Scientific Research Publishing

Open Journal of Ecology, 2019, 9, 458-477
https://www.scirp.org/journal/oje
ISSN Online: 2162-1993
ISSN Print: 2162-1985

Phytoplankton Productivity and Hydrology in an Impacted Estuarine Complex in Northeastern Brazil

Laisa Madureira da Silva[1], Fernando Antônio do Nascimento Feitosa[1], Manuel de Jesus Flores Montes[1], Amanda Yumi Otsuka[1], Flávia Saldanha-Corrêa[2], Carlos Noriega[1*]

[1]Oceanography Department, Federal University of Pernambuco—UFPE, Recife, Brazil
[2]Oceanographic Institute of the University of São Paulo, University of São Paulo—USP, São Paulo, Brazil
Email: *carlos.delnor@gmail.com

How to cite this paper: da Silva, L.M., Feitosa, F.A. do N., Flores Montes, M. de J., Otsuka, A.Y., Saldanha-Corrêa, F. and Noriega, C. (2019) Phytoplankton Productivity and Hydrology in an Impacted Estuarine Complex in Northeastern Brazil. *Open Journal of Ecology*, **9**, 458-477.
https://doi.org/10.4236/oje.2019.910030

Received: August 23, 2019
Accepted: October 18, 2019
Published: October 21, 2019

Abstract

The aim of the current study was to evaluate the productive capacity of the phytoplankton community and other environmental variables in the estuarine area of Suape; while considering the constant morphological, sedimentological and hydrological changes, the site has been facing due to the implementation and expansion of an industrial and port complex. The study comprised 6 campaigns: 3 in the dry season and 3 in the rainy season. Water samples were collected from the surface layer of the internal and external portions of the estuarine bay during low spring tides. The salinity ranged from 32.20 to 37.10, the water temperature ranged from 26.60˚C to 29.40˚C, and the oxygen saturation rate ranged from 58.5% to 114.5%. There was significant seasonal variation. The nitrite concentration was higher during the rainy season, whereas the ammonia concentration was higher during the dry season; the higher ammonia concentration helped increase chlorophyll-*a* levels and rates of primary productivity, which ranged from 0.02 - 2.45 $mg \cdot m^{-3}$ and from 0.34 to 4.32 $mg \cdot C \cdot m^{-3} \cdot h^{-1}$, respectively. Chlorophyll-*a* < 20 µm was the fraction of biomass most commonly present in the estuarine ecosystem, accounting for 88.6% of the chlorophyll-*a*-containing biomass, and this reflected the low nutrient content in the water and indicated that the area was free from eutrophication processes. The decrease of rainfall during the sampling months and the anthropogenic changes in the environment led to reduced continental contributions, increased marine interference, nutrient dilution and loss of phytoplankton production capacity in Suape Bay, which severely damaged other trophic links in the ecosystem.

Keywords

Estuarine Area, Phytoplankton, Primary Productivity, Chlorophyll *a*, Suape Bay

1. Introduction

Estuaries are dynamic environments found in the transition zone between the continent and the ocean. In addition, they have high variability in terms of physical and hydrochemical parameters [1].

They are also unique systems, seen as aquatic-life nurseries, since they provide ideal protection and abundant food, which enable different organisms to inhabit them and reproduce [2].

Certain aspects of estuarine ecosystems, such as their high productivity, ease of navigation and the shelter they provide against waves and currents, make them a desirable place for the establishment of residential, recreational, industrial and port endeavors [3].

The economic importance of ports to international trade has significantly increased, mainly in developing countries. Thus, ports have become a vital component of the global economy [4]. However, several anthropogenic activities, such as vegetation suppression, earthwork, embankments, dredging [5], and changes in sediment distribution patterns and coastal currents [6], are linked to port construction and expansion processes.

Changes in estuarine geomorphology, sedimentology and hydrodynamics directly affect phytoplankton physiology [7], biomass and community structure [8], in addition to influencing local primary production [9].

Primary production always depends on the synergistic effects of meteorological, physical, chemical and biological factors that limit or stimulate the activity of chlorophyll-containing planktonic organisms [10] [11].

The determination of the rate of primary productivity based on ^{14}C has been used to characterize the trophic state of water bodies [12], since phytoplankton reacts rapidly to physical and chemical changes taking place in this medium, and since it is a sensitive and precise technique [13].

The Suape estuarine system is one of the regions of greater ecological and economic relevance in Pernambuco State. In recent years, the estuary has faced a continuous degradation process due to the construction and expansion of an industrial and port complex. Several studies have focused on evaluating the quality of the water ([14] [15] [16] [17]) and investigating the local biodiversity ([18] [19] [20] [21]).

Accordingly, the aim of the current study was to help improve our understanding of the primary productivity capacity of the phytoplankton community (based on the ^{14}C technique) and of various environmental variables by considering the constant anthropic changes that have been taking place in the Suape coastal area.

2. Materials and Methods

2.1. Study Site and Sampling Protocol

The Suape estuarine system is located approximately 50 km away from the capital city of Pernambuco State (08˚23'45"S 34˚58'04"W) (**Figure 1**). According to

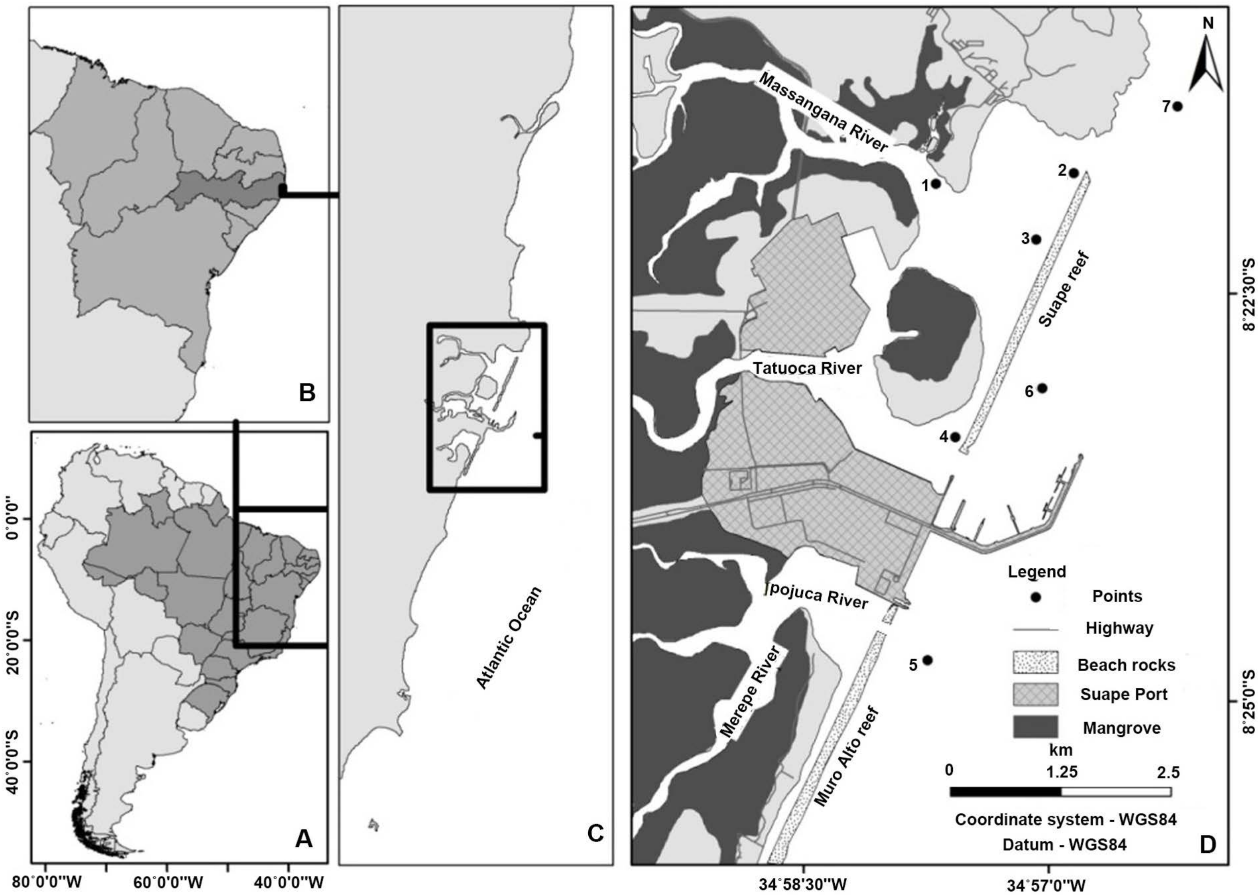

Figure 1. Location of sampling points and Suape Industrial and Port Complex, Pernambuco, Brazil. Source: Produced by the authors, 2016.

the Köppen classification, the climate in the region is hot and humid (As') with well-defined rainy (March to August) and dry seasons (September to February). Annual rainfall ranges from 1850 to 2364 mm, mean air temperature is 24˚C, relative humidity is higher than 80% and southeast winds prevail in the region [22] [23].

