

ECOLOGICAL STUDIES IN THE BAY OF PARANAGUA. II. SOME PHYSICAL AND CHEMICAL CHARACTERISTICS.

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ABSTRACT

A first insight into the physical and chemical behaviour of Paranaguá Bay is presented. Data on the physiography, the tidal regime, the spatial and temporal variation of salinity and dissolved inorganic nutrients are given. In addition, the total fresh water input to the bay and the flushing time of the middle section of the bay is estimated. The mean annual fresh water input to the bay was estimated at about $75\text{m}^3/\text{s}$ but large short temporal and seasonal variations to the mean prevailed. The bay is classified according to the pattern of stratification as a partially mixed Type B estuary with some lateral inhomogeneity particular within the middle section of the bay. An attempt to classify the bay according to the stratification-circulation diagram (Hansen & Rattray, 1966) revealed a 2a Type estuary. Flushing times estimated for the middle section of the bay ranged between 13 and 24 days. Estimates utilizing the "fresh water fraction method" and the "simple tidal prism method" (Dyer, 1973) yielded similar results. More substantial quantitative studies are necessary to underline these results. A non conservative behaviour was detected for the nutrients nitrite, nitrate, ammonia and orthophosphate. Silicate exhibited, in general, a conservative behaviour. The middle section of the bay represented a sink to nitrogen-nutrients and a source to ortho-

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phosphate. The former was primarily attributed to biological uptake, the latter to the impact of domestic discharge from the harbour city of Paranaguá. Although the fresh water input of nutrients is unknown, the concentrations of nitrate and ammonia within the upper section of the bay suggested that acute eutrophication from these species is not yet to be expected. In order to better understand the physical and chemical behaviour of the bay, future studies within the head section and the fresh water sources are a prerequisite.

Key Words: Water masses, stratification, classification, nutrients, behaviour, Bay of Paranaguá, Brazil.

RESUMO

Estudos ecológicos na Baía de Paranaguá. II. Características físico-químicas. Uma análise preliminar do comportamento físico-químico da Baía de Paranaguá é apresentada. São fornecidas informações sobre a fisiografia, regime de marés e variações espaciais e temporais da salinidade e nutrientes inorgânicos dissolvidos. A entrada total de água doce na baía e o tempo de renovação em sua seção mediana foram estimados. A entrada anual média de água doce foi estimada em $75\text{m}^3/\text{s}$, com acentuadas variações temporais e espaciais em relação à média. A baía é classificada, de acordo com o padrão de estratificação, como estuário do tipo B parcialmente misturado, com alguma inhomogeneidade lateral, particularmente na seção mediana. De acordo com o diagrama de estratificação-circulação (Hansen & Rattray, 1966), a baía pode ser classificada como estuário do Tipo 2a. O tempo de renovação estimado para a seção mediana da baía variou de 13 a 24 dias. Estimativas utilizando o "método da fração de água doce" e o "método de prisma de marés simples" (Dyer, 1973) deram resultados similares. Estes resultados devem ser reforçados por estudos quantitativos mais detalhados. Comportamento não conservativo foi detectado para os nutrientes nitrato, nitrito, amônia e ortofosfato. Silicato, em geral, apresentou comportamento conservativo. A seção mediana da baía constitui uma área de perda para nutrientes nitrogenados e uma fonte de ortofosfato, pro-

vavelmente devido à demanda biológica e ao impacto da descarga doméstica da cidade portuária de Paranaguá. Embora a entrada de nutrientes com a água doce seja desconhecida, as concentrações de nitrato e amônia na cabeceira da baía sugerem que não se deve esperar eutrofização aguda por esses elementos. Para a melhor compreensão do comportamento físico-químico da baía, estudos futuros da cabeceira e das fontes de água doce são necessários.

Palavras-Chave: massas de água, estratificação, classificação, nutrientes, comportamento, Baía de Paranaguá, Brasil.

INTRODUCTION

In recent years, the estuarine system of Paranaguá, southern Brazil, has been subject to chemical and biological studies that dealt with the spatial and temporal variation of dissolved inorganic nutrients and phytoplankton composition and production (Brandini, 1985a; 1985b) and the composition of zooplankton (Montú & Cordeiro, in press), ichthyoplankton (Sinque *et al.*, 1982), and macrobenthos (Lana, 1986). Information on the quantity and quality of suspended particulate organic matter and phytoplankton biomass in mangrove waters has been presented by Knoppers & Opitz (1984).

However, studies on the physical regime of the bay have to a large extent been neglected. Information is restricted to some knowledge on the distribution of temperature and salinity (*cit. op.*) and in part on the tides and tidal currents (IPqM, 1969). The physiography of the drainage system and sedimentology of the bay and some aspects on its fresh water input has been studied by Bigarella (1978).

This study represents a compilation of physical and some chemical results obtained in support to various of the above cited biological investigations and also harbours additional results from specific physical studies conducted between the years 1981 and 1984. An attempt is made to estimate the total fresh water input into the bay, some insight is given on the be-

haviour of the tidal regime and a classification of the bay according to the pattern of stratification and, on a preliminary basis, also circulation is suggested. The behaviour of dissolved inorganic nutrients in relation to the distribution of water masses is also evaluated.

STUDY AREA

The Bay of Paranaguá forms part of a complex estuarine system situated in the State of Paraná, southern Brazil (Lat. 25.°, 16-34'S; Long. 48.°, 17-42'W). The bay represents the east-west axis the system and congregates at its lower premises with the Bay of Laranjeiras (Fig. 1). The physiographic data presented in Table I demonstrate that Paranaguá Bay surpasses Laranjeiras Bay with respect to its length, area and water volume. The data were estimated by planimetry from nautical and geological charts supplied by the Brazilian Navy and the Department of Geology, Federal University of Paraná. The areal delimitation of both bays (Fig. 1, dashed line) was conducted according to the bathymetry and pattern of circulation as the terrestrial boundaries of the lower section of the estuarine system do not show a clear functional division between both bays.

The system has access to the open sea via two tidal channels which are separated by an Island (Fig. 1). The northern channel exhibits a cross-sectional area of $34 \times 10^3 \text{m}^2$ and a maximum depth of 27m. It bifurcates within the lower section of the system towards both bays. In contrast, the southern channel, with a cross-sectional area of $27 \times 10^3 \text{m}^2$ and a maximum depth of 33m, proliferates only towards Paranaguá Bay (Fig. 1, 10m isobath).

The tides are characterized by diurnal inequality and attain maximum and minimum amplitudes in turn of 2.0m and 0.5m respectively. The drainage system of Paranaguá Bay has an area of 1918 km² and receives a mean annual precipitation of about 2000mm (Maack, 1968). Anthropogenic influence is encountered at the harbours cities of Paranaguá and Antonina (Fig. 1) and in some sections of the drainage system in terms of acute deforestation (Bigarella, 1978).

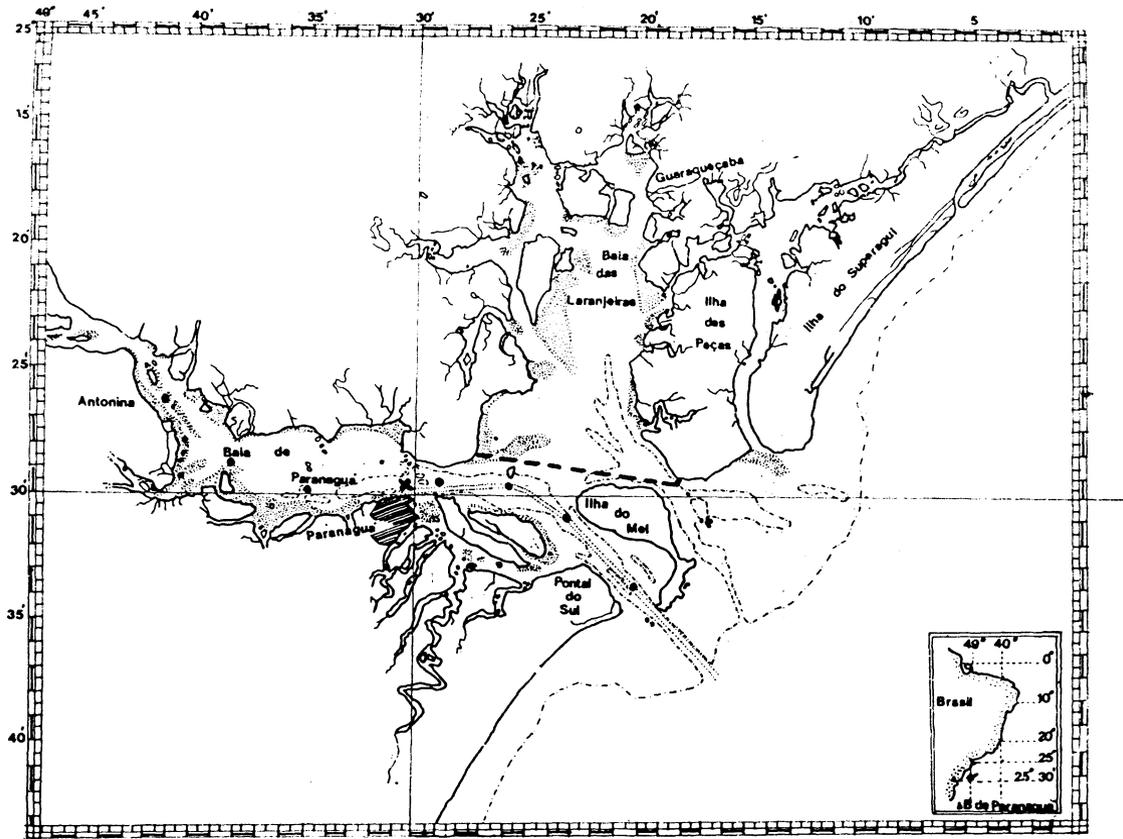


Fig. 1. The study area and sampling stations. The site of the diurnal study is delineated with a cross.

Table 1. Physiographic data of Paranaguá Bay in comparison to Laranjeiras Bay. Data were estimated by planimetry from nautical charts (DHN-30, Brazilian Navy) and geological charts (Department of Geology, University of Paraná).

SITE	Area Km²	Volume m³ x 10⁶	Mean Depth m	Max. Depth m
PARANAGUÁ BAY	256	1404	5,4	33
Lower section	139	980	7,0	33
Middle section	82	356	4,3	17
Upper section	35	68	1,9	8
LARANJEIRAS BAY	200	500	2,5	27

MATERIAL AND METHODS

Sampling — The data were obtained at irregular sampling frequencies between the years 1981 and 1984. The spatial distributions of water properties was studied at five to seven station spiked along transects between the mouth and the upper section of Paranaguá Bay. At each station, temperature, salinity and current velocity profiles were conducted with a vertical resolution at 1 m intervalls. Sampling was conducted at slack tide or early flood flow conditions but could not always be maintained at similar tidal amplitudes. Further physical and chemical properties were analysed from surface samples obtained with a Van Dorn type water bottle. With the exception of pH, all properties were analysed in the laboratory.

The surface distribution of temperature and salinity was also studied during an annual cycle from 1982 to 1983. Measurements were conducted at approximately monthly intervalls. In addition, the short temporal variation of physical properties was monitored during one and a half tidal cycles at a fixed station situated in the middle section (Fig. 1) and also during one tidal cycle at a grid of nine station within the lower section of Paranagua Bay. In situ profiles and surface water samples were obtained at hourly intervalls. Physical and chemical data related to the marine end member were furnished by the Brazilian Navy; The measurements were conducted approximately twenty miles offshore within the coastal current.

Methods and Instrumentation — Temperature and salinity were measured with a T/S — Sensor, type MC 5, Electronic Switchgear, London. Current velocity was measured with a current cross as described by Pritchard & Burt (1951) and calibrated for interchangeable weights according to Kjerfve (1982). Values of pH were obtained with a combined electrode, type WTW-Weilheim, and dissolved oxygen, nitrate, nitrite, orthophosphate and silicate were analysed as in Strickland & Parsons (1972). Ammonia was measured according to Liddicoat *et al.* (1975).

RESULTS AND DISCUSSION

In the following, an attempt is made to estimate the fresh water input into the bay, to give a general description of the tidal regime, and to classify the bay with respect to its pattern of stratification. Information of the preliminary results on the pattern of circulation and prevailing flushing times are presented for the middle section of Paranagua bay only, as knowledge of the bathymetry of the head of the estuary and the behaviour of the tidal river section is still scarce.

DRAINAGE

The total fresh water input to the bay has up till now been unknown. The information available is restricted to the input of the main tributaries situated at the upper reaches of Paranagua Bay. Bigarella (1978) estimated their average input over a period of twenty years $44\text{m}^3/\text{s}$. The additional contribution of the numerous small rivers and mangrove channels "Marigots" spiked along the middle and lower reaches of the bay remains to be assessed.

An estimate of the mean annual fresh water contribution to the entire bay is conducted, by considering the mean annual precipitation corrected for evaporation over the drainage basin and the water surface of the bay, and from the relationship between precipitation and river flow available from some specific sites within the upper drainage system. For this purpose, meteorological data were obtained from various sources (National Institute of Meteorology — 7th district, Paranagua City; the Administration of Hydrological Resources, ARH, Paranagua City; the Department of Meteorology, Federal University of Parana; Maack, 1968; Bigarella, 1978). The data represent averages of over thirty years. The mean annual precipitation amounts to 2000mm. Figure 2 gives an example of an annual cycle of precipitation during the study period 1983-1984. For the calculations, the drainage system was sectioned into five sub-systems according to the known spatial variation in precipitation and the relationship between precipitation and river flow, the topography and forest coverage. The sub-systems correspond to a large extent to those classified by Maack (1968) and Bigarella (1978).

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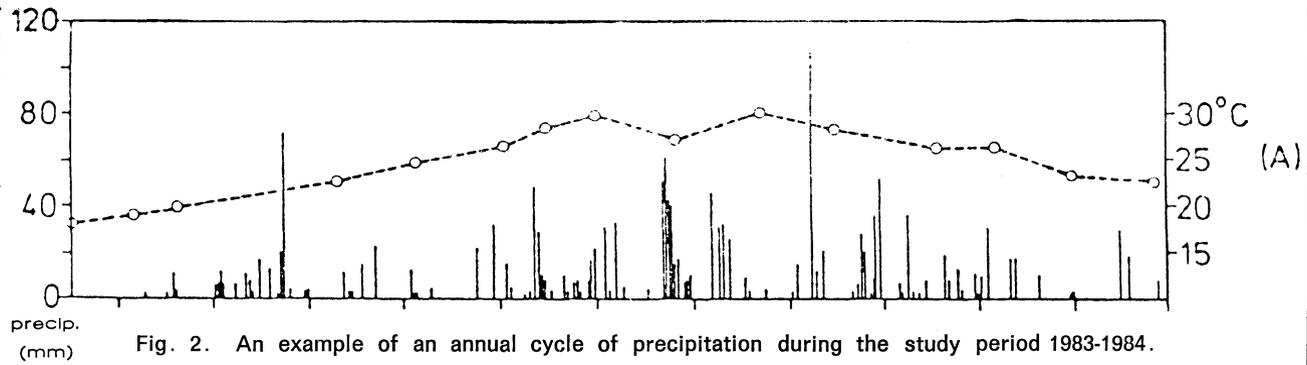


Fig. 2. An example of an annual cycle of precipitation during the study period 1983-1984.

The relationship between river flow and precipitation ranged between 0.2 and 0.85 within the study area. Highest values were recorded by Bigarella (1978) at the lower premises of the drainage system, and the same author states that in some areas values may attain unity due to acute deforestation. The relationship between evaporation and precipitation for the drainage basin of the lower section of the bay was estimated at 0.47. As no information is available on the fresh water inflow in this area, calculations should slightly underestimate the fresh water input. However, the lower section represents no more than 31% of the total drainage basin. On the whole, the Paranagua drainage system seems to exhibit a mean run-off ratio around 0.6. This value is slightly higher than the mean encountered in sub-tropical forest covered systems (Holland, 1978). Acute deforestation (Bigarella, 1978) is probably responsible for the high run-off ratio.

The total mean annual fresh water input to the bay was estimated at $75\text{m}^3/\text{s}$ and the contribution from the upper drainage system at $50\text{m}^3/\text{s}$. The latter estimate seems feasible as it is slightly higher than the value recorded by Bigarella (1978) who considered the main tributaries only. The total fresh water input to Paranagua Bay, lies within the same order of magnitude as observed for the Santos estuarine system and by a factor of two lower than for the Itajai-Açu system (Döbereiner, 1984; 1986). Both estuaries lie within the same mountain range as Paranagua Bay. The differences in fresh water inflow of the systems are mainly attributed to variations in the ratio between the area of the drainage system and the surface area of the estuaries.

TIDAL REGIME

The tides are characterized by diurnal inequality and reach a near to semi-diurnal pattern during the presence of maximum tidal amplitudes. As the estuary is ascended, the time of high or low tide occurs progressively later. