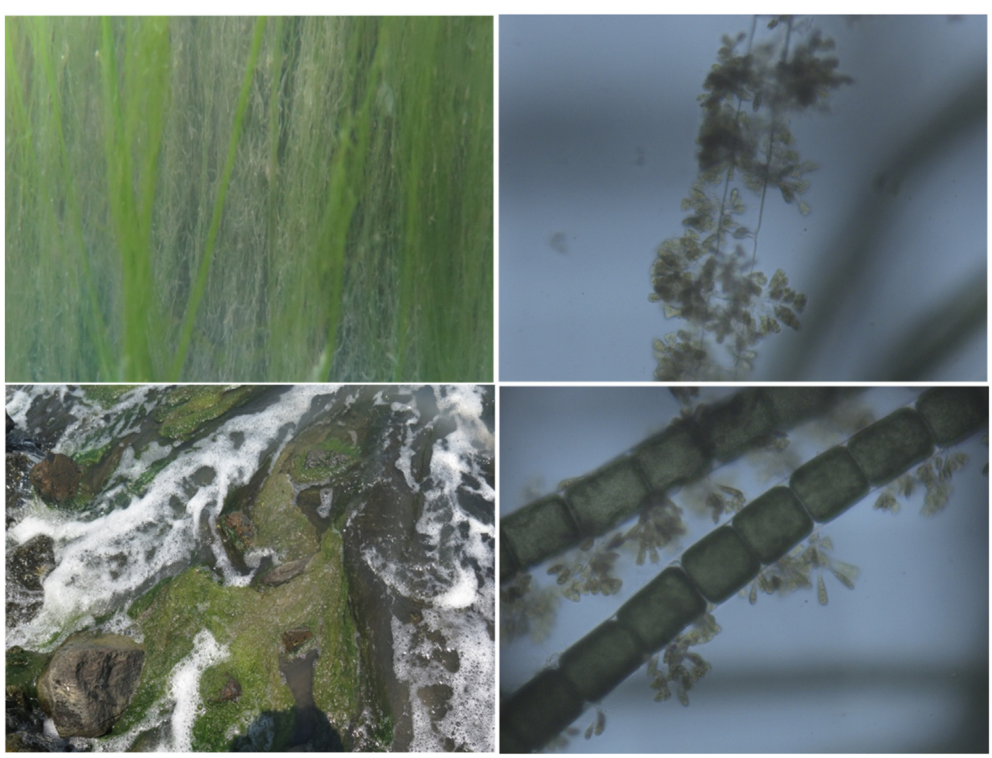

Fig. 4. Depicting epibiotic diatom on symbiotic *Phormidium* sp.

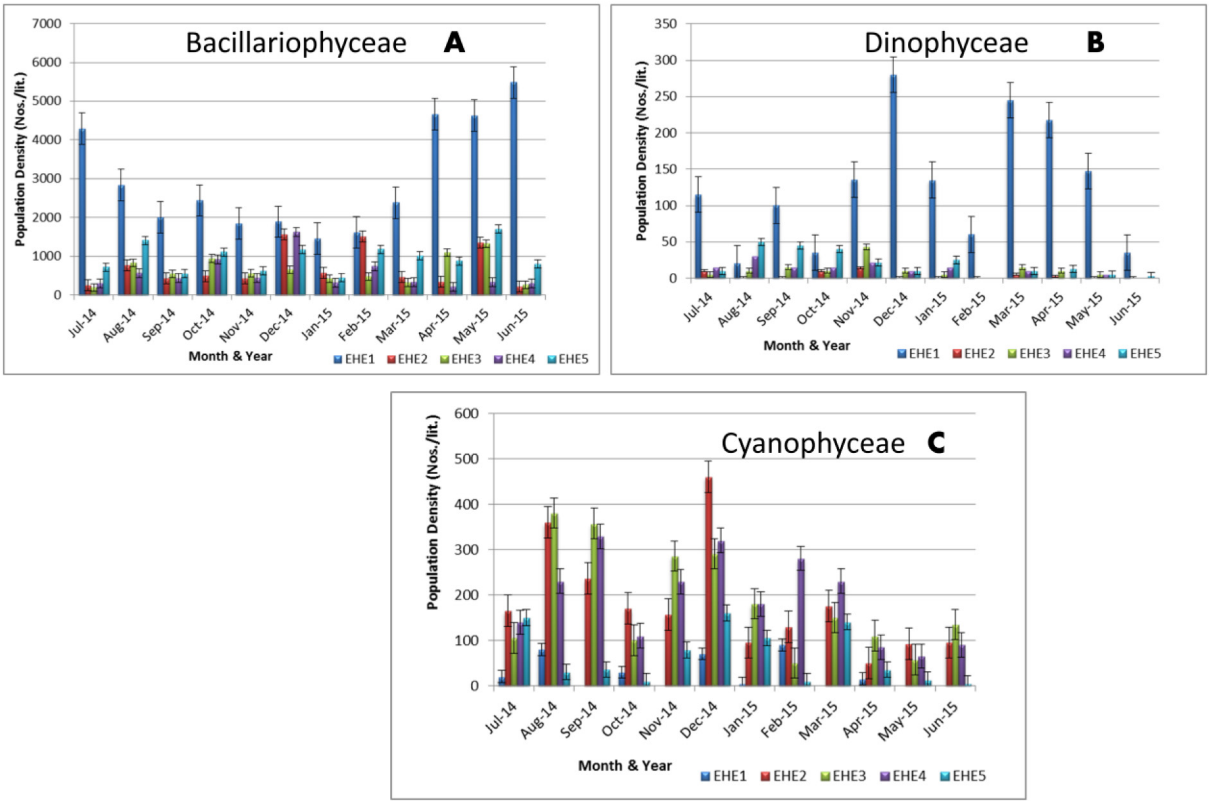

Fig. 5. Spatial & temporal variation of major phytoplankton group population density.