With respect to oceanographic features, the region has semidiurnal tides, which are classified as mesotides based on their amplitude [23].

Prior to the construction of Suape Industrial and Port Complex (SIPC), four rivers (Massangana, Tatuoca, Ipojuca and Merepe) converged towards Suape Bay, where their water was channeled through a continuous line of sandstone reefs, which ended in northern Santo Agostinho Cape. The construction of the port blocked the flow of the Ipojuca and Merepe rivers, which resulted in water retention and in the accumulation of substantial amounts of suspended material. A partial opening was made in the reef line near the mouth of the Ipojuca Riverto minimize the problem [24]. Years later, a second opening was made to allow vessels to have access to the inner portion of the port, dividing the original reef into two parts: the Muro Alto Reef (south) and the Suape Reef (north).

Water samples for nutrients (inorganic nitrogen compounds, phosphate, silicate), dissolved oxygen, chlorophyll and phytoplanktonic productivity were collected in November 2015, January 2016 and January 2017 (dry season), as well as in April, July and August 2016 (rainy season), during low spring tides.

Sampling was carried out in the internal (P1, P2, P3 and P4) and external portions of the port (P5, P6 and P7); P5 was under the influence of the plume of the Ipojuca and Merepe rivers.

2.2. Climatology and Environmental Variables

Pluviometric data were provided by the National Institute of Meteorology (INMET) [25].

The hydrological parameters determined herein comprised bathymetry, based on echo sounding (digital echo sounder, mark LCD resolution: 0.1 m); water transparency, based on a Secchi disk; suspended particulate matter (SPM), based on the gravimetric volatilization method adopted by [26]; temperature and salinity, from CTD measurements; dissolved oxygen (DO) concentration, based on the modified method by Winkler, described by [26] (precision of ±1.3 μM); oxygen saturation rate, based on the table by [27]; dissolved nutrients such as ammonia (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-), based on the method described by [26]; phosphate (PO_4^-) and silicate (SiO_2^-), based on the method described by [28]. Dissolved inorganic nitrogen (DIN) was calculated based on the sum of NH_4^+ + NO_2^- + NO_3^-, dissolved inorganic silicate (DIS) was analyzed via SiO_2^-, and dissolved inorganic phosphorus (DIP) was analyzed via PO_4^-. Stoichiometric phytoplankton limitations were evaluated with respect to the Redfield ratio, based on [29] and [30]. The precision was ±0.02 μmol for NO_3^-, ±0.02 μmol for NO_2^-, ±0.02 μmol for NH_4^+, and 0.01 μmol for PO_4^-. The accuracy was ±2% for PO_4^-, ±3% for NO_3^- and NO_2^-, and ±5% for NH_4^+.

2.3. Chlorophyll *a* and Phytoplanktonic Productivity

Total and fractionated chlorophyll *a* were analyzed based on the spectrophotometry method described by [31]; the calculations with the equation from [32], and the results were expressed in $mg \cdot m^{-3}$.

Primary productivity was determined based on the ^{14}C method described by [33]: 120 ml aliquots of each sample were inoculated with 1 ml sodium bicarbonate solution ($NaHC^{14}O_3$), which had an equivalent of 10 μCi of radioactive tracer, and subjected to a 4-hour incubation *in situ*, which was followed by vacuum filtration using 0.45-μm porosity and 47-mm diameter filters. The results were calculated based on [34] and expressed in $mg \cdot C \cdot m^{-3} \cdot h^{-1}$.

2.4. Statistical Analyses

The normality and homogeneity of the assessed variables were analyzed using the Komogorov-Smirnov and Levene tests, respectively. After nonnormality of the data was identified, the nonparametric Mann-Whitney test was used to check for seasonal differences (2 samples), whereas the nonparametric

Kruskal-Wallis test was used to check for spatial differences (>3 samples); variables with $p < 0.05$ were significant. All calculations were performed using Statistic 7® software. The multivariate analysis applied to the investigated parameters was based on principal component analysis (PCA) using the program XLStat 2019®.

3. Results

3.1. Climatology and Environmental Variables

The total monthly rainfall ranged from 292.4 mm in July 2017 to 28.7 mm in January 2017. The study period did not show a significant difference from the historical values (Mann-Whitney; p = 0.19 and p = 0.93 for the dry and rainy seasons, respectively; $\alpha = 0.05$) (**Table 1**), although the months of sampling (except January 2016) showed monthly rainfall below the average for the last 30 years (1985-2014) (**Figure 2**).

The local depth ranged from 21.0 m for P6 (July 2016) to 1.30 m for P3 (April 2016). There was significant spatial variation (Kruskal-Wallis test; α: 0.05; p = 0.00). The internal points were the shallowest, except for P4 (located at the entrance and exit of the port), whereas the external points presented the greatest depths (**Table 1**).

Water transparency ranged from 4.40 m (P4) to 0.80 m (P1) in January 2017. There were significant spatial (Kruskal-Wallis test; α: 0.05; p = 0.01) and seasonal (p = 0.04) differences, and the values recorded for points internal to the reef line were significantly lower (Mann-Whitney test; α: 0.05; p: 0.04) during the rainy season (1.5 m; **Table 1**).

The SPM concentration ranged from 49.00 $mg \cdot L^{-1}$ in P1 (November 2015) to 23.30 $mg \cdot L^{-1}$ for P7 (January 2017). There was a significant seasonal difference, and the highest SPM values were recorded during the rainy season (Mann-Whitney test; α: 0.05; p = 0.01) (**Table 1**).

The water temperature ranged from 29.44˚C for P7 (April 2016) to 26.55˚C for P2 (July 2016), and the thermal amplitude was 2.89˚C. There was a significant seasonal difference (Mann-Whitney test; α: 0.05; p = 0.04), with the lowest temperatures occurring in the rainy season (**Table 1**).

Salinity hada maximum value of 37.10 for P6 and P7 (August 2016) and a minimum value of 32.15 for P5 (November 2015, January 2016) and P6 (April 2016) (**Figure 3(a)**). There were significant spatial (Kruskal-Wallis test; α: 0.05; p = 0.02) and seasonal (Mann-Whitney test; α: 0.05; p = 0.04) differences, and the lowest salinity values were recorded for P5 during the rainy season (**Table 1**).

Dissolved oxygen and oxygen saturation had a maximum concentration of 5.19 $ml \cdot L^{-1}$ and a maximum rate of 114.46%, respectively, for P7 (August 2016), as well as a minimum concentration of 2.60 $ml \cdot L^{-1}$ and a minimum rate of 58.53%, respectively, for P1 (January 2016). There was significant spatial and seasonal variation in the DO concentration (Kruskal-Wallis test; α: 0.05; p = 0.00; Mann-Whitney test; α: 0.05; p = 0.02, respectively) and in the oxygen

Table 1. Abiotic and biological variables in rainy and dry seasons (Min = minimum, Max = maximum, Med = median, and SD = standard deviation) and the non-parametric tests (MW = Mann-Whitney; KW = Kruskal-Wallis) with p-values for the various treatments (seasonal and spatial) $*p < 0.05$ (SPM = Suspended particulate matter; Chl*a* = Chlorophyll *a* total; Chl*a* < 20 µm = Chlorophyll *a* fractional).

