ECOLOGICAL STUDIES IN THE BAY OF PARANAGUA. III. SEASONAL AND SPATIAL VARIATIONS OF NUTRIENTS AND CHLOROPHYLL a.

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ABSTRACT

Nutrients, chlorophyll **a** and basic field data were obtained at 7 stations distributed along the main axis of the Bay of Paranagua, from November 1985 to December 1986, with the purpose of studying the patterns of spatial and seasonal changes of these parameters in relation to the rainfall regime.

A typical rainy period was observed between January and April with maxima biweekly precipitations of 296mm and a daily maximum of 97mm in February. The dry season, including the wintertime, extended from May to October. The temperature, salinity and pH varied from 21 to 31.5 °C, 5.84 to 34.44% and 6.0 of 8.0, respectively. The observed spatial gradients of salinity impart an estuarine character to the inner bay which is greatly affected by the rainfall regime. The concentrations of DO varied irregularly during the sampling period, between 4.7 and 8.4 ml/l. The concentrations of ammonia-N, nitrate-N phosphate-P and silicate-Si ranged from < 1.0 — 10.08, < 1.0 — 8.82, < 0.4 — 2.48 and < 10 — 50μg-at/l, respectively. Nitrate-N and ammonia-N showed non-conservative patterns of spa-

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tial distribution and similar patterns of temporal variation with high mean concentrations during the rainy period, decreasing in the dry season. Phosphate-P showed seaward decreasing spatial gradients during the rainy period and an almost homogeneous distribution in the dry season. Silicate-Si behaved more conservatively, with high concentrations in the inner bay decreasing seawards during the whole yearly cycle.

The surface seston and chlorophyll **a** ranged from 3.84 to 50.28 mg/l and 0.75 to 24.6 μg/l, respectively with maxima concentrations obtained in the inner bay during the rainy season. The amplitude of variation was higher in the innermost areas and close related to the rainfall regime.

Key Words: nutrients, chlorophyll **a**, seasonal variation, spatial distribution, Paranagua Bay.

RESUMO

Nutrientes, clorofila-a e parlâmetros hidrográficos básicos foram obtidos em 7 estações distribuídas ao longo da Baía de Paranaguá, entre novembro de 1985 e dezembro de 1986, com o objetivo de estudar os padrões de distribuição sazonal e espacial desses parâmetros em relação ao regime de chuvas da região.

O período chuvoso ocorreu entre janeiro e abril com precipitações quinzenais máximas de 296mm e diárias máximas de 97mm em fevereiro. A estação seca incluiu o período de inverno, extendendo-se de maio a outubro. A temperatura, salinidade e o pH da superfície variaram de 21.0 a 31.5°C, 5.84 a 34.44‰ e 6 0 a 8 0 respectivamente. Os gradientes de salinidade observados dão um caráter estuarino à parte mais interna da baía bastante afetada pela pluviosidade. As concentrações de oxigênio dissolvido variaram irregularmente entre 4.7 e 8.4 ml/l durante o período amostrado, mas a média de todos os valores obtidos durante o ciclo anual foi semelhante em todas as estações, ao redor de 6 ml/l. As concentrações de amônia, nitrato, nitrito, fosfato e silicato variaram respectivamente de 1.0 a 10.0, 1.0 a 8.8, 0.4 a 2.4 e 10 a 50μg-at/l. Nitrato e amônia apresentaram padrões não conservativos de distribuição espaço-temporal ao longo da baía, com valores médios mais elevados durante o período chuvoso, decrescendo nos períodos mais secos. O fosfato apresentou gradientes espaciais decrescentes em direção ao mar durante os períodos chuvosos e uma distribuição mais homogênea nos meses mais secos. O silicato comportou-se mais conservativamente em relação aos demais nutrientes, com altas concentrações nas áreas internas da baía decrescendo em direção ao mar durante todo o período de estudo.

A clorofila-a na superfície variou de 0.7 a 24.6 mg/m^3, com máximos nas áreas internas durante os períodos de chuva decrescendo em direção ao mar. A amplitude de variação foi maior nas áreas mais internas demonstrando uma forte relação com o regime de chuvas.

Palavras chave: nutrientes, clorofila-a, variação espaço-temporal, Baía de Paranaguá.

INTRODUCTION

The economical and social importance of mangrove environments, such as Paranagua Bay, where comercially exploited populations of fish, crabs and oysters feed on the organic production of the mangrove forests and other macrophytes, has been commented in several publications (Odum & Heald, 1975; Por & Dor, 1984; Saenger **et al.**, 1983; Schaeffer-Novelli, 1982). However, a great amount of suspended particulate organic material (plankton and detritus) and dissolved substances, which are not incorporated into the local food web, belongs to the bulk of organic and inorganic elements exported seaward. They play an essential role for the development of the pelagic and benthic communities of the adjacent Continental Shelf.

The hydrography and the plankton population of Paranagua Bay have been studied recently (Sinque **et al.**, 1982; Brandini, 1985a, 1985b; Montu & Alves Cordeiro, 1987; Montu & Fernandes, in press.; Knoppers **et al.**, 1987). Knoppers & Opitz (1984) and Brandini (1985a and b) reported that pluviosity has a direct effect upon the physico-chemical environment, the phytoplankton biomass and succession, and on the quality and quantity of the suspended matter of the inner western bay, while the environmental features of the outer eastern bay are similar to the adjacent sea. The border between these two sectors is indicated by the formation of environmental gradients with and estuarine character where the greater concentrations of phytoplankton were previously associated to high nutrients content, optimum salinity range and comparatively less turbid waters (Brandini, 1985a). Recently, Knoppers **et al.** (1987) reported basic informations regarding the physiography and hydrography of the ecosystem such as total area, water volume, currents, residence time, precipitation and drainage of continental water, tide characteristics and chemical behaviour of nutrients.

However, the informations about the seasonal dynamics and spatial distributions of inorganic nutrients, seston and chlorophyll **a** within the bay are still scarce and must be considered for a better comprehension of the biological processes taking place in the aquatic environment of mangrove ecosystems.

The present paper presents the results of surface phytoplankton biomass in terms of chlorophyll **a** and physicochemical data obtained within an interdisciplinary sampling program conducted between 1985 and 1986, with the purpose to obtain information on the behaviour of nutrients and phytoplankton biomass which serves as a prerequisite to the understanding of the potential productivity of the area and also serves as baseline data for future monitoring programs.

MATERIAL AND METHODS

Physico-chemical analyses of surface water samples were conducted every two weeks in 7 stations distributed along the Bay of Paranagua, from Galheta Channel to the innermost Antonina area (Fig. 1), between November 1985 and December 1986.

The measurements of temperature (standard thermometer), salinity (Harvey), pH (pHmeter), and dissolved oxygen (Winkler)

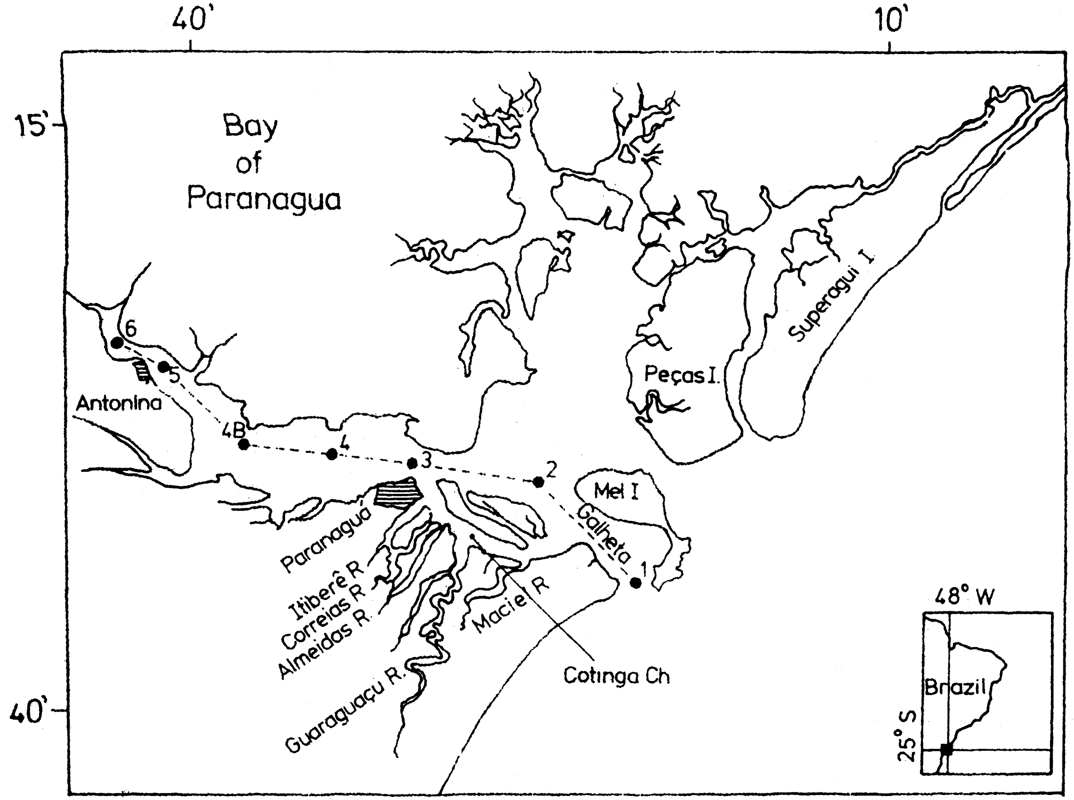

Fig. 1: Map of Paranagua Bay and stations position.

were made by conventional techniques. Nitrate-N, phosphate-P and silicate-Si were analysed according to Strickland & Parsons (1972) and ammonia-N according to Liddicoat **et al.** (1975) with some modifications regarding the light conditions for color development (the samples were placed in the dark).