recorded in the form of the order of dominance, did not reach back to the natural condition of the site EHE1 after the heated effluent discharge points such as EHE3 to EHE5 (Fig. 5). Yvon-Durocher et al. (2015) also recorded the change in the structure of the phytoplankton communities under experimental warming conditions.

The observation of phytoplankton community structural changes such as the dominance of Cyanophyceae group and reduction in Dinophyceae as well as Bacillariophyceae seems to have ecological significance. An experimental study on thermal elevation suggested that the Cyanophyceae group holds the capability to adapt to such variations (Schabhu¨tt et al., 2013). Although the Ennore coast was fed with polluted waters containing high nutrient sources from Ennore, Cooum, and Adyar estuaries (Shanthi and Ramanibai, 2011), augmented supply of microscopic cell clusters from repositories of the Ennore creek system may proliferate algal cells, thereby leading to bloom shortly. Notably, Pravakar Mishra et al. (2015) recorded *Trichodesmium* sp. bloom along the Ennore coast, and this was also reported in the present investigation performed in the Ennore creek system.

The change in phytoplankton community also reflected toward the reduction in population diversity. The average Shannon Index (SI) score of natural coastal seawater at the site EHE1 (SI score: 3.1) reduced significantly after the water passed through the once-through cooling water system of NCTPS (SI score: 1.8) at the discharge site EHE2 (Fig. 6B). Later, it gradually improved to 2.3, 2.6, and 2.7, respectively, along the sites EHE3 to EHE5 with increasing distance from the discharge site at the Ennore creek system (Fig. 6B). It was reported that short time temperature peaks induced reduction in cultured phytoplankton communities or diversity under experimental conditions (Schabhu¨tt et al., 2013).

The period of dominance of the two pedunculate fouling diatoms during February 2015 in the present study has recorded a very low diversity score (SI score: 1.08), thus indicating an inverse relationship chronicled during the three months, i.e., August 2014, December 2014, and May 2015 (Fig. 6A). The Margalef index and Pielou's evenness index were also suggestive of phytoplankton diversity reduction at the site EHE2 when compared with the site EHE1 following the trend of SI diversity scores.

The mesocosm experimental study on the increment of temperature resulted in a decrement in phytoplanktonic diversity in the evenness-pushed dominance of certain planktonic communities such as Cyanobacteria and Chlorophyta (Rasconi et al., 2017). The dominance of a specific group of plankton was interpreted as an adaptation to thrive at irregular ambient temperature (Rasconi et al., 2017).

In the natural environment, ocean surface temperature alters the stratification patterns that lead to limited nutrient availability to govern the phytoplankton population densities in oceanic waters (Kamykowski and Zentara, 1986). Thermal stress was found to be a major cause of transiting plankton mortality (Marumoet al., 1992; Taylor, 2006). Among the three major classes of phytoplankton observed, Dinophyceae recorded heavy mortality rate followed by Bacillariophyceae. However, the net primary productivity estimate of planktonic biomass was found to be the key matrix for ecosystem health (Behrenfeld et al., 2001).

The net primary productivity values were comparatively lower (range between 0.12 and 0.48 $\mathrm{mg\,C\,m^{-3}\,h^{-1}}$) at the discharge point (EHE2) than at the intake point (range between 0.42 and 0.6 $\mathrm{mg\,C\,m^{-3}\,h^{-1}}$) compared to other nearby stations along the creek (Fig. 7). It accounts to a loss of 0.69 tons of organic carbon every year. The productivity values of intake water were comparable with those of the past studies conducted along the south Chennai coast of Bay of Bengal (Subramanian and Mahadevan, 1999). The present observation showed that a reduction in net primary productivity at the site EHE2 indicates the impact on plankton population mortality rate, which was shown by findings of previous studies (Morgan and Stross, 1969; Takesue and Tsuruta, 1978).

Moreover, overall phytoplankton population density did not restore to background levels (as the levels of marine intake at EHE1) after the drastic reduction that occurred because of passing through the once-