Variables	Rainy				Dry				KW	MW
	Máx.	Mín.	Med.	±SD	Máx.	Mín.	Med.	±SD	Spatial	Seasonal
Rainfall 2015-2017 (mm)	292.40	57.50	110.30	123.24	124.00	28.70	30.60	54.48	-	0.19
Rainfall 1985-2014 (mm)	657.30	46.80	352.05	431.68	276.40	8.70	142.55	189.29	-	0.93
Depth (m)	21.00	1.30	10.40	6.04	17.40	1.50	10.00	5.45	0.00*	0.10
Transparency (m)	3.00	1.30	1.50	0.66	4.40	0.80	2.05	0.91	0.01*	0.04*
SPM ($\mu mol \cdot L^{-1}$)	47.00	28.40	36.03	4.45	49.00	23.30	31.60	6.28	0.54	0.01*
Temperature (˚C)	29.44	26.55	26.90	1.23	29.03	28.12	28.54	0.25	0.65	0.04*
Salinity	37.10	32.16	36.00	1.10	37.04	32.15	35.71	1.89	0.02*	0.04*
Dissolved oxygen ($ml \cdot L^{-1}$)	5.19	3.45	4.40	0.53	4.74	2.60	4.01	0.56	0.00*	0.02*
Oxygen saturation rate (%)	114.46	76.81	97.43	11.58	106.69	58.53	90.52	12.66	0.00*	0.03*
Nitrite ($\mu mol \cdot L^{-1}$)	0.14	0.01	0.07	0.04	0.06	0.01	0.01	0.01	0.72	0.00*
Nitrate ($\mu mol \cdot L^{-1}$)	2.40	0.01	0.80	0.62	4.40	0.01	0.38	0.97	0.85	0.05
Ammonia($\mu mol \cdot L^{-1}$)	0.28	0.01	0.06	0.07	0.84	0.01	0.14	0.23	0.94	0.01*
Phosphate ($\mu mol \cdot L^{-1}$)	0.35	0.04	0.11	0.06	0.34	0.06	0.14	0.07	0.00*	0.29
Silicate ($\mu mol \cdot L^{-1}$)	24.20	3.60	8.35	4.79	16.30	1.90	6.30	4.37	0.00*	0.02*
DIN:DIP	28.00	0.73	10.10	7.43	22.30	0.13	6.69	6.35	0.08	0.10
DIN:DIS	0.25	0.02	0.12	0.07	0.86	0.00	0.17	0.22	0.21	0.30
DIS:DIP	268.88	37.00	94.39	64.53	142.85	13.18	51.7	35.46	0.01*	0.00*
Chl*a* ($mg \cdot m^{-3}$)	1.20	0.14	0.41	0.24	2.45	0.02	0.55	0.68	0.90	0.71
Chl*a* < 20 µm ($mg \cdot m^{-3}$)	1.13	0.02	0.16	0.28	2.17	0.02	0.53	0.59	0.33	0.30
Phytoplankton productivity ($mg \cdot C \cdot m^{-3} \cdot h^{-1}$)	3.53	0.58	1.78	1.00	4.32	0.34	2.46	1.16	0.56	0.40
Assimilation rate ($mg \cdot C \cdot mg \cdot Chl\text{-}a^{-1} \cdot h^{-1}$)	15.36	1.32	5.45	3.66	23.93	1.14	2.71	6.55	0.90	0.65

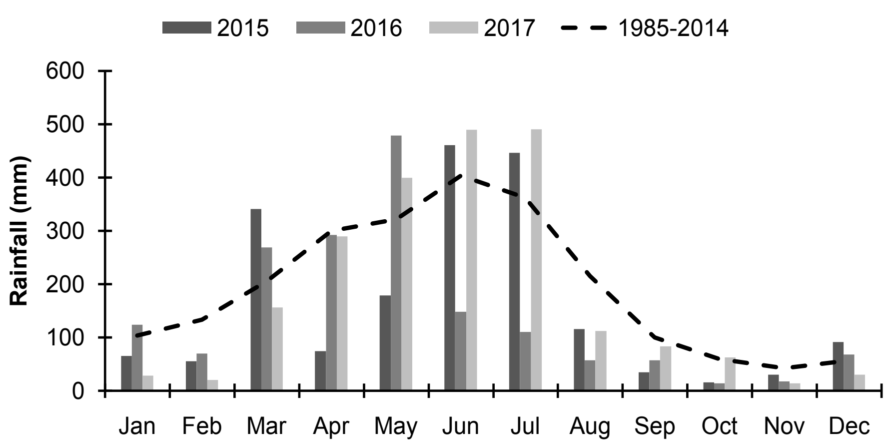

Figure 2. Rainfall data from the Experimental Station of Curado-Pernaambuco state between 2015 and 2017 and the average historical monthly values (1985-2014). Source: INMET.

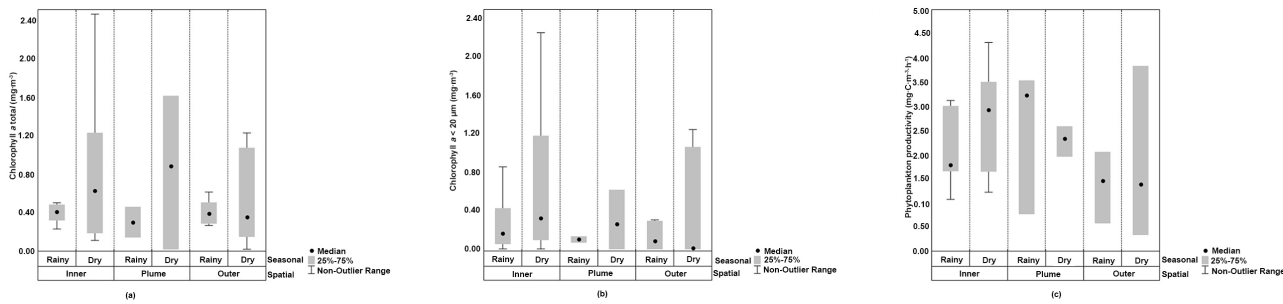

Figure 3. Seasonal and spatial variation of abiotic variables: Salinity (a), Ammonia (b), Nitrite (c), Nitrate (d), Phosphate (e) and Silicate (f), during the study period in the port region of Suape, Pernambuco, Brazil.

saturation rate (p = 0.00; p = 0.03) (**Table 1**). Both parameters had their highest values at points external to the reef line and during the rainy season.

Overall, the nitrogenous compound (NO_2^-, NO_3^- and NH_4^+) concentrations were low. NO_3^- concentrations had the highest values, which ranged from 4.40 μmol·L^{-1} to 0.01 μmol·L^{-1} (**Figure 3(d)**), in comparison with those of NH_4^+ and NO_2^-, there was no significant spatial or seasonal difference. NH_4^+ concentrations ranged from 0.84 μmol·L^{-1} to 0.01 μmol·L^{-1} (**Figure 3(b)**), whereas NO_2^- concentrations ranged from 0.14 μmol·L^{-1} to 0.01 μmol·L^{-1} (**Figure 3(c)**). The concentrations of both had significant seasonal variation during the dry (Mann-Whitney test; *α*: 0.05; p = 0.01) and rainy seasons (Mann-Whitney test; *α*: 0.05; p = 0.00), respectively (**Table 1**).

The PO_4^- concentrations ranged from 0.35 μmol·L^{-1} (P5) to 0.04 μmol·L^{-1} (P3) in April 2016 (**Figure 3(e)**). There was only significant spatial variation (Kruskal-Wallis test; α: 0.05; p = 0.00), especially for P5 (**Table 1**).

SiO_2^- ranged from 24.20 μmol·L^{-1} for P1 (July 2016) to 1.90 μmol·L^{-1} for P6 (January 2016) (**Figure 3(f)**). There were spatial (Kruskal-Wallis test; *α*: 0.05; p = 0.00) and seasonal variations (Mann-Whitney test; *α*: 0.05; p = 0.02) (**Table 1**). The highest silicate concentrations were recorded at points internal to the reef line and during the rainy season.

The DIN:DIP ratio ranged from 0.13 for P4 (January 2017) to 28.00 for P1 (July 2016); there was no spatial (Kruskal-Wallis test; *α*: 0.05; p = 0.08) or seasonal (Mann-Whitney test; *α*: 0.05; p = 0.10) variation. The DIN:DIS ratio ranged from 0.00 for P6 (January 2017) to 0.86 for P7 (January 2016); there was no spatial (Kruskal-Wallis test; *α*: 0.05; p = 0.21) or seasonal (Mann-Whitney test; *α*: 0.05; p = 0.30) variation. The DIS:DIP ratio ranged from 13.18 for P6 (November 2015) to 268.88 for P1 (July 2016); there were significant spatial (Kruskal-Wallis test; *α*: 0.05; p = 0.01) and seasonal (Mann-Whitney test; α: 0.05; p = 0.00) variations (**Table 1**). Thus, nitrogen was the limiting element regardless of spatial (internal and external) and seasonal variations.

3.2. Chlorophyll a and Phytoplanktonic Productivity

Total chlorophyll-a concentrations ranged from 0.02 mg·m^{-3} for P5 and P6 (January 2017) to 2.45 mg·m^{-3} for P3 (November 2015) (**Figure 4(a)**), while