Water samples were filtered through Whatmann GF/C filters and the analyses of chlorophyll **a** were performed following the spectrophotometric techniques of UNESCO (1966). The concentrations were calculated with the equations of Jeffrey & Humphrey (1975).

Annual precipitation was measured in the meteorological station of the INPH Agency located in Pontal do Sul.

RESULTS

The pluviosity during the sampling period is indicated in Fig. 2. The rainfall regime in 1986 depicted a typical rainy season from January to April, with biweekly maxima of 296 mm and a maximum daily precipitation of 97mm in February. The dry season started in June and extended until October with the beginning of a new rainy period in November and December.

The surface temperature varied from 21 to 31.5 °C during the sampling period showing weak spatial gradients only in summertime (December ⟶ March) with maximum in the inner bay decreasing seaward. In wintertime (June ⟶ August) minima temperatures of 22 °C were homogeneously distributed along the bay (Fig. 3). This spatial homogeneity lasted until the end of the sampling period.

The pattern of seasonal variation of surface salinity (Fig. 4) was greatly affected by the rainfall regime. The salinity ranged from 5.84‰ (Stn.6) to 34.44‰ (Stn.1). The spatial gradients were stronger during the rainy season comparing to the dry wintertime, showing low values in the innermost part of the bay increasing towards the outer bay.

The pattern of seasonal-spatial variation of surface pH (Fig. 5) did not correlate with the annual precipitation. The low-

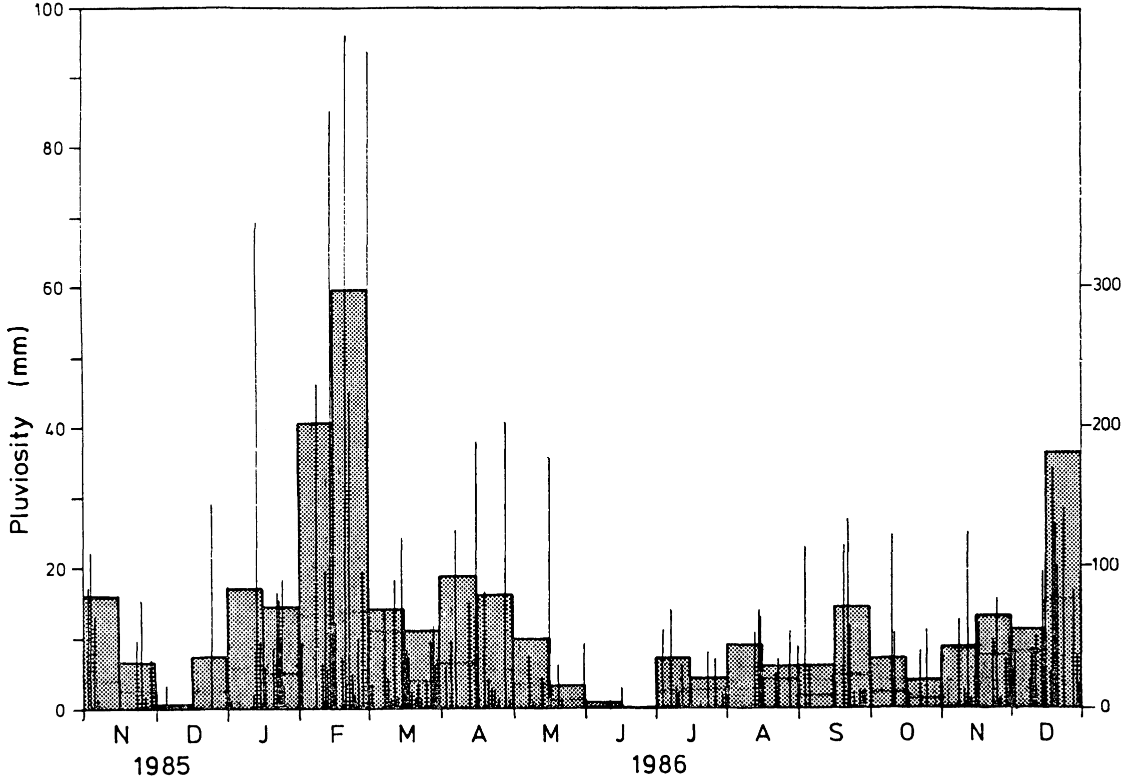

Fig. 2: Annual cycle of precipitation in the Bay of Paranagua in 1985/86. Vertical bars and lines indicate respectively biweekly and daily rates.

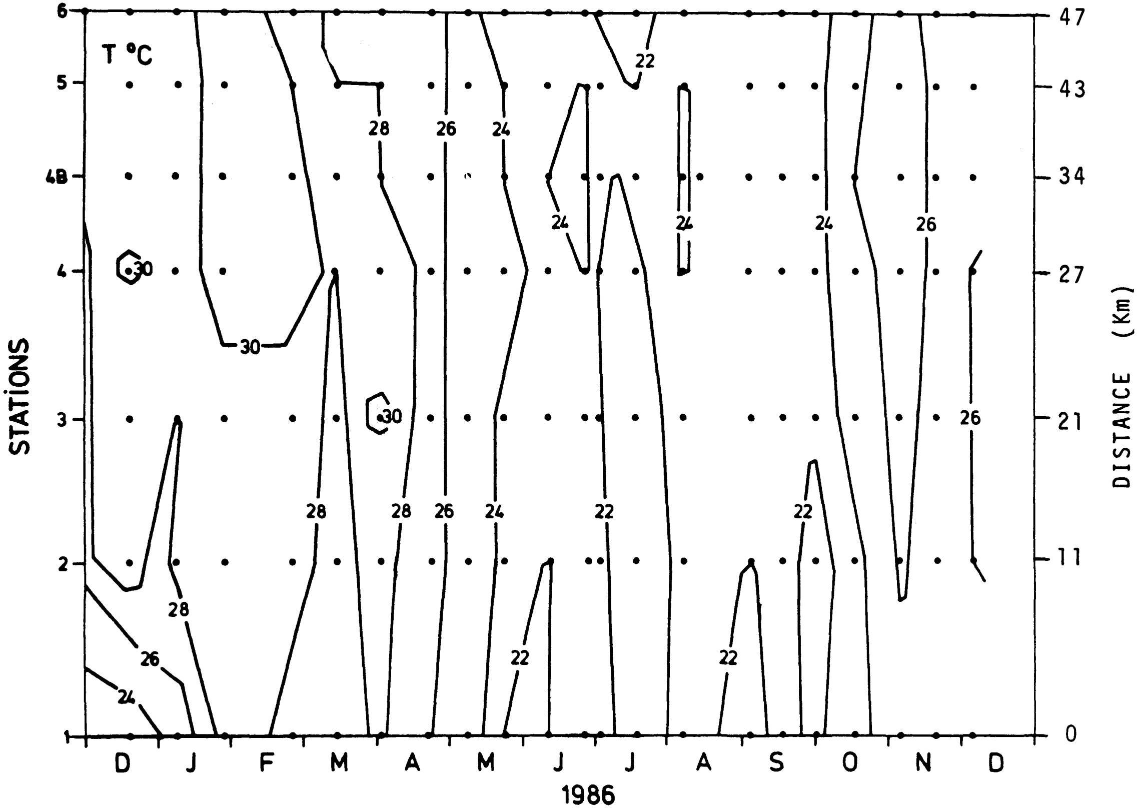

Fig. 3: Seasonal-spatial distribution of surface temperature in the Bay of Paranagua in 1985/86.