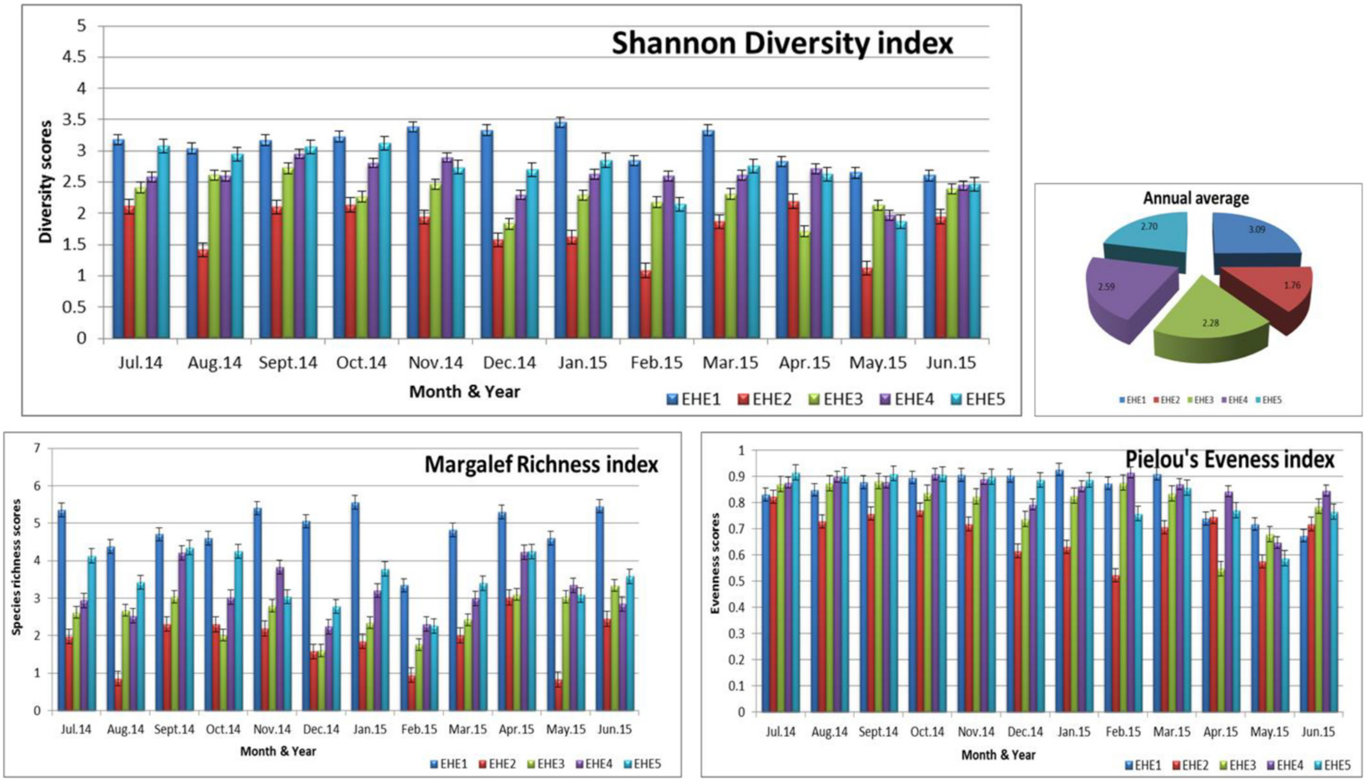

Fig. 6. Spatial & temporal variation of phytoplankton diversity during the study period.

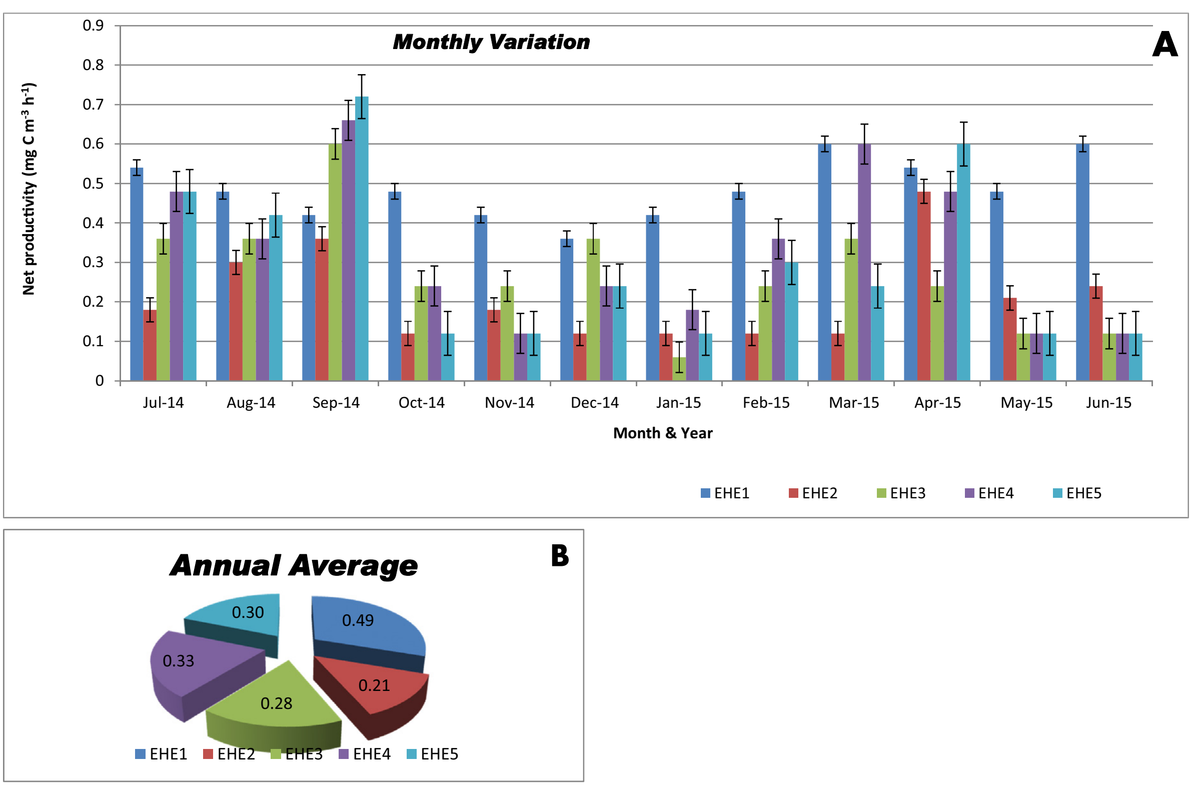

Fig. 7. Spatial & temporal variation of plankton productivity along the study area.