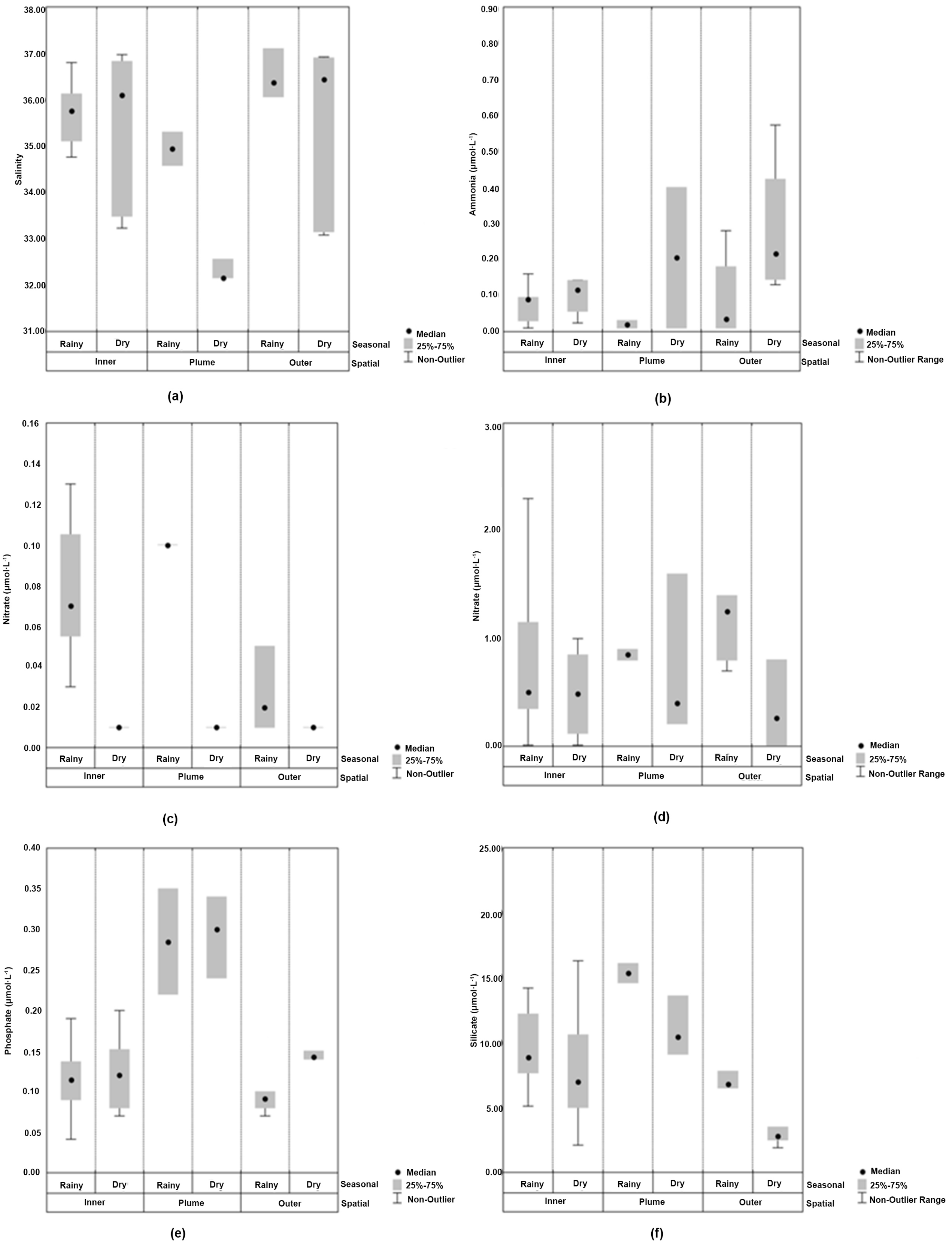

Figure 4. Seasonal and spatial variation of biological variables: Chlorophylla*a* total (a), Chlorophylla*a* < 20 µm (b) and Primary productivity (c), during the study period in the port region of Suape, Pernambuco, Brazil.

fractionated chlorophyll ranged from 0.02 mg·m^{-3} (for several months and sampled points) to 2.17 mg·m^{-3} for P3 (November 2015) (**Figure 4(b)**). There were no statistically significant variations in the total and fractionated chlorophyll-a concentrations (seasonal; Mann-Whitney test; α: 0.05; p = 0.71; spatial; Kruskal-Wallis test; α: 0.05; p = 0.90; **Table 1**), although they were slightly higher in the dry season than in the rainy season and at the innermost points of the port compared to those farther outside the port. The fraction of plankton < 20 μm, corresponding to the peak and nanophytoplankton, contributed the most to the increase in the phytoplankton biomass (88.57%).

Primary productivity ranged from 0.34 mg·C·m^{-3}·h^{-1} for P7 (January 2017) to 4.32 mg·C·m^{-3}·h^{-1} for P3 (November 2015); the median value was 2.01 mg·C·m^{-3}·h^{-1} (**Figure 4**). The phytoplankton assimilation rate ranged from 1.14 mg·C·m^{-3}·h^{-1} for P7 (January 2017) to 23.93 mg·C·m^{-3}·h^{-1} for P3 (November 2015); the median value was 4.99 mg·C·m^{-3}·h^{-1} (**Figure 4(c)**). There was no significant variation in any of the parameters, although they presented a pattern similar to that of chlorophyll-*a* (**Table 1**).

3.3. Statistical Analyses

According to the PCA, the two components explained 52.32% of the data variance (**Figure 5**). For the first component, 28.66% of the variance was directly correlated with total chlorophyll, chlorophyll < 20 μm, primary productivity and temperature, indicating that the increase in temperature in the dry period promoted an increase in the metabolism of phytoplanktonic organisms. For the second component (23.66%), dissolved oxygen showed a direct correlation with salinity and an inverse correlation with silicate, indicating that in the area external to Suape port, hydrodynamics keep the water more oxygenated (**Table 2**).

4. Discussion

The incidence of rainfall is among the main factors responsible for modulating and conditioning changes in the hydrological and geomorphological parameters of estuaries and other coastal ecosystems [10].

The rainfall rate recorded in the coastal zone of Suape during the months of sampling (except January 2016) was lower than that of the historical average over the last 30 years (1985 to 2014). Although precipitation was lower than expected, it was sufficient to increase nitrite, silicate, and SPM concentrations as well as decrease water temperature and transparency within the SIPC area.

Given the relevant morphological changes that have taken place in the area, saltwater intrusion has also been a determining factor for changes found in some of the hydrological parameters. Among them, one finds an increase in salinity, a dilution of nutrient salts and, consequently, a decrease in chlorophyll-*a* concentrations and primary productivity. Studies conducted in the past have reported that changes in the coastal dynamics in the Suape port area affected nutrient and algal biomass contents [15], as well as the species composition of phytoplankton [35] and zooplankton populations [36].

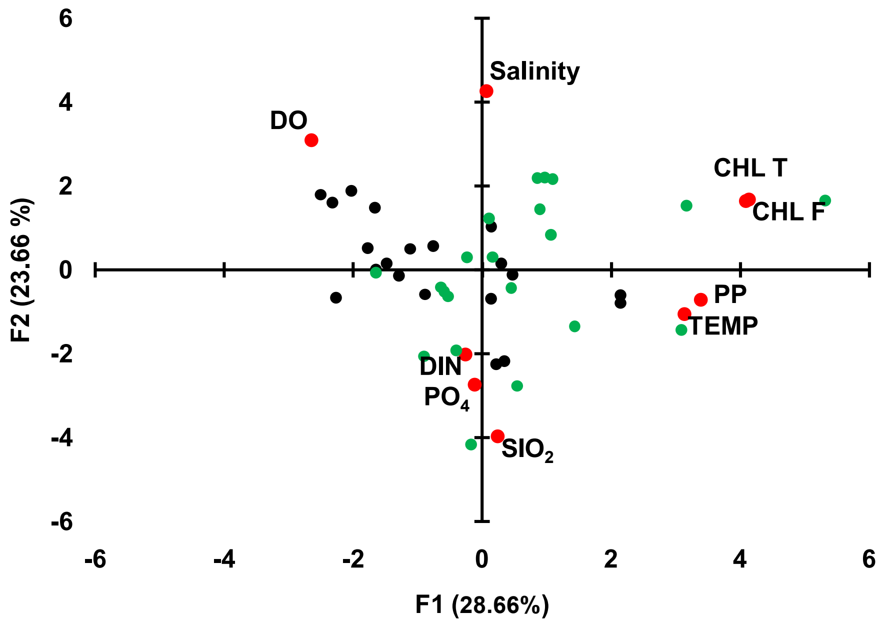

Figure 5. Principal Component Analysis (PCA) of the abiotic and biological variables of the port region of Suape, Pernambuco, Brazil. Analyzed for the two principal component. Subtitles: CHLA T = Chlorophylla *a* total; CHLA F = Chlorophylla *a* < 20 µm; DIN = Ammonia + Nitrite + Nitrate; DO = Oxygen Dissolved; PO_4 = Phosphate; PP = Primary productivity; SIO_2 = Silicate; TEMP = Temperature.

Table 2. Correlation analysis with factor loading of the variables (DO = Oxygen dissolved; TEMP= Temperature; SAL = Salinity; PO_4 = Phosphate; SIO_2 = Silicate; CHL T = Chlorophylla *a* total; CHL F = Chlorophylla *a* < 20 µm; PP = Primary productivity; DIN = Ammonia + Nitrite + Nitrate. The bold values indicate significant load factors.

	F1	F2	F3	F4
OD	−0.54	**0.57**	−0.15	0.41
TEMP	**0.63**	−0.19	−0.49	−0.30
SAL	0.01	**0.79**	0.49	−0.02
PO_4	−0.02	−0.50	−0.36	**0.69**
SIO_2	0.04	**−0.73**	0.44	0.16
CLORO T	**0.84**	0.31	0.03	0.36
CLORO F	**0.83**	0.30	0.09	0.32
PP	**0.69**	−0.13	0.18	−0.20
DIN	−0.05	−0.37	**0.74**	0.13

Water transparency in estuarine ecosystems may vary depending on rainfall intensity and duration. Such transparency follows an increasing gradient towards the portion of the ecosystem with greater marine influence, in addition to its being a limiting factor for the development of phytoplanktonic organisms [37].

In Suape, water transparency followed the spatial and seasonal pattern of estuarine environments in that the waters were less transparent in the inner portion of the bay due to increased concentrations of the allochthonous material arriving in the region during the rainy season. These trends in water transparency and particulate matter have been reported in other estuaries in Pernambuco State by [38] in the estuary of the Sirinhaém River, by [39] in the coastal zone of Ipojuca, and by [40] in the estuarine ecosystem of Barra das Jangadas.

The water temperature was always high and presented a low thermal amplitude; the lowest values were recorded during the rainy season. It is noteworthy that such low thermal variations occurred gradually throughout the months, which allowed planktonic organisms to adapt to new conditions [41].

Low thermal amplitude and seasonal differences were also reported in other coastal regions of Pernambuco State, such as in the inner portion of Suape Port [42], the Porto de Galinhas beach [43] and the estuary of Maracaípe River [39]. The aforementioned studies associated this pattern with efficient water renewal resulting from tidal actions.

Salinity is another important parameter for the coastal zone; its dynamics are controlled by the influx of freshwater from the rivers, by tides and by meteorological and geomorphological factors. In addition, salinity is able to strongly influence the distribution and succession of phytoplankton species [44].

According to previous data recorded by [45], the local ecosystem was divided into three areas before the implementation of the SIPC: the first area covered Suape Bay and varied from euhaline to polyhaline; the second area comprised the Massangana and Tatuoca rivers and was characterized as an estuarine zone with salinity ranging from polyhaline to mesohaline; and the third area comprised the estuary of the Ipojuca River, with salinity ranging from polyhaline to limnetic.

The opening made on the reef allowed access to the internal port and the loss of communication between the Ipojuca and Merepe rivers, causing changes in the current salinity regime in Suape Bay and in the mouth of the Massangana River to euhaline, a fact that was also reported by [18] [46] and [47]. According to [36], Suape Bay had a typical estuarine zooplankton community prior to the implementation of the port; however, this community was replaced by a group of coastal-water copepod species, which accounts for approximately 73% of the total zooplankton population.

Contrary to our expectations, the lowest salinity value was recorded in the external portion of the port (P5 and P6), possibly due to the inflow of less saline water from the Ipojuca and Merepe rivers. It is worth emphasizing that [24] and [35] found over a 2-hour delay in tidal dynamics at the mouths of the Ipojuca and Merepe estuaries due to the previously mentioned changes in coastal dynamics and morphology; such a delay changed the saline regime in the region, which currently oscillates between polyhaline and euhaline. According to [35], increased salinity levels have significantly increased the incidence of marine dinoflagellate species (from 3.33% to 27.41%) in the lower estuary of the Ipojuca River.

With respect to gases dissolved in water, oxygen is one of the most important in the dynamics of aquatic environments, and its concentration changes depending on biochemical and biological processes, such as respiration and production. Oxygen is also an important indicator of the quality of water bodies [48].

Based on the classification system developed by [49], the oxygen saturation rate in the waters adjacent to the SIPC varied from saturated to supersaturated, thus indicating that this environment receives low organic contributions and substantial amounts of seawater. This outcome corroborated results found by [50] on the northern coast of Bahia State, by [51] in Maracajaú (RN), and by [43] in Porto de Galinhas.

Nutrients such as nitrogen and phosphates play a key role in aquatic environments because, along with light, they are the main limiting factors for primary production and, consequently, they affect the entire trophic web [9].

Nitrogenous compound concentrations were particularly low in Suape; nitrogen was the element limiting the development of phytoplanktonic organisms.

NO_2^- had the lowest concentrations, followed by NH_4^+ and NO_3^-. [43] and [52] conducted studies in Porto de Galinhas and Serrambi, respectively, and they reported NO_2^- values (0.01 - 0.17 μmol·L^{-1} and DIN - 0.13 μmol·L^{-1}, respectively) very close to those found in the aforementioned study. The authors associated such outcomes with the good environmental quality of the investigated ecosystems.

NH_4^+ had significant seasonal variation; the highest values were recorded during the dry season, when there was lower organic matter dilution. P1 had the highest spatial concentration of NH_4^+, probably due to the influence of Barbosa stream, which crosses a village and disembogues shortly before the mouth of the Massangana River. Among the forms of dissolved organic nitrogen, NH_4^+ is preferred by phytoplanktonic organisms, which consume it rapidly, thus reducing its levels in aquatic ecosystems.

The maximum NO_3^- value recorded in the present study was 4.40 μmol·L^{-1}, which is unlike what was observed by [35] in the estuary of the Ipojuca River, The Brazilian environmental legislation [53] indicates a limit value of 0.4 mg·L^{-1} (23.5 μmol·L^{-1}).

PO_4^- only had spatial variation; the highest concentrations were found for P5, and they were possibly influenced by the Ipojuca and Merepe rivers. The values observed here were close to the values specified by the Brazilian environmental resolution [53] (**Table 1**).

According to [40], the highest PO_4^- concentrations were found on the continental shelf of Pernambuco State, which is strongly influenced by the Jaboatão River. On the other hand, [54] showed that the plumes of the Capibaribe and Beberibe rivers contributed to the coastal environment by increasing nutrient salts and chlorophyll-*a* contents in the surrounding seawater.

Silicate had the highest concentrations in the waters adjacent to the SIPC in comparison to the concentrations of other inorganic nutrients; however, since it is an estuarine region, silicate values were classified as low, which can be explained by the reduced silicate transport in the Massangana and Tatuoca rivers (coastal and lowland rivers with small hydrographic basins) and by the loss of silicate contribution from the Ipojuca River.

With respect to spatial-temporal variation, silicate had higher concentrations in the inner points of Suape and during the rainy period. The same pattern was found in the estuarine environment of the Ariquindá River [55] and in the estuary of the Timbó River [56], which was explained by increased continental contributions and influenced by the incidence of rainfall.

Phytoplankton found in tropical coastal regions are susceptible to environmental changes to which they respond rapidly due to their short life cycle [10]. Consequently, they are globally used as bioindicators of water quality and trophic status, in addition to being valuable tools for the environmental management of coastal zones [41].

In Suape, the chlorophyll-*a* concentration and phytoplankton productivity were moderately higher at inner points of the port during the dry period, which conformed to increases in the photic layer, NH_4^+ concentration and water temperature. According to [57], the water temperature increase plays a fundamental role in changing photosynthetic and microalgae respiration rates.

The spatial-temporal pattern of chlorophyll-*a* observed in the present study was also observed by [58] in the estuarine zone of the Ilhetas and Mamucabas rivers, by [59] in Golfão Maranhese (Maranhão state, Brazil), and by [40] in the estuary of Barras das Jangadas. These authors attributed the observed outcome to an increase in suspended material concentrations and a decrease in the photic layer. These phenomena often occur during the rainy season when light is a limiting factor for phytoplankton development.

Chlorophyll-a < 20 μm was the one that most contributed to the phytoplankton biomass of the system (88.57%). A similar result was observed by [42] in Suape Bay and by [55] in the estuarine zone of the Ariquindá River. These outcomes can be explained by the better photosynthetic efficiency of this fraction of the phytoplankton population in regions facing nutrient scarcity and hydrological parameter variability, as well as by the ability of this fraction to tolerate variations in environmental conditions.

Based on the classification by [60], the waters adjacent to the SIPC were typical of oligotrophic environments.

Other researchers also observed low chlorophyll-*a* levels (values < 6.00 $mg \cdot m^{-3}$) along the Brazilian coast, among them were the following: [50] in Todosos Santos Bay on the northern coast of Bahia State, [61] in Bragantina Peninsula (Pará state, Brazil), and [62] in the estuary of Paraíba do Sul River (Rio de Janeiro state, Brazil).

Opposite results were recorded by [63] in the estuary of the Jaboatão River, by [64] in the port region of Recife, and by [65] in the Pina basin (values > 100 $mg \cdot m^{-3}$). According to the aforementioned authors, these values indicated strong eutrophication, which was mainly influenced by untreated domestic and industrial effluents released in these ecosystems.

With respect to primary productivity and considering the classification of [66], it is possible to state that the values recorded in Suape were typical of unpolluted coastal environments, a fact that was confirmed by the low nutrient salt and chlorophyll-*a* concentrations that is found in such environments.