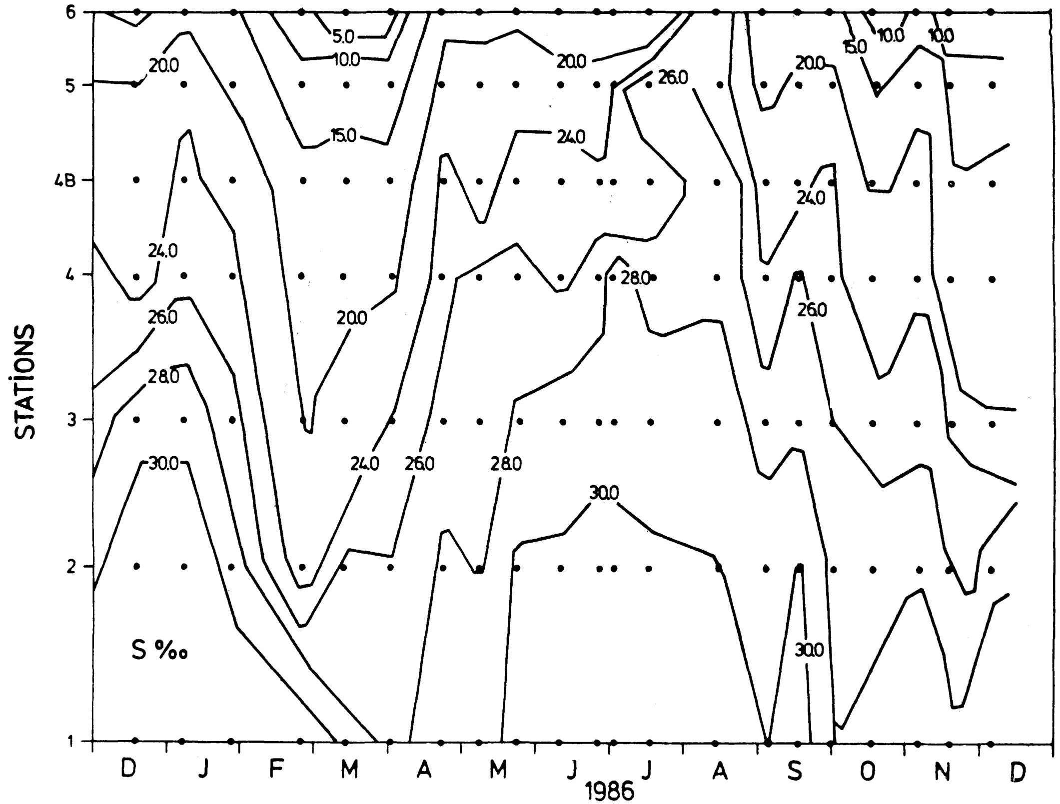

Fig. 4: Seasonal-spatial distribution of surface salinity in the Bay of Paranagua in 1985/86.

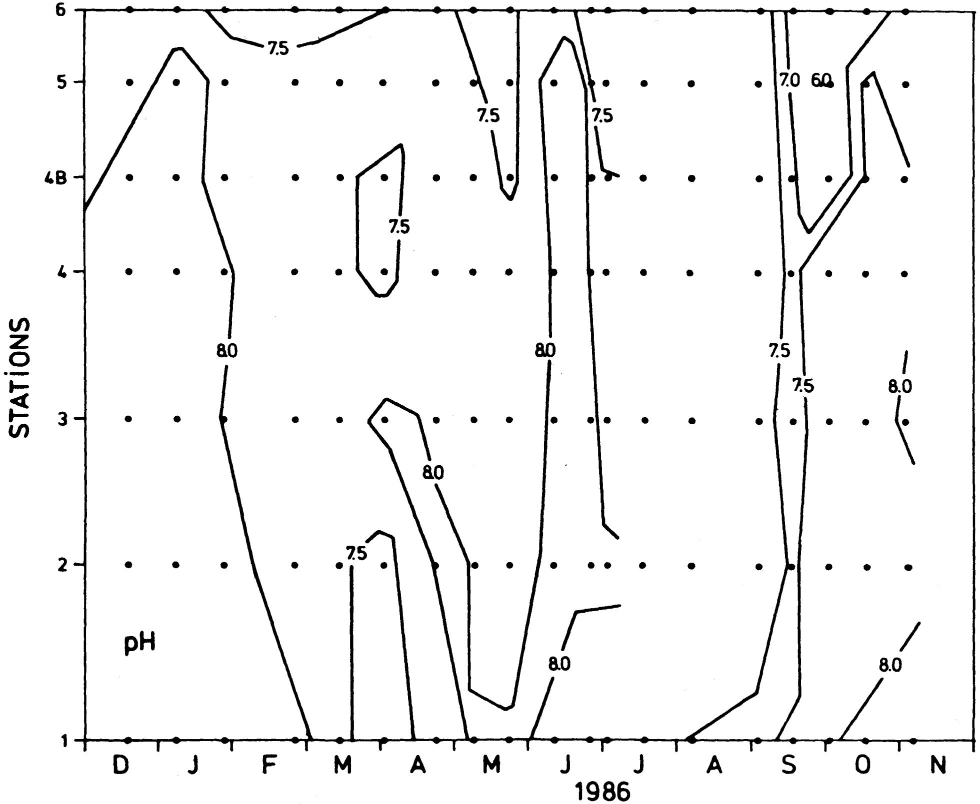

Fig. 5: Seasonal-spatial distribution of surface pH in the Bay of Paranagua in 1985/86.

est values was about 6.0 obtained at Stn.5 in October, and the maximum of 8.0 was measured in the western areas more affected by the sea. Strong spatial gradients and seasonal trends were not detected.

The concentration of dissolved oxygen (DO) ranged from 4.1 (Stn. 6, November 5) to 8.4 ml/l (Stn. 6, October 6). Both the spatial and seasonal variations were completely irregular showing no relationship with the precipitation regime. According to Fig. 6a and b, the annual mean concentration of DO as well as the mean percentage saturation values in each station showed no significant differences along the sampling track. Supersaturation of oxygen was constantly observed in all the stations, except in few occasions during summertime when oxygen deficiency was detected in the inner areas.

The levels of nitrate and ammonia at the surface ranged from very low undetected values til 8.8 and 10.1 μg-at/l, respectively. The patterns of seasonal-spatial variation of both nutrients were similar (Figs. 7 and 8) with concentrations between 1 and 3 μg-at/l distributed homogeneously throughout the sampling track during the rainy summer period. In the dryer wintertime concentrations of less than 1.0 μg-at/l were measured in most of the bay. In the inner areas (Stns. 6 and 7) of Antonina the concentrations were high during the whole sampling cycle, reaching maxima of 6.0 and 5.0 μg-at/l of nitrate and ammonia, respectively. The nitrite varied from less than 0.05 to more than 0.5 μg-at/l (Fig. 9). The seasonal variation seems to correlate positively with precipitation. In general, those periods of high concentrations coincided with periods of maximum pluviosity (February/May and November/December 1986) while minima values were distributed homogeneously in the whole bay right before the beginning of the rainy seasons (November/December 1985 and July/October 1986).

The surface concentration of phosphate ranged from undetected values til $>$ 1.4 μg-at/l, with maxima concentrations observed between the innermost Stns.4 and 6 during the rainy season (Fig. 10). Seaward decreasing gradients were also more defined during this time especially in February and March when