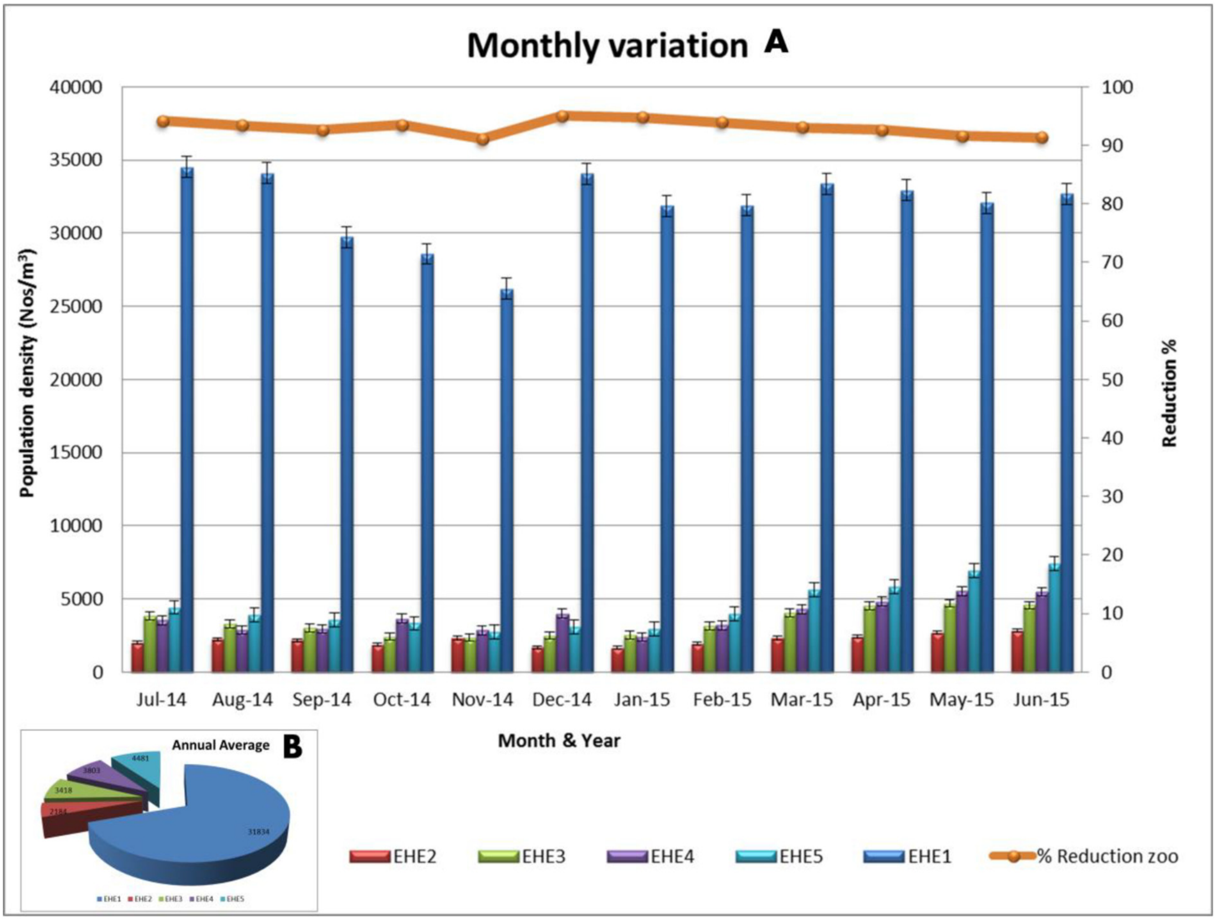

Fig. 8. Spatial & temporal variation of zooplankton population density along the study area.

through cooling system of NCTPS power plant (EHE2), and a gradual increase is depicted along the sites EHE3 to EHE5 (Fig. 2B). This helped us to understand that large-scale pollutant discharges from various industries along the Manali industrial belt reduced the phytoplankton population density considerably at the Ennore creek system, further loading with thermal pollutants from NCTPS, which never recovered the background levels, unlike the site EHE1.

In general, the effects of power plant discharges on planktonic population reduction were detectable neither beyond the immediate discharge zone nor within few meters (Krezoski, 1969; Jordan et al., 1983). Under scrutiny, the plankton population density did not recuperate to the background levels as it used to be the case reported along this coast. It led us to assume that the cumulative impact of the thermal and toxic industrial discharges reflected on the restoration of plankton population inside the Ennore creek system.

The density variations in plankton population often dropped to background levels within few meters away from the power plant discharge points along the coastal line (Poornima et al., 2005). The impact of thermal discharges was found to be very minimal (Natesan et al., 2015). The discharges from Tuticorin Thermal Power Station located further south in the same coast recorded suppression of phytoplankton, zooplankton, finfishes, and shellfish population densities up to few hundred meters away from the discharge site (Pitchaikani et al., 2010). In general, the impact of coolant water discharge from the power plant was observed up to 200 m away from the discharge point (Fox and Moyer, 1975, Shiah, 2006, Youngbluth, 1976, Choi et al., 2002,). By contrast, few studies reported nondetectable impact beyond the actual discharge point (Carpenter et al., 1974; Jordan et al., 1983).

Studies performed at different geographical locations suggested that the optimal or upper limiting temperatures for tropical populations often varies 1° to 2 °C higher than the ambient temperature (Coles et al., 1976; Kolehmainen et al., 1975). Earlier, it was reported that a slight variation in temperature could exert sublethal stresses, alter growth and reproduction of residing organisms, and become a limiting factor for life sustenance in Indian coastal water bodies (Krishnakumar et al., 1991). The present observations of a reduction in plankton population density, productivity, and diversity owing to the thermal impact of once-through cooling systems installed in coastal power plants were in agreement with those of previous reports from other sites (Morgan and Stross, 1969; Takesue and Tsuruta, 1978; Capuzzo, 1980; Taylor, 2006).

Zooplanktons that are represented by 54 species are grouped under 22 orders, namely, Foraminifera, Ciliata, Siphonophora, Hydrozoan, Ctenophora, Annelida, Calanoida, Cyclopoida, Harpacticoida, Cladocera, Ostracoda, Malacostraca, Amphipoda, Decapoda, Mollusca, Echinodermata, Chaetognatha, Brachiopoda, Bryozoan, Urochordata, Thaliacea, and Chordata. Among these zooplanktons, Calanoida dominated at various stations and were reported as the major food sources for commercial fishes (Mauchline, 1998).

Zooplankton communities dominated the chain of energy transfers in the marine ecosystem compared to rest of the organisms living in that habitat (Severini et al., 2009). Observations showed nearly 94% of zooplankton population density reduction at the discharge point EHE2 compared with the intake point EHE1 located along the Bay of Bengal coast (Fig. 8B). The effects of power plant passages on zooplankton mortalities are significantly greater in discharge waters than in intake waters, which are proved by eight-year studies along Lake Michigan, USA (Evans et al., 1986). Further, the zooplankton reduction has also shown seasonal changes similar to those of the phytoplankton in the present study (Fig.8A).

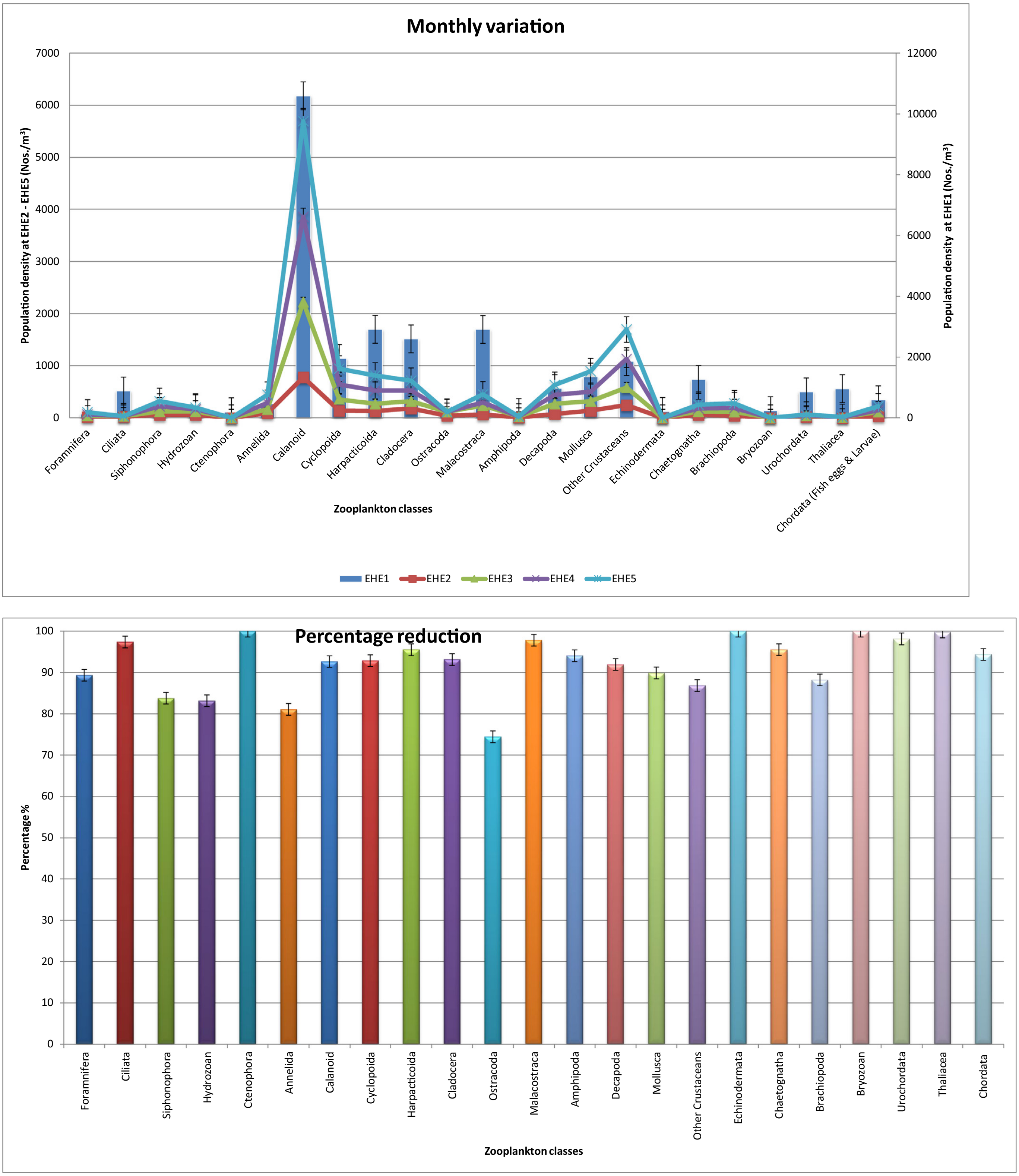

Fig. 9. Spatial & temporal variation of population density of different zooplankton groups along the study area.

Remarkably, a maximum reduction of zooplankton (95%) was observed during December 2014 and January 2015 (Fig.8A). The observation of higher reduction rate during colder seasons than warmer seasons suggested that copepods living in cold ambient temperature may not possess tolerance to face a sudden increase in temperature, as critical thermal maximum stays well below the exposure temperature of waste heat discharged from the power plant (Choi et al., 2012). Among the 23 classes segregated during the present study, classes such as Ctenophora, Echinodermata, Bryozoan, and fish larvae recorded 100% mortality (Fig. 9B), and they accounted a considerable difference

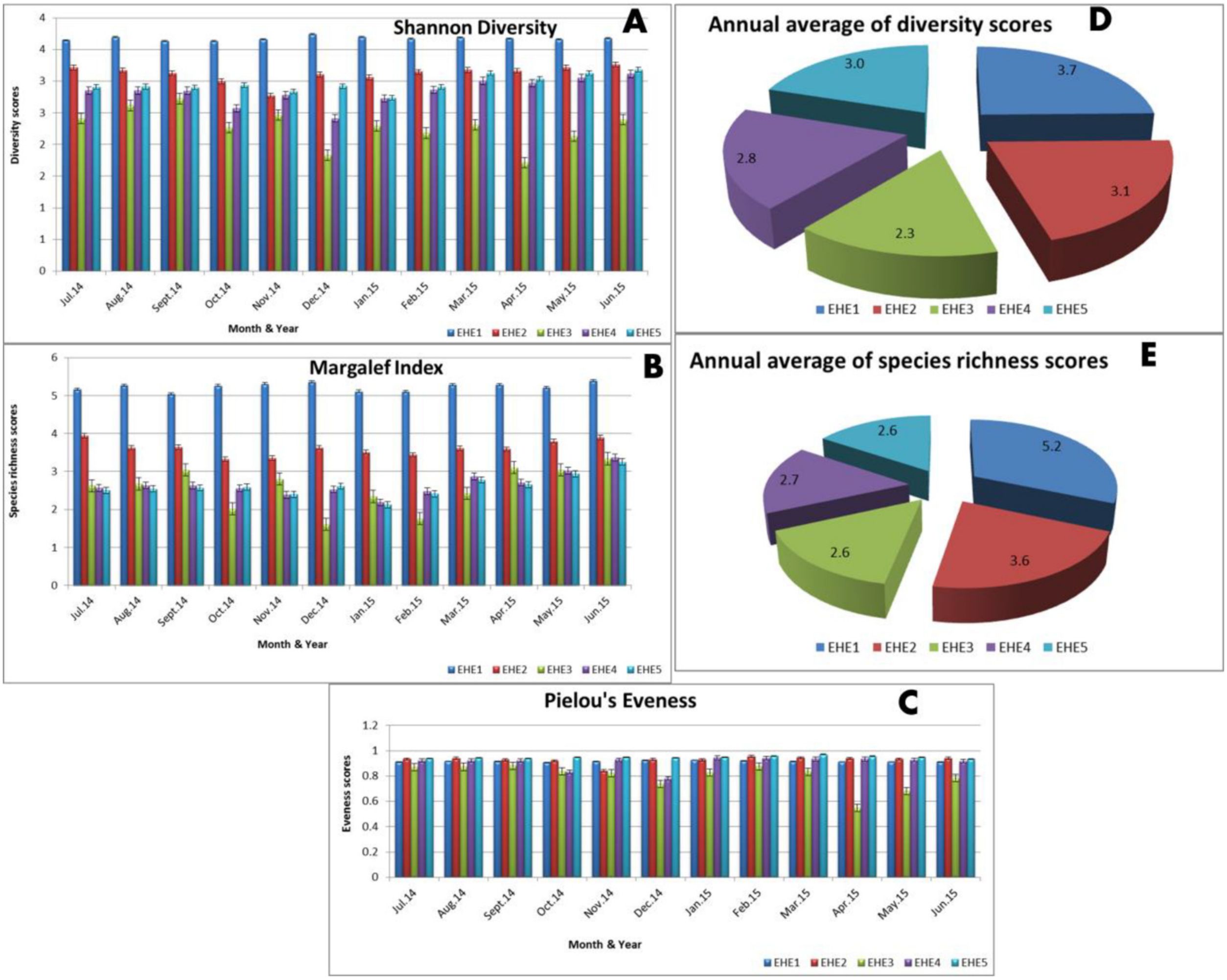

Fig. 10. Spatial & temporal variation of phytoplankton diversity during the study period.

between intake (EHE1) and discharge (EHE2) points. These findings indicated that zooplanktons belonging to classes mentioned above were highly susceptible to rapid thermal variation.

The meroplankton community of facultative planktonic larval forms recorded high reduction exposed to temperature increase (Capuzzo, 1980). Among meroplankton communities, classes such as Decapoda, Calanoid, Cyclopoid, Cladocera, Amphipoda, Chordata, Harpacticoida, Chaetognatha, Ciliata, Malacostraca, Urochordata, and Thaliacea displayed 91% to 100% reduction at the discharge site EHE2 (Fig. 9B). They are referred to as moderately susceptible to thermal variation. Further, classes such as Annelida, Hydrozoan, Siphonophora, other Crustaceans, Brachiopoda, Foraminifera, Mollusca were referred to as lesser susceptible to thermal variation (mortality rate of 81% to 90%).

The average SI diversity scores of zooplankton varied from 3.67 to 2.28 among EHE1 to EHE5 stations (Fig. 10D). Reduction in diversity varied between intake (EHE1) and discharge (EHE2) points and was 3.67 and 3.12, respectively. However, the average Margalef index scores of species richness recorded a drastic reduction from 5.23 at the site EHE1 to 3.61 at the discharge point (EHE2). The reduction in species richness resulted in the disappearance of three classes, namely, Ctenophora, Echinodermata, and Bryozoan at the discharge site (EHE2).

Interestingly, stations EHE3 to EHE5 displayed a drastic reduction in species richness scores, which was as 2.56, 2.66, and 2.61, respectively (Fig. 10E). It indicates the discharge of polluted industrial wastes into the creek system led to the eradication of more zooplankton species. The toxic discharges into the Ennore creek system were evident from a study (Joseph and Srivastava, 1993) and fish deaths have been recorded in recent past (Sachithanandam et al., 2017). These aid to presume the three additional groups Amphipoda, Ciliata, and Ostracoda, and they were the next set of candidates to get affected by industrial discharges around the sites EHE3to EHE5.

The loss of primary consumer groups such as Ciliata (voracious grazers) and Amphipoda (mesograzers) might encourage the propagation of primary producers such as microalgae consequently to algal blooming. Further, loss of carnivores such as Ctenophora and Ostracoda groups (bathypelagic or mesopelagic zooplankton feeders) that control the phytoplankton grazers also unleashed the propagation of micro plants. This type of shift at the base of the food chain reflected in lower consumer/producer biomass, which in turn altered energy transfer at the trophic level along the entire aquatic food web (Rasconi et al., 2017).

Ironically, a 100% reduction in fish larva and 91% reduction in fish eggs at the site EHE2 suggested the need for focus on the scientific community in this arena (Fig. 9A). A comparative review of fish eggs and larval reduction due to power plant effluent was less than 100% (Mayhew et al., 2000). Hence, the fish hindcast modeling was adopted to understand the loss of fecundity. It estimates the loss of potential female reproductive spawn, and this determines future fishery of an area by accounting the loss of fish egg and larvae combined with female fecundity and demography (Ehrler et al., 2002). The estimated fecundity loss of the dominant species *M. cephalus* was up to 2,470,496 potential fertile eggs per annum followed by *S. longiceps* up to 2,058,724 fertile eggs. This suggested that the loss of dominant fish

Table 2
Spatial & temporal variation of physic chemical parameters along the study area.