The low primary phytoplankton productivity values observed in the present study were similar to those recorded by [67] in Tamandaré Bay, by [68] in a profile perpendicular to the coast at Piedade beach, by [51] in Maracajaú (Rio Grande do Norte state, Brazil), and by [43] in the reef environments of Porto de Galinhas. On the other hand, the present results were different from the high phytoplankton productivity levels observed by [69] in Pina basin, by [38] upstream in the Sirinhaém River, and by [70] in the estuary of the Timbó River, which are highlyeutrophic ecosystems.

The phytoplankton assimilation rate corresponds to the ratio between productivity and chlorophyll-*a* values. Based on [71], it is possible to say that the water adjacent to the SIPC was mesotrophic, although it had a strong tendency towards oligotrophy.

The comparison of previous and current data allowed us to identify significant loss of phytoplankton production efficiency in the estuarine system of Suape. Before implementation of the SIPC, the total phytoplankton density in the estuary of the Ipojuca River varied from 416.00 to 5,748.00 cells·L^{-1} [72]. After its implementation, cell density decreased by 70% [35]. With respect to zooplankton, [73] indicated an expressed cellular biovolume decrease in comparison to that recorded before such development occurred [74].

[75] reported a significant decrease in the number of ichthyoplankton families and species in comparison to previous information recorded by [76]. It is worth emphasizing that Suape Bay was one of the largest fish larvae nurseries and distributing centers in the coastal region of Pernambuco State before the port was built [77].

The local decrease in fishing resources has caused severe ecological damage. Shark species that use the Suape estuarine complex as a source of food and protection now swim towards highly urbanized adjacent coastal areas where they cause serious accidents involving human beings [20] [21].

5. Conclusion

In light of the foregoing results, it is possible to conclude that decreased rainfall indices and constant changes in the coastal morphology and dynamics of the estuarine ecosystem investigated herein were the strongest factors affecting the environmental parameters analyzed in the current study. The loss of contribution from the Ipojuca River and the strong saltwater intrusion have changed the salinity regime of Suape Bay (currently classified as euhaline), leading to nutrient dilution and reduced primary productivity. Picoplankton and nanoplankton were the fractions of phytoplankton that most contributed to the system

(88.6%), reflected the low nutrient content and indicated that the area is free from eutrophication processes. However, the decreased fertility of the waters adjacent to the SIPC has had negative impacts on other links in the trophic web.

Acknowledgements

The authors are grateful to LABFITO, LOQUIM-UFPE and LARADOB-USP for the analysis and data availability. C. Noriega acknowledges the National Council for Scientific and Technological Development (CNPq) for financial support for the project (No. 465634/2014-1; INCT-AmbiTropic; Process No. 370821/2019-0).

Financial Support

The current research is part of a larger project entitled "Studies on Dissolved Inorganic Carbon Cycle in Northeastern and Coastal Areas in Brazil and its Relation to Ocean Acidification Processes (DICAM)" funded by the Coordination for the Improvement of Higher Education Personnel (CAPES).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Azhikodan, G. and Yokoyama, K. (2015) Temporal and Spatial Variation of Mixing and Movement of Suspended Sediment in the Macrotidal Chikugo River Estuary. *Jounal Coastal Research*, **31**, 680-689. https://doi.org/10.1016/j.csr.2016.07.006

[2] Beck, M.W., Heck, Jr., K.L., Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Halpern, B., Hays, C.G., Hoshino, H., Minello, T.J., Orth, R.J., Sheridan, P.F. and Weinstein, M.P. (2001) The Identification, Conservation and Management of Estuatine and Marine Nurseries for Fish and Invertebrates. *BioScience*, **51**, 633-641. https://doi.org/10.1641/0006-3568(2001)051[0633:TICAMO]2.0.CO;2

[3] George, B., Nirmal Kumar, J.L. and Kumar, N. R. (2012) Study on the Influence of Hydro-Chemical Parameters on Phytoplankton Distribution along Tapi Estuarine Area of Gulf of Khambhat, India. *Egyptian Journal of Aquatic Research*, **38**, 157-170. https://doi.org/10.1016/j.ejar.2012.12.010

[4] Valadez-Rocha, V. and Ortiz-Lozano, L. (2013) Spatial and Temporal Effects of Port Facilities Expansion on the Surface Area of Shallow Coral Reefs. *Environmental Management*, **52**, 250-260. https://doi.org/10.1007/s00267-013-0098-5

[5] Douven, W.J.A.M., Buurman, J.J.G. and Kiswara, W. (2003) Spatial Information for Coastal Zone Management: The Example of the Banten Bay Seagrass Ecosystem, Indonesia. *Ocean and Coastal Management*, **46**, 615-634. https://doi.org/10.1016/S0964-5691(03)00038-3

[6] Cicin-Sain, B. and Belfiore, S. (2005) Linking Marine Protected Areas to Integrated Coastal and Ocean Management: A Review of Theory and Practice. *Ocean and Coastal Management*, **48**, 847-868. https://doi.org/10.1016/j.ocecoaman.2006.01.001

[7] Li, G., Gao, K., Yuan, D., Zheng, Y. and Yang, G. (2011) Relationship of Photosynthetic Carbon Fixation with Environmental Changes in the Jiulong River Estuary of the South China Sea, with Special Reference to the Effects of Solar UV Radiation.

Marine Pollution Bulletin, **62**, 1852-1858.
https://doi.org/10.1016/j.marpolbul.2011.02.050

[8] Licursi, M., Sierra, M.V. and Gómez, N. (2006) Diatom Assemblages from a Turbid Coastal Plain Estuary: Río de la Plata (South America). *Journal Marine Systems*, **62**, 35-45. https://doi.org/10.1016/j.jmarsys.2006.03.002

[9] Yang, D., Wang, F., Gao, Z., Chen, Y. and Xie, L. (2006) An Approach to the Effect of Physicochemical Factors on Primary Production in the Changjiang Estuary. *Advences Marine Science*, **24**, 97-107.

[10] Eskinazi-Leça, E., Neumann-Leitão, S. and Costa, M.F. (2004) Oceanografia: Um Cenário Tropical. EditoraBagaço.

[11] Hall, N.S., Paerl, H.W., Peierls, B.L., Whipple, A.C. and Rossignol, K.L. (2013) Effects of Climatic Variability on Phytoplankton Community Structure and Bloom Development in the Eutrophic, Microtidal, New River Estuary, North Carolina, USA. *Estuarine, Coastal and Shelf Science*, **117**, 70-82.
https://doi.org/10.1016/j.ecss.2012.10.004

[12] Andersen, J.H., Schlüter, L. and Ærtebjerg, G. (2006) Coastal Eutrophication: Plankton Recent Developments in Definitions and Implications for Monitoring Strategies. *Journal of Plankton Research*, **28**, 621-628.
https://doi.org/10.1093/plankt/fbl001

[13] Smith, V.H. (2007) Using Primary Productivity as an Index of Coastal Eutrophication: The Units of Measurement Matter. *Journal of Plankton Research*, **29**, 1-6.
https://doi.org/10.1093/plankt/fbl061

[14] Muniz, K., Neto, B.B., Macêdo, S.J. and Filho, W.C.P. (2005) Hydrological Impact of the Port Complex of Suape on the Ipojuca River (Pernambuco-Brazil). *Journal of Coastal Research*, **21**, 909-914. https://doi.org/10.2112/03-0070.1

[15] Alves, G., Flores-Montes, M., Gaspar, F., Gomes, J. and Feitosa, F. (2013) Eutrophication and Water Quality in a Tropical Brazilian Estuary. *Journal of Coastal Research*, **65**, 7-12. https://doi.org/10.2112/SI65-002.1

[16] Batista, T.N.F. and Flores-Montes, M.J. (2014) Trophic State of the Ipojuca and Merepe Rivers Estuaries PE. *Tropical Oceanography*, **42**, 22-30.
https://doi.org/10.5914/tropocean.v42i3.5767

[17] Lemos, R.T.O., Carvalho, P.S.M. and Zanardi-Lamardo, E. (2014) Petroleum Hydrocarbons in Water from a Brazilian Tropical Estuary Facing Industrial and Port Development. *Marine Pollution Bulletin*, **82**, 183-188.
https://doi.org/10.1016/j.marpolbul.2014.03.010

[18] Reis, T.N.V., Guimarães-Barros, N.C., Vasconcelos, E.R.T.P.P., Cocentino, A.L.M. and Fujii, M.T. (2011) Influence of the Industrial Port Complex of Suape (Western Tropical Atlantic) on the Biodiversity and Biomass of Phaeophyceae. *Tropical Oceanography*, **39**, 142-154. https://doi.org/10.5914/tropocean.v39i2.5184

[19] Costa, D.L., Santos, A.M., Silva, A.F., Padilha, R.M., Nogueira, V.O., Wanderlei, E.B., Bélanger, D., Gomes, P.B. and Pérez, C.D. (2013) Biological Impacts of the Port Complex of Suape on Benthic Reef Communities (Pernambuco-Brazil). *Journal of Coastal Research*, **294**, 362-370.
https://doi.org/10.2112/JCOASTRES-D-13-00055.1

[20] Hazin, F.H.V., Burgess, G.H. and Carvalho, F.C. (2008) A Shark Attack Outbreak off Recife, Pernambuco, Brazil: 1992-2006. *Bulletin of Marine Science*, **82**, 199-212.