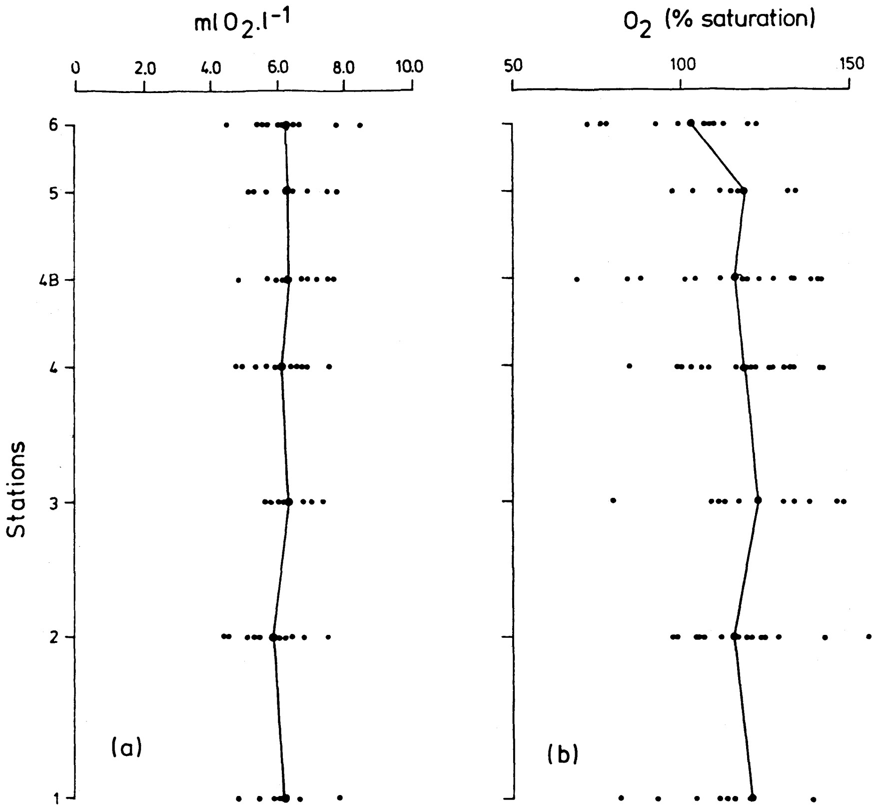

Fig. 6: Total range and mean concentrations of surface dissolved oxygen along the sampling track in the Bay of Paranagua in 1985/86.

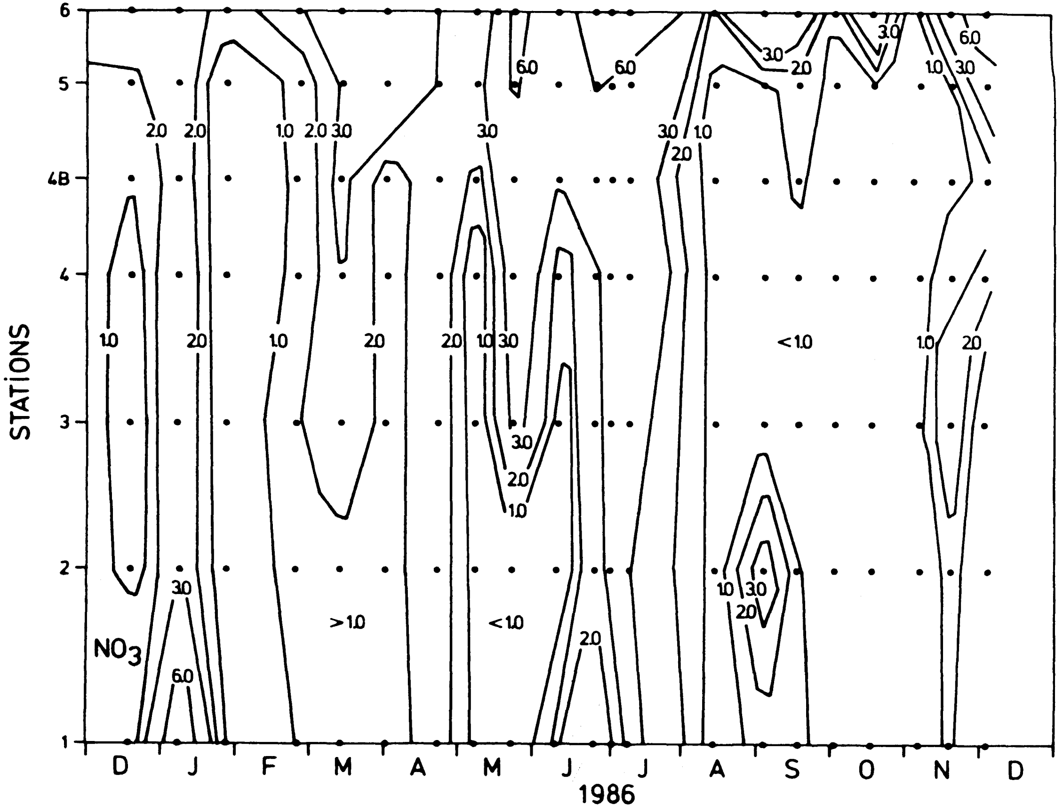

Fig. 7: Seasonal-spatial distribution of surface nitrate-N (μg-at/l) in the Bay of Paranagua in 1985/86.

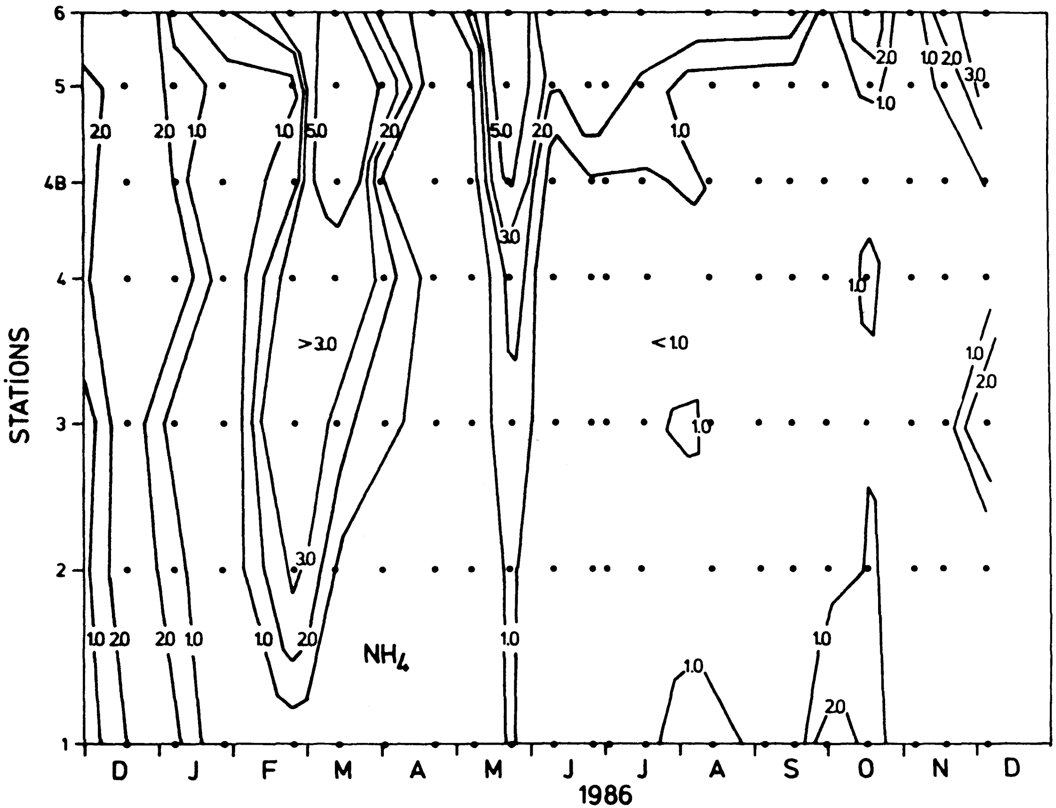

Fig. 8: Seasonal-spatial distribution of surface ammonia-N (μg-at/l) in the Bay of Paranagua in 1985/86.