Station code/months	EHE1	EHE2	EHE3	EHE4	EHE5
A Water temperature (°C)					
Jul-14	31.1	37.3	35.3	32.9	35.5
Aug-14	30.9	36.4	35.7	32.6	33.4
Sep-14	30.5	34.5	34.0	30.9	33.2
Oct-14	30.2	34.9	31.1	30.2	31.1
Nov-14	29.8	35.5	30.1	30.1	29.9
Dec-14	29.5	35.1	29.6	29.1	29.8
Jan-15	30.5	34.9	29.8	30.2	31.0
Feb-15	31.6	35.1	32.4	31.2	31.4
Mar-15	33.1	35.6	34.2	32.9	34.1
Apr-15	35.6	37.8	35.5	33.6	35.3
May-15	36.2	39.0	36.7	34.5	36.5
Jun-15	36.5	38.5	36.5	35.1	36.8
B Salinity (PSU)					
Jul-14	35.5	36.5	36.0	33.5	34.4
Aug-14	35.1	37.9	37.6	34.8	34.2
Sep-14	35.0	36.0	36.0	32.6	34.0
Oct-14	35.2	36.0	35.5	32.1	33.8
Nov-14	35.0	35.5	35.0	31.5	33.3
Dec-14	34.9	35.0	35.0	31.1	33.0
Jan-15	34.0	35.2	34.5	32.0	32.5
Feb-15	34.5	35.5	35.0	32.2	33.2
Mar-15	34.9	36.1	35.4	32.0	33.6
Apr-15	35.1	36.6	35.6	31.5	34.1
May-15	35.5	36.0	36.0	32.4	34.3
Jun-15	35.6	36.5	36.4	33.0	34.6
C Conductivity (mS/cm)					
Jul-14	52.51	55.08	53.87	51.04	52.26
Aug-14	53.12	55.95	55.55	50.77	51.99
Sep-14	53.87	54.41	54.31	49.81	51.71
Oct-14	53.33	54.74	52.76	49.13	51.44
Nov-14	52.98	54.07	52.78	48.31	50.77
Dec-14	52.93	55.87	52.89	47.76	50.36
Jan-15	51.44	53.33	49.21	48.99	48.89
Feb-15	52.39	53.21	52.90	49.27	50.63
Mar-15	52.94	54.54	48.78	48.99	49.11
Apr-15	53.37	55.21	53.88	48.65	51.85
May-15	52.67	53.47	53.01	49.54	52.12
Jun-15	53.87	54.88	54.75	50.47	52.53
D Dissolved oxygen (mg/l)					
Jul-14	6.0	6.3	6.5	6.0	6.4
Aug-14	5.5	6.5	6.6	6.6	6.9
Sep-14	7.2	6.6	6.7	6.1	6.5
Oct-14	7.5	6.6	6.9	6.7	6.8
Nov-14	7.6	6.9	6.5	6.8	6.9
Dec-14	7.5	7.2	7.4	6.8	7.3
Jan-15	6.9	6.6	6.8	6.9	7.0
Feb-15	6.5	5.2	6.7	5.2	6.9
Mar-15	6.1	6.6	6.1	5.4	6.2
Apr-15	5.4	6.5	6.3	5.7	6.1
May-15	5.8	6.4	6.0	5.5	5.1
Jun-15	6.2	5.7	5.0	5.4	6.4

brood certainly has an impact on coastal fishery at the regional scale. However, fish kills reported from Tapi River are also due to the discharges of a thermal electric power plant in India (Sonawane, 2015).

A recent study on the impact of climate changes conducted by Cheung et al. (2016) proposed that fishes were forced to migrate toward cooler waters because of increase in water temperatures and fish fecundity loss augments the impact of global warming in the near future. However, loss of regional scale fish productivity is envisioned.

The ambient conditions during the study period do not record any significant variations but document seasonal changes (Table 2A). Interestingly, the conductivity was recorded the maximum at the site EHE2 compared to those at other remaining stations and a peak value of 55.95 mS/cm was recorded during August 2014 (Table 2C). It leads to a conclusion that the suspended solid contribution from dead planktonic material might reflect in the conductivity records. However, no significant variation was observed in DO and salinity values (Table 2B & 2D).

As a whole, the plankton biodiversity of the Ennore creek system has been impacted by synergistic effects of heated discharges from the power plant and pre-existing toxins in the polluted creek waters. Further studies are warranted to understand the distorted Ennore creek ecosystem, subjected to mounting industrial and population pressures.

In general, the stipulation of the regulatory agencies for the power station discharge criteria is based on temperature, which is supposed to be the most dominant stress factor. However, the existing vague discharge criteria for the pre-existing power stations in India was that they were permitted to discharge up to 10 °C above the ambient temperature, and newer power stations were guided to release a maximum of 7 °C. This specified limitation on coolant water discharges was framed to maintain the natural cycle of temperature variation in the receiving water body. Hence, power stations tend to draw more water than the regular quantities to achieve the stipulated values. This additional coolant water withdrawal along with planktonic organisms through the intake point may increase the mortality rate of entrained and impinged marine organisms such as planktons and fishes. In India, there is no clear guideline for regulatory measures to enforce the use of wedge–-wire screen pre-filters at marine intake facilities to reduce the loss of entrainment and impingement, which is found to be an accepted practice worldwide. Hence, the emerging technology of subsurface intake systems called beachwell provides an effective engineering solution. This intake system includes wells of vertical, angle, and radial types located on either the beach or the seabed. The natural geological properties of sediments and rocks facilitate to strain biological removal of organic matter, suspended sediment, and dissolved organic compounds before being drawn into the desalination process plant (Missimer et al., 2013). These kinds of the subsurface intake systems were already utilized in coastal desalination plants having large seawater requirements (Missimer et al., 2013).

Scientific investigations recorded a marked improvement in water quality produced from subsurface intake facilities. It includes lowered silt density index (75% to 90%), filtration of nearly entire planktonic forms, containment of bacterial population (more than 90%), total organic carbon reduction, dissolved organic carbon, and virtual elimination of biopolymers as well as polysaccharides cause organic biofouling of membranes (Missimer et al., 2013; Dehwah and Missimer, 2016). Although this technology requires significantly higher capital investment, the low overall operational cost (5% to 30%) for a period of 10 to 30 years during desalination plant operation seems to be economically viable (Missimer et al., 2013). Because the operational cost of this marine desalination plants is similar to that of coastal power plants in terms of avoiding biofouling, entrainment, and impingement of marine organisms as well as removal of biofilm materials, it requires large investors and policymakers' attention. Hence, advocating this technology for the conservation of planktonic biomass is found to be the cornerstones for large marine ecosystems.

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