[21] Chapman, B.K. and McPhee, D. (2016) Global Shark Attack Hotspots: Identifying Underlying Factors behind Increased Unprovoked Shark Bite Incidence. *Ocean and Coastal Management*, **133**, 72-84. https://doi.org/10.1016/j.ocecoaman.2016.09.010

[22] Nimer, E. (1979) Rainfall and Water Resources of the States of Pernambuco and Paraíba. Suoren, Rio de Janeiro. (In Portuguese)

[23] Muehe, D. (2006) Erosion and Progradation of the Brazilian Coast. Ministério do Meio Ambiente, Brasília. (In Portuguese)

[24] Neumann-Leitão, S., Koening, M.L., Macêdo, S.J., Medeiros, C., Muniz, K. and Feitosa, F.A.N. (1999) Plankton Disturbanceat Suape Estuarine Area Pernambuco: Brazil after a Port ComplexImplantation. *Transactions on Ecology and the Environment*, **27**, 47-56.

[25] (2018) INMET: National Institute of Meteorology. http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep

[26] Strickland, J.D.H. and Parsons, T.R. (1972) A Pratical Handbook of Seawaters Analysis. *Bulletin Fisheries Research Board of Canada*, **167**, 207-211.

[27] UNESCO—United Nations Educational Scientific and Culture Organization (1986) International Oceanographic Tables. Vol. 4, NIO-UNESCO, Paris, 193 p.

[28] Grasshoff, K., Ehrhardt, M. and Kremling, K. (1983) Methods of Seawaters Analysis. 2th Edition, VelagChemie, New York.

[29] Pavlidou, A., Kontoyiannis, H. and Psyllidou-Giouranovits, R. (2004) Trophic Conditions and Stoichiometric Nutrient Balance in the Inner Saronikos Gulf (Central Aegean Sea) Affected by the Psittalia Sewage Outfall. *Fresenius Environmental Bulletin*, **13**, 1509-1514.

[30] Xu, J., Ho, A.Y.T., Yin, K., Yuan, X., Anderson, D.M., Lee, J.H.W. and Harrison, P.J. (2008) Temporal and Spatial Variations in Nutrient Stoichiometry and Regulation of Phytoplankton Biomass in Hong Kong Waters: Influence of the Pearl River Outflow and Sewage Inputs. *Marine Pollution Bulletin*, **5**, 335-348. https://doi.org/10.1016/j.marpolbul.2008.01.020

[31] UNESCO (1966) Determination of Photosynthetic Pigments in Sea Waters. Report of SCOR/UNESCO Working Group 17 with Meat from 4 to 6 June 1964, Monographys on Oceanology Methodology, Paris, 66 p.

[32] Parsons, T.R. and Strickland, J.D.H. (1963) Discussion of Spectrophometria Determination of Marine-Plant Pigments, with Revised Equations for Ascertaining Clorophyll*a* and Carotenoids. *Journal of Marine Research*, **21**, 155-163.

[33] Steemann-Nielsen, E. (1952) The Use of Radioactive Carbon (C14) for Measuring Organic Production in the Sea. *Journal du Conseil Permanent International Pour L'Exploration de el Mer*, *Copenhagen*, **18**, 117-140. https://doi.org/10.1093/icesjms/18.2.117

[34] Teixeira, C. (1973) Introduction to Methods for Measuring Primary Production of Marine Phytoplankton. *Boletim Instituto Oceanográfico Universidade de São Paulo*, **22**, 8-92. (In Portuguese) https://doi.org/10.1590/S0373-55241973000100004

[35] Koening, M.L., Eskinazi-Leça, E., Neumann-Leitão, S. and Macêdo, S.J. (2002) Impacts of the Construction of the Suape Port on the Phytoplankton Community in the Ipojuca River Estuary (Pernambuco-Brazil). *Acta Botanica Brasílica*, **16**, 407-420. (In Portuguese) https://doi.org/10.1590/S0102-33062002000400004

[36] Silva, A.P., Neumann-Leitão, S., Schwamborn, R., Gusmão, L.M.O. and Silva, T.A. (2004) Mesozooplankton of an Impacted Bay in North Eastern Brazil. *Brazilian Archives of Biology and Technology*, **47**, 485-493. https://doi.org/10.1590/S1516-89132004000300020

[37] May, C.L., Koseff, J.R., Lucas, L.V., Cloern, J.E. and Schoellhamer, D.H. (2003) Effects of Spatial and Temporal Variability of Turbidity on Phytoplankton Blooms.

Marine Ecology Progress Series, **254**, 111-128. https://doi.org/10.3354/meps254111

[38] Honorato da Silva, M. (2009) Structure and Productivity of the Phytoplankton Community of Tropical Estuary (Sirinhaém, Pernambuco, Brazil). PhD Thesis, Federal University of Pernambuco, Recife. (In Portuguese)

[39] Bastos, R.B., Feitosa, F.A.N., Koening, M.L., Machado, R.C.A. and Muniz, K. (2011) Characterization of a Tropical Coastal Zone (Ipojuca-Pernambuco-Brazil): Phytoplankton Productivity and Other Environmental Variables. *Brazilian Journal of Aquatic Science and Technology*, **15**, 1-10. https://doi.org/10.14210/bjast.v15n1.p1-10

[40] Otsuka, A.Y., Feitosa, F.A.N., Flores-Montes, M.J. and Silva, A. (2016) Dynamics of Chlorophyll *a* and Oceanographic Parameters in the Coastal Zone: Barra das Jangadas-Pernambuco, Brazil. *Journal of Coastal Research*, **32**, 490-499. https://doi.org/10.2112/JCOASTRES-D-14-00135.1

[41] Passavante, J.Z.O. and Feitosa, F.A.N. (2004) Phytoplankton Productivity Dynamics in the Marine Coastal Zone. In: Eskinazi-Leça, E., Neumann-Leitão, S. and Costa, M.F., Eds., *Oceanografia*: *Um Cenário tropical*, Bagaço, Recife, 425-440. (In Portuguese)

[42] Cordeiro, I.A., Feitosa, F.A.N., Flores Montes, M.J., Otsuka, A.Y. and Costa Silva, A. (2018) Environmental Conditionsofthe Suape Estuarine-Port Complex Area (Pernambuco, Brazil): Phytoplankton Biomass and Hydrological Parameters. *Journal of the Marine Biological Association of the United Kingdom*, **99**, 291-301. https://doi.org/10.1017/S0025315418000176

[43] Machado, R.C.A., Feitosa, F.A.N., Koening, M.L., Flores-Monte, M.J., Bastos, R.B. and Jales, M.C. (2014) Phytoplankton Productivity and Hydrology of Porto de Galinhas Reef Ecosystem (Pernambuco, Brazil). *Journal of Coastal Research*, **30**, 371-378. https://doi.org/10.2112/JCOASTRES-D-13-00007.1

[44] Sierra, J.P., Sánchez-Arcilla, A., González Del Rio, J., Flos, J., Movellán, E., Mösso, C., Martínez, R., Rodilla, M., Falco, S. and Romero, I. (2002) Spatial Distribution of Nutrients in the Ebro Estuary and Plume. *Continental Shelf Research*, **22**, 361-378. https://doi.org/10.1016/S0278-4343(01)00061-9

[45] CONDEPE (1983) Characterization of the Estuarine-Lagoon Complex of Suape Area (Pernambuco-Brazil): Ecological Synthesis. Recife.

[46] Borges, G.C.P. (2011) Phytoplanktonic Community of the Massangana River Estuary (Pernambuco-Brazil). Dissertation (Master), Federal University of Pernambuco, Recife. (In Portuguese)

[47] Santos Június, A.C. and Flores Montes, M.J. (2014) Organic Carbon, Phosphorus and Nitrogen Fractions in Suape Port Industrial Estuaries, Pernambuco, Brasil. *Tropical Oceanography*, **42**, 1-23. https://doi.org/10.5914/tropocean.v42i1.5782

[48] Gardner, L.R. and Kjerfve, B. (2006) Tidal Fluxes of Nutrients and Suspended Sediments at the North Inlet-Winyah Bay National Estuarine Research Reserve. *Estuarine*, *Coastal and Shelf Science*, **70**, 682-692. https://doi.org/10.1016/j.ecss.2006.06.034

[49] Macêdo, S.J. and Costa, K.M.P. (1978) Ecological Study of the Region of Itamaracá Pernambuco—Brazil, Hydrological Conditions of the Botafogo River Estuary. *Ciência e Cultura*, **30**, 368-373.

[50] Mafalda Jr., P.O., Sinque, C., Brito, R.R.C. and Santos, J.J. (2004) Planktonic Biomass, Hydrography and Rainfall on the Northern Coast of Bahia, Brasil. *Tropical Oceanography*, **32**, 143-158. https://doi.org/10.5914/tropocean.v32i2.8023

[51] Feitosa, F.A.N. and Bastos, R.B. (2007) Phytoplankton Productivity and Hydrology of the Coastal Ecosystem of Maracajaú RN. *Arquivos de Ciências do Mar*, **40**, 26-36.

(In Portuguese)

[52] Jales, M.C., Feitosa, F.A.N., Koening, M.L., Bastos, R.B. and Machado, R.C.A. (2012) Serrambi Reef Ecosystem (Northeast Brazil) Phytoplankton Biomass and Hydrological Parameters. *Atlântica*, **34**, 87-102. (In Portuguese)

[53] CONAMA National Council of the Environmental (2005) Resolution 357: Classification of the Water Bodies and Environmental Guidelines. http://www.mma.gov.br/port/conama

[54] Resurreição, M.G., Passavante, J.Z.O. and Macêdo, S.J. (1996) Continental Shelf Study in the Recife Area (Brazil): Seasonal Variation of Phytoplankton Biomass (08˚03'38" lat. S; 34˚42'28" a 34˚52'00" long. W.). *Trabalhos Oceanográficos Universidade Federal de Pernambuco*, **24**, 39-59. (In Portuguese)

[55] Grego, C.K.S., Feitosa, F.A.N., Silva-Cunha, M.G.G. and Nascimento-Filho, G.A. (2009) Phytoplankton of the Ariquindá River Estuarine Ecosystem (Tamandaré, Pernambuco, Brazil): Environmental Variables, Biomass and Primary Productivity. *Atlântica*, **31**, 183-198. (In Portuguese) https://doi.org/10.5088/atl.2009.31.2.183

[56] Grego, C.K.S., Feitosa, F.A.N., Honorato da Silva, M. and Flores Montes, M.J. (2004) Seasonal Spatial Distribution of Chlorophyll to Phytoplankton and Hydrology of the Timbó River Estuary (Paulista PE). *Tropical Oceanography*, **32**, 181-199. (In Portuguese) https://doi.org/10.5914/tropocean.v32i2.8025

[57] Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M. and Boss, E.S. (2006) Climate-Driven Trends in Contemporary Ocean Productivity. *Nature*, **444**, 752-755. https://doi.org/10.1038/nature05317

[58] Losada, A.P.M., Feitosa, F.A.N. and Lins, I.C. (2003) Seasonal and Spatial Variation of Phytoplankton Biomass in Ilhetas and Mamucaba (Tamandaré PE) Estuaries Related to Hydrological Parameters. *Tropical Oceanography*, **31**, 1-26. (In Portuguese) https://doi.org/10.5914/tropocean.v31i1.4987

[59] Azevedo, A.C.G., Feitosa, F.A.N. and Koening, M.L. (2008) Spatial Temporal Distribution of Phytoplankton Biomass and Environmental Variables in Golfão Maranhense, Brasil. *Acta Botanica Brasílica*, **22**, 870-877. (In Portuguese) https://doi.org/10.1590/S0102-33062008000300022

[60] Vollenweider, R.A. and Kerekes, J. (1982) Eutrophication of Waters: Monitoring, Assessment and Control. Report of the Cooperative Program on Eutrophication. Organization for the Economic Development and Cooperation, Paris.

[61] Sousa, E.B., Costa, V.B., Pereira, L.C.C. and Costa, R.M. (2009) Temporal Variation of Phytoplankton and Hydrological Parameters of the Ilha Canela Surf Zone (Bragança, Pará, Brasil). *Acta Botânica Brasílica*, **23**, 1084-1095. (In Portuguese) https://doi.org/10.1590/S0102-33062009000400018

[62] Costa, L.S., Huszar, V.L.M. and Ovalle, A.R. (2009) Phytoplankton Functional Groups in a Tropical Estuary: Hydrological Control and Nutrient Limitation. *Estuaries and Coasts*, **32**, 508-521. https://doi.org/10.1007/s12237-009-9142-3

[63] Noriega, C.D., Costa, K.M.P., Feitosa, F.A.N., Flores Montes, M.J., Grego, C.K.S., Soares, G.S.S. and Silva, H.P. (2005) Spatial Distribution of Phytoplankton Biomass and Its Relationship with Nutrient Salts in the Estuarine System of Barra das Jangadas (Pernambuco Brasil). *Arquivos de Ciências do Mar*, **38**, 5-18. (In Portuguese)

[64] Otsuka, A.Y., Feitosa, F.A.N., Flores-Montes, M.J. and Silva, A. (2018) Influence of Fluvial Discharge on the Dynamics of Chlorophyll-*a* in the Continental Shelf Adjacent to the Recife Port Basin (Pernambuco-Brazil). *Brazilian Journal of Oceanography*, **66**, 91-103. https://doi.org/10.1590/s1679-87592018149106601

[65] Santos, T.G., Bezerra-Junior, J.L., Costa, K.M.P. and Feitosa, F.A.N. (2009) Phytoplankton Biomass Dynamics and Variables in a Tropical Estuary (Bacia do Pina, Recife, PE). *Revista Brasileira de Engenharia de Pesca*, **41**, 95-109. (In Portuguese)

[66] Tundisi, J.G. and Tundisi, T.M. (1976) Organic Production in Aquatic Ecosystems. *Ciência e Cultura*, **28**, 864-887. (In Portuguese)

[67] Moura, R.T. (1991) Biomass, Phytoplankton Primary Production and Some Environmental Factors in Tamandaré Bay, Rio Formoso, Pernambuco Brasil. PhD Thesis, Federal University of Pernambuco, Recife. (In Portuguese)

[68] Passavante, J.Z.O. and Feitosa, F.A.N. (1995) Primary Phytoplankton Production from the Continental Shelf of Pernambuco (Brasil): Piedade Area. *Boletim Técnico Científico do Cepene*, **3**, 7-22. (In Portuguese)

[69] Feitosa, F.A.N. and Passavante, J.Z.O. (1991/1993) Seasonal Variation of Primary Production of Phytoplankton in the Pina Basin (Pernambuco Brasil). *Trabalhos Oceanográficos da Universidade Federal de Pernambuco*, **22**, 65-82. (In Portuguese)

[70] Grego, C.K.S., Feitosa, F.A.N., Silva-Cunha, M.G.G., Honorato da Silva, M. and Nunes, R.V. (2016) Phytoplankton Productivity in an Impact Estuary of the North Coast of Pernambuco-Timbó River (Paulista). *Tropical Oceanography*, **44**, 25-42. (In Portuguese) https://doi.org/10.5914/tropocean.v44i1.8029

[71] Vollenweider, R.A., Talling, J.F. and Westlake, D.F. (1974) A Manual in Method for Measuring Primary Production in Aquatic Environments, Including a Chapter on Bacteria. In: *International Biological Program Handbook*, Blackwell, Oxford, 225 p.

[72] Koening, M.L. and Eskinazi-Leça, E. (1991) Quantitative Aspects of Phytoplankton in the Suape Estuarine Area (Pernambuco). In: *Anais 4° Encontro Brasileiro de Plâncton*, Universidade Federal de Pernambuco, Recife, 55-60. (In Portuguese)

[73] Neumann-Leitão, S. and Matsumura-Tundisi, T. (1998) Dynamics of a Perturbed Estuarine Zooplanktonic Community: Port of Suape, PE, Brazil. *Verhand Lungen Internationale Vereinigung Limnologie*, **26**, 1981-1988. https://doi.org/10.1080/03680770.1995.11901089

[74] Paranaguá, M.N. (1985/1986) Zooplankton of Suape Area (Pernambuco-Brazil). *Trabalhos Oceanográficos da Universidade Federal de Pernambuco*, **19**, 113-124. (In Portuguese) https://doi.org/10.5914/tropocean.v19i1.2619

[75] Bezerra Junior, J.L., Diaz, X.G. and Neumann-Leitão, S. (2011) Diversity of Fish Larvae from Inner and Outer Areas of Suape Harbor (Pernambuco-Brazil). *Tropical Oceanography*, **39**, 1-13. (In Portuguese) https://doi.org/10.5914/to.2011.0048

[76] Vasconcelos Filho, A.L., Guedes, D.S. and Sobrinho, D.G. (1990) Taxonomy and Ecology of the Ichthyological Fauna of Suape Area (Pernambuco-Brasil). *Trabalhos Oceanográficos da Universidade Federal de Pernambuco*, **21**, 305-343. (In Portuguese) https://doi.org/10.5914/tropocean.v21i1.2651

[77] Motta, E.J.O. and Carvalho, A.S.C. (1979) Suape Industrial-Port Complex and Its Consequences for Fishing off the Coast of Pernambuco. *Cadernos Ômega*, **3**, 227-232. (In Portuguese)