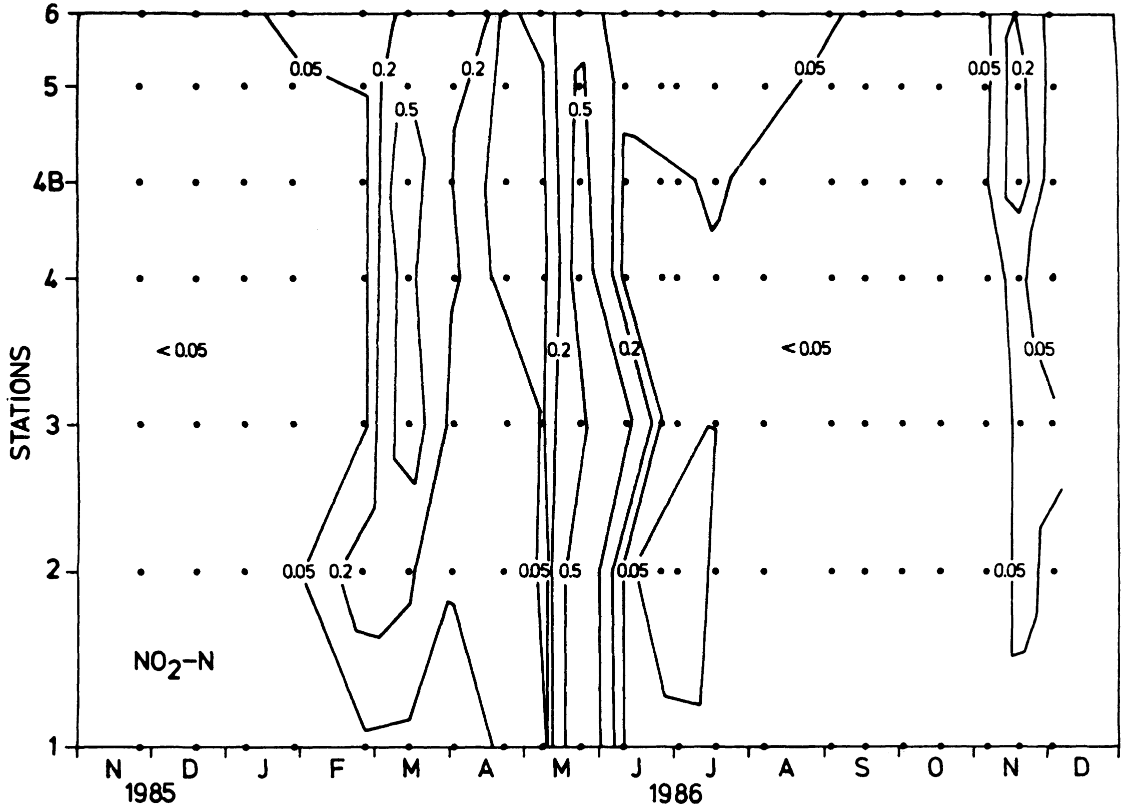

Fig. 9: Seasonal-spatial distribution of surface nitrite-N (μg-at/l) in the Bay of Paranagua in 1985/86.

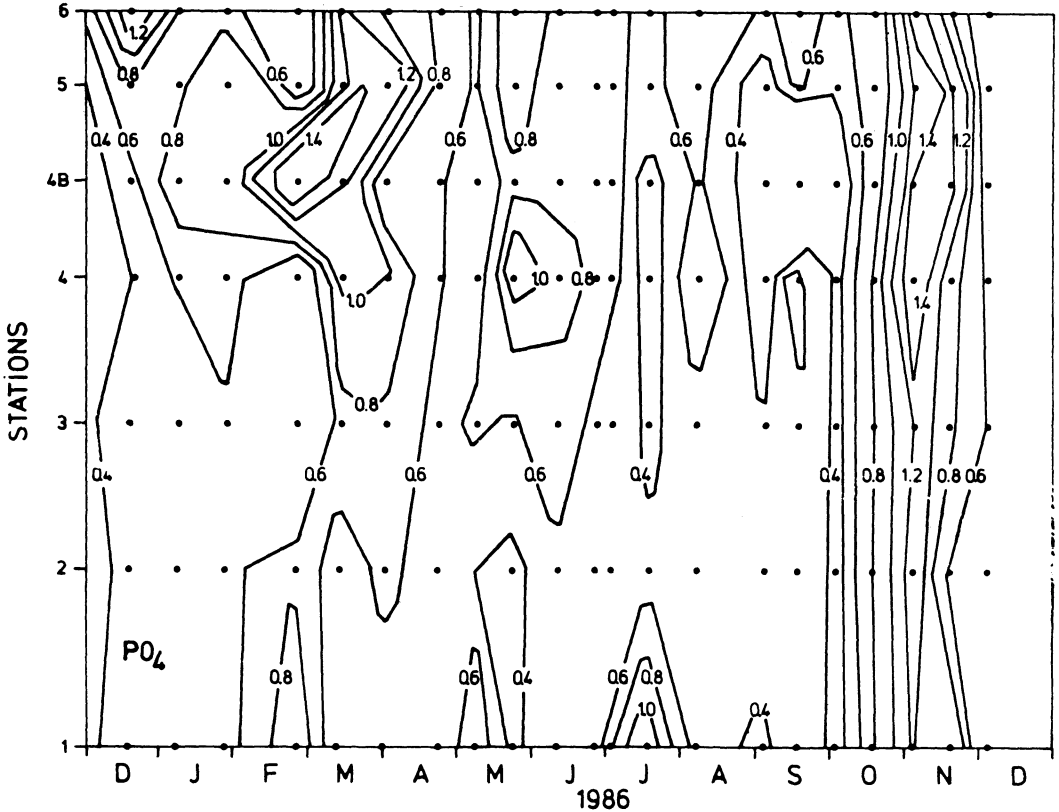

Fig. 10: Seasonal-spatial distribution of surface phosphate-P (μg-at/l) in the Bay of Paranagua in 1985/86.

the maxima concentrations were measured between Stns. 4B and 5. During the dry season, the average concentrations decreased fluctuating between 0.4 and 0.6 μg-at/l and were more homogeneously distributed along the stations track. In the end of the sampling period, the average phosphate concentrations gradually increased with the beginning of a new rainy season but the horizontal distribution did not show strong spatial gradients.

The continental drainage mantained the surface concentrations of silicate higher than 50 μg-at/l in the innermost eastern bay (between Stns.5 and 6) during the whole sampling period except during April/May when the concentrations of silicate decreased within the whole bay to comparatively low values around 10 μg-at/l, distributed homogeneously along the sampling track (Fig. 11). In the outermost western sector between Stns.1 and 3, the concentrations were usually higher than 10 μg-at/l during the rainy season decreasing during the dry season.

The surface concentrations of seston (<300 μm) varied from 4.20 to 33.96, 3.84 to 51.96 and 6.22 to 50.28 mg/l at Stns 2, 4 and 4B, respectively (Fig. 12). During the two rainy seasons observed within the sampling period the mean concentrations were higher with maxima mean values in the inner Stns 4 and 4B in November/December 1986. Minima mean concentrations were measured in the outer Stn.2, in September 1986. The seasonal variations at the three stations were clearly associated to the precipitation cycle.

The surface chlorophyll **a** concentrations varied from 0.75 to 24.6 μg/l, with minima observed in the eastern sector of the study area more afected by the sea, increasing towards the inner bay (Fig. 13) where very sharp spatial gradients and the highest concentrations were observed during the rainy periods of summer. During the dry season, the mean concentrations decreased and the spatial gradients were not as strong as during the rainy period. Low amplitude in the chlorophyll **a** seasonal variation characterized the areas more influenced by the sea.

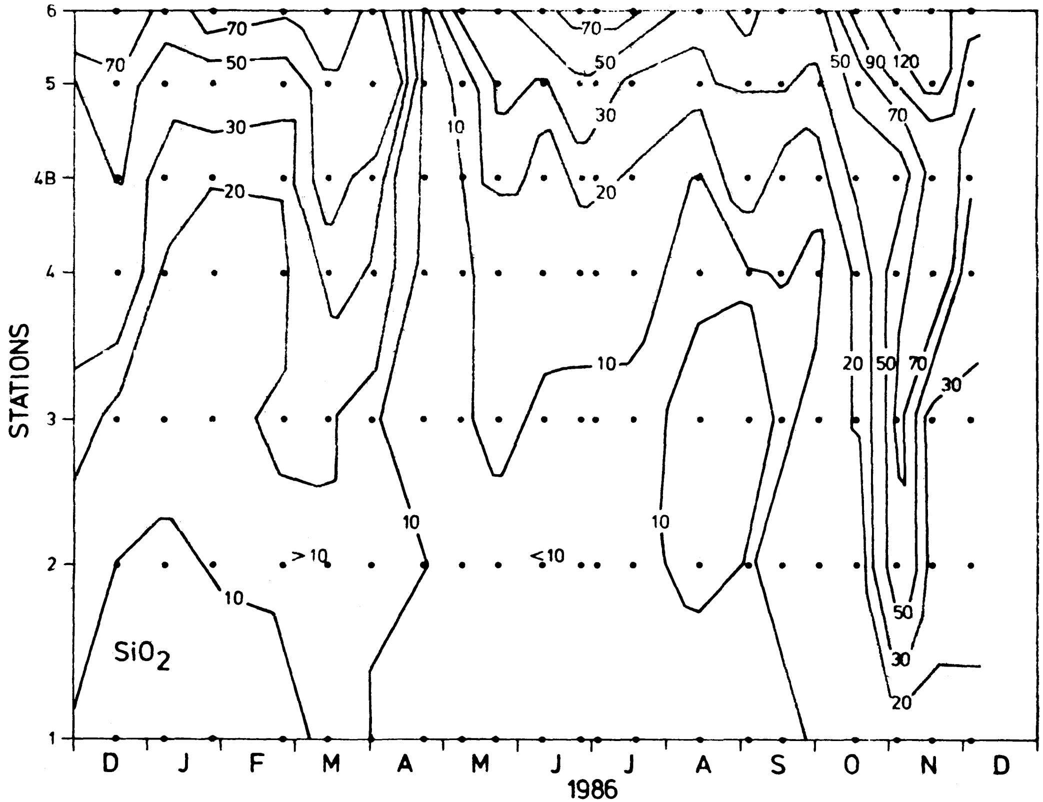

Fig. 11: Seasonal-spatial distribution of silicate-Si (μg-at/l) in the Bay of Paranagua in 1985/86.

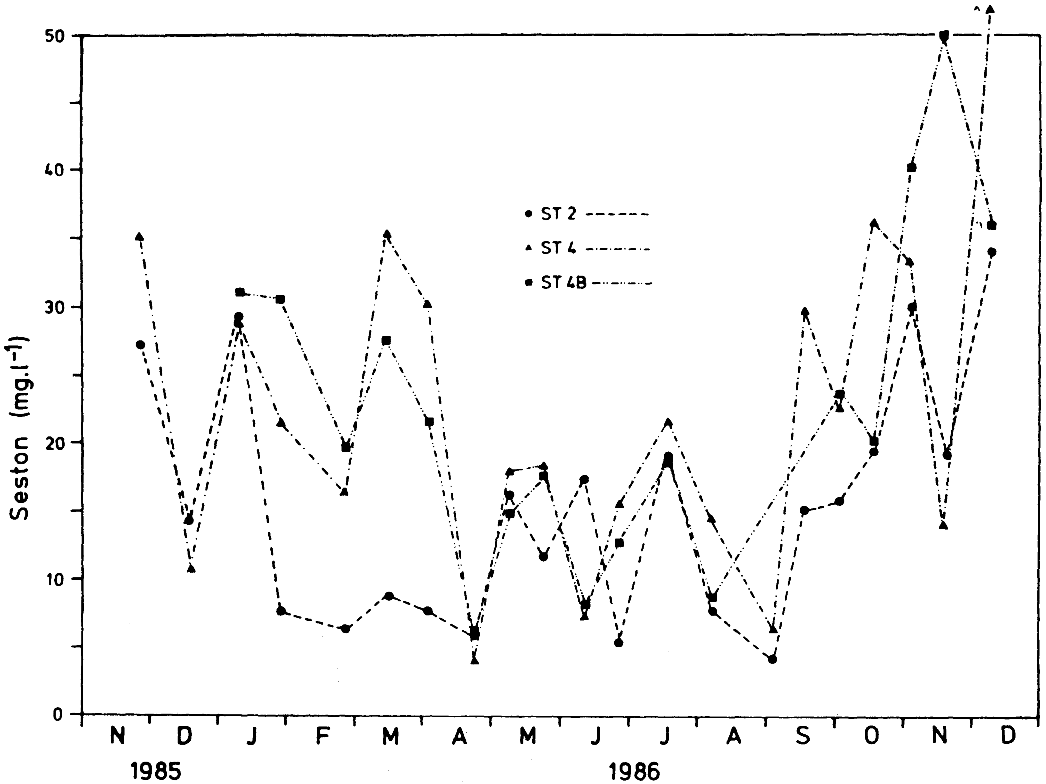

Fig. 12: Seasonal variation of surface seston (< 300 μm) at Stns. 2, 4 and 4B in 1985/86.

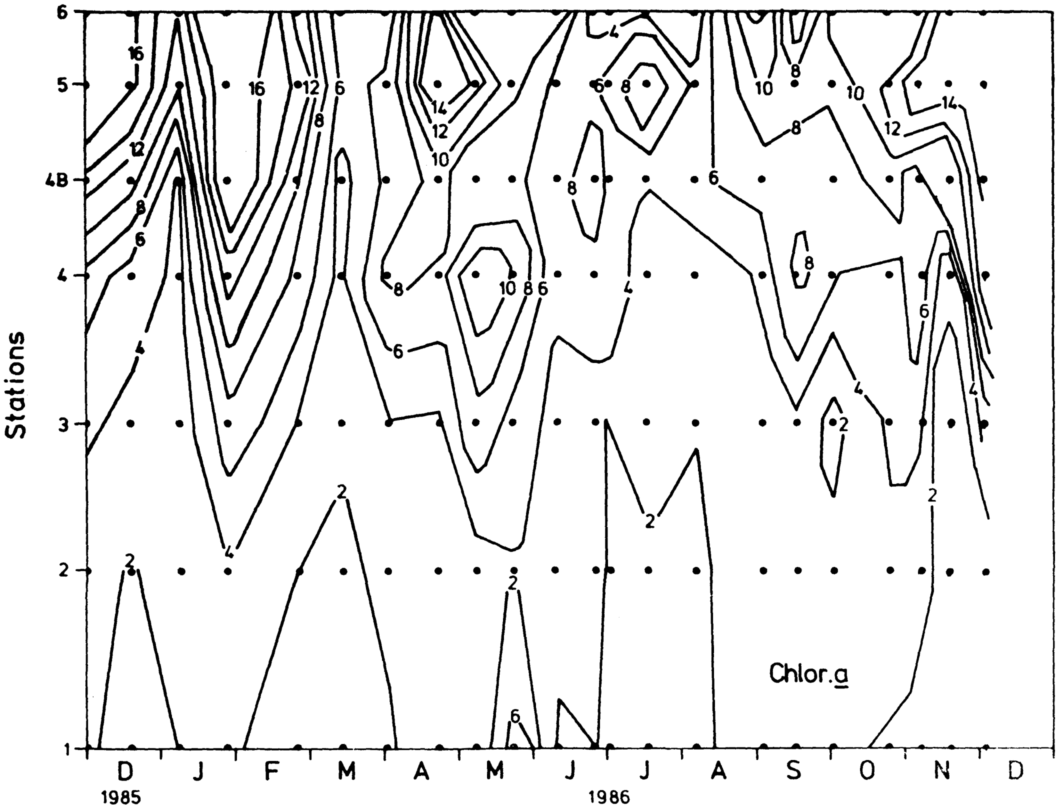

Fig. 13: Seasonal-spatial distribution of surface chlorophyll a (μg/l) in the Bay of Paranagua in 1985/86.

DISCUSSION

The patterns of temporal-spatial variations of the hydrographic parameters obtained during 1986 confirm previous observations (Brandini, 1985a). In the innermost sectors of the Bay of Paranagua, the surface physico-chemical environment is deeply related to the rainfall regime. The same is not true for the outer western sector of the bay, where the hydrographic temporal changes are less intense due to the influence of the adjacent sea flowing via Galheta and Barra Norte Channels into the bay during the tidal cycle.

The great environmental variability observed in the inner parts of the bay during the present work is, therefore, related to the local precipitation which improves the freshwater discharge and transports more particulate and dissolved matter into the system. The greater amounts of nutrients found in these areas promote the development of phytoplankton cells and consequently, the measurements of high chlorophyll **a** concentrations (Brandini, 1985a).

The characteristics of temporal and spatial patterns of chlorophyll **a** distribution inside Paranagua Bay were already discussed for the period of July 1983 to June 1984 (Brandini, 1985a). However, the relationships between the seasonal and spatial distributions of chlorophyll **a** and the rainfall regime were much better defined in the present investigation. This is probably due to a more frequent sampling of chlorophyll data and a more clearly defined pattern of precipitation cycle obtained during 1986 in comparison to those obtained in 1983/84. High chlorophyll concentrations were associated with high nutrient contents and lower salinities observed in the inner parts of the bay. On the other hand, the greater amounts of suspended matter observed in these areas (Fig. 12) increase water turbidity which controls the growth of phytoplankton cells and certainly affects more intensely the patterns of temporal and spatial variations in the innermost areas.

In more than one occasion, chlorophyll was higher in the outermost stations than in mid-estuarine waters indicating the importance of the Galheta Channel as the major gate for the exchange of particulate matter between the bay and the adjacent sea. Knoppers **et al.** (1987) showed that this is the main area of exchange of water for Paranagua Bay.

A difficult task regarding the seasonal and spatial dynamics of nutrients inside the bay is to interpret their chemical behaviour during the mixing of freshwater with seawater. In a previous publication, Knoppers **et al**. (1987) reported that all inorganic nutrients, except silicate, depicted a non-conservative behaviour. The middle section of the bay was considered as the main source to phosphate and the main sink to nitrate and ammonia. Although nutrient concentrations were not obtained along the many freshwater tributary streams, which would be necessary for a complete analyses of nutrient behaviour within Paranagua Bay, the wide range of salinity measured throughout repetitive sampling trips permits the discussion of general characteristics regarding the spatial distribution of nitrate, phosphate and silicate along the low and middle sections of the estuarine system on a time-averaged basis. The total data of nitrate, ammonia, phosphate and silicate x salinity plots are shown in Fig. 14. In general, only silicate behaved more or less conservatively (Fig. 13A) as also observed by Knoppers **et al.** (op. cit.). However, a tendency towards a slight sink may be observed on some occasions in the higher salinity regions which may be attributed to phytoplankton incorporation (diatoms). The other plots show a great scattering of points indicating the non-conservativeness of inorganic nitrogen and phosphorus (Fig. 14 B, C and D).

However, considering the plots obtained for each sampling cruise, some other details regarding nutrients behaviour in the bay may be recognized. The biological uptake of inorganic nitrogen and phosphorus by autotrophic organisms and the various sources of lateral input along the sampling track have a great influence in the pattern of horizontal distributions observed and may explain the different types of non-conservative behaviours depicted in Figs. 15 and 16, which were obtained in different seasonal and tidal periods. The 1st type of nitrate behaviour (Fig. 15A) shows high concentrations in the entrance of the bay, greatly affected by the sea (28-32‰), which may be due to the high freshwater run-off from several rivers flowing via the

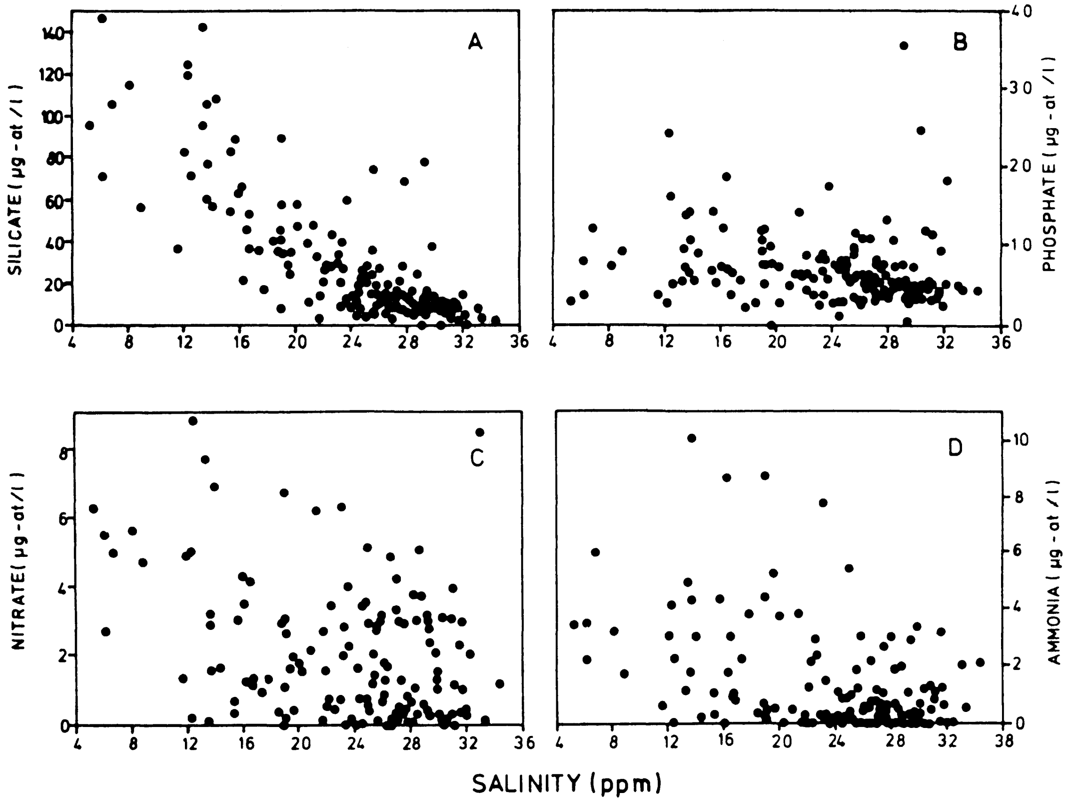

Fig. 14: Surface silicate, phosphate, nitrate and ammonia X salinity plots from the whole set of data obtained along the sampling track during 1985/86, in the Bay of Paranagua.

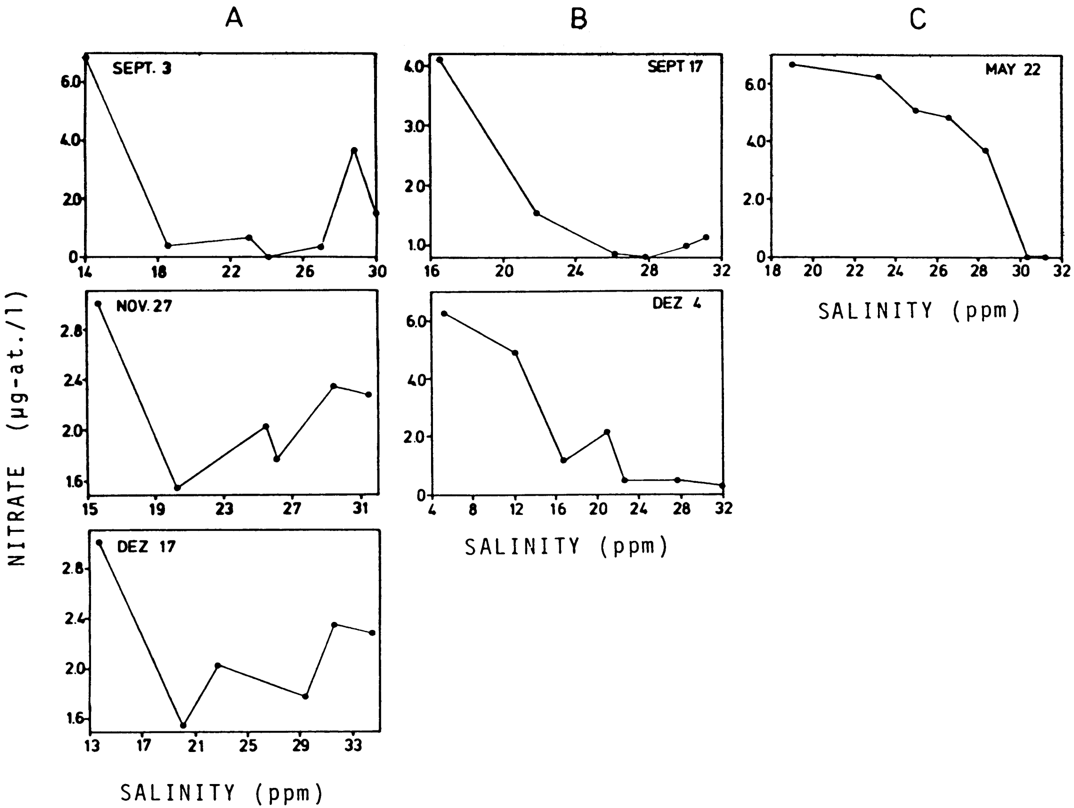

Fig. 15: Nitrate X salinity plots obtained in different sampling cruises along the Bay of Paranagua during 1985/86.

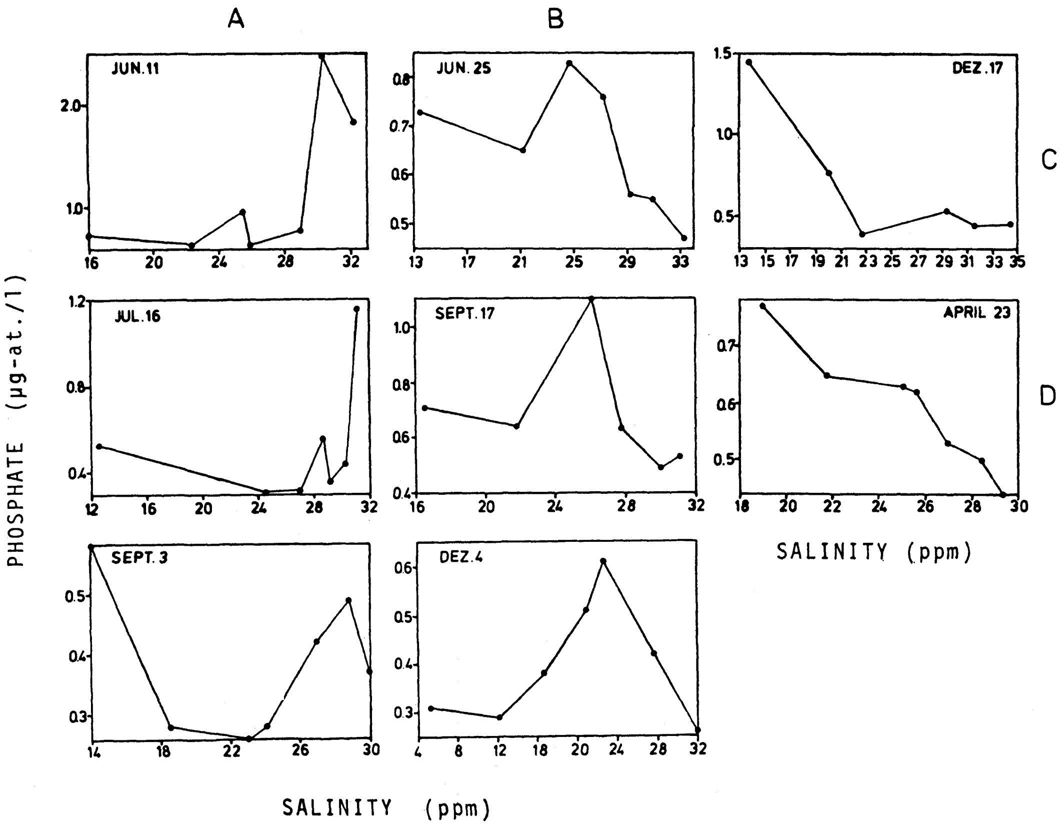

Fig. 16: Phosphate X salinity plots obtained in different sampling cruises along the Bay of Paranagua during 1985/86.

Cotinga Channel towards Galheta Channel (Fig. 1). Itibere River transports the domestic discharge of ammonia from Paranagua City towards Cotinga Channel increasing the potential levels of inorganic nitrogen, such as nitrate, in the lower sectors between Stns.1 and 2. The middle section of the bay removes most of the nitrate due to well growing phytoplankton populations in an optimum range of salinity and less turbid waters (Brandini, 1985a).

The main input of nitrate to the system seems to be the innermost areas. The 2nd type of behaviour (Fig. 15B) is similar to the 1st type except that the nitrate levels at the entrance of the bay are lowered by the flood tides which diminish the influence of Cotinga Channel over Stn. 1. The 3rd type (Fig. 15C) shows the middle section as being a source to nitrate not detected by Knoppers **et al.** (1987). This may be the effect of intense lateral inputs during a period of continuous precipitation in the second half of May 1986.

In the case of phosphate, four types of behaviour were observed (Fig. 16 A, B, C and D). The 1st type (Fig. 16A) indicates high phosphate concentrations in the lower bay due to the contributory freshwaters along Cotinga Channel, specially the effluents of Paranagua City flowing via Itibere River. The innermost areas were also an important source to the bay. The removal of great amounts of phosphate in the mid-estuarine region may be not only due to biological uptake but also the adsorption onto suspended particles may be take into account as an important factor causing the lost of phosphate to the bottom sediments (Liss, 1976). The physical chemistry of the adsorption processes involves the interactions of many factors including salinity, pH and quality of the suspended solids, and was described in detail by Parks (1975). The adsorption mechanism may be improved in the lower salinity and pH conditions occurring in the middle section of the bay (Liss, 1976). The release from bottom sediments, the high freshwater run-off during rainy periods and the contribution of Paranagua City, may explain the 2nd type of behaviour (Fig. 16B) showing the middle section as the most important source for the bay. Occasionally, the 3rd type may be observed (Fig. 16C) showing again

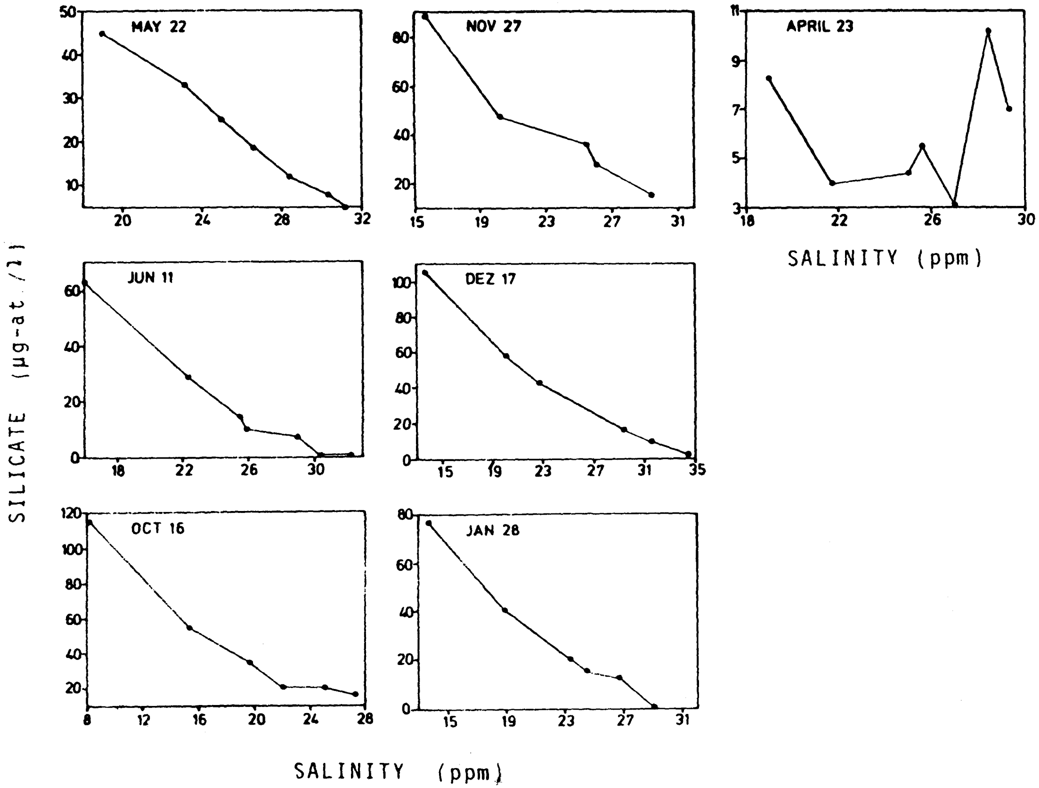

Fig. 17: Silicate X salinity plots obtained in different sampling cruises along the Bay of Paranagua during 1985/86.

the middle section as a sink and the inner bay as the main source. The 4th type (Fig. 16D) represents a rare case of conservative behaviour obtained in April 1986. In reality, what seems to be conservativeness may just be the interactions of lateral inputs plus the release from bottom sediments (increasing the phosphate) with the biological consuption by phytoplankton cells and mangrove plants associated to the adsorption of dissolved phosphate onto solid particles (decreasing the phosphate) giving rise to a pseudo-conservative behaviour. Obviously, non-biologically mediated mechanisms, such as the phosphate buffering processes (Burton & Liss, 1976), must be considered in all this types of behaviour as they are important for mantaining the phosphate levels irrespective of salinity, pH or temperature changes within estuarine systems. A good example was reported by Morris **et al.** (1981) in the Tamar Estuary, southwest England.

The most uncommon feature of the seasonal-spatial pattern of silicate distribution was the sudden decrease of surface concentrations in April/May (Fig. 11) which was probably related to (i) the uptake of diatom blooms occurring in that period (unfortunatelly this can not be confirmed because phytoplankton samples were not analysed) and (ii) the end of the first rainy period which decreases the land drainage contribution of dissolved silica into the system. In the present investigation, most of the silicate x salinity plots obtained (Fig. 17) were slightly concave (except in May 22) probably due to diatoms uptake between the middle and lower sectors of the bay. However, it may happen a completely non-conservative situation as the one observed in April 23 (Fig. 16B).

CONCLUDING REMARKS

1) The rainfall regime is the primary factor affecting the seasonal changes of nutrients, salinity, seston and chlorophyll **a** in the inner Bay of Paranagua. The rainy periods increase the surface levels of nitrate, nitrite, ammonia, phosphate and seston. The chlorophyll **a** also increase in such periods as the consequence of increasing nutrients and lower salinities, specially

in the mid sectors dominated by less turbid waters than the innermost areas.

2) The hydrographic and morphological features of the bay, as well as the domestic discharge of Paranagua City and many others tributary streams, cause many sources of lateral inputs of nutrients to the system. This must be associated to bottom release, adsorption onto suspended particles and biological activity, in order to interpret correctly the various type of chemical behaviour of nutrients (specially phosphate) observed in this investigation.

3) The high concentrations of nutrients and sometimes chlorophyll **a** frequently observed at Stn.1 during low tides in comparison to Stn.2, indicate that the Galheta Channel is the main via of transport of particulate and dissolved material from the contributory rivers along the Cotinga Channel towards the open sea.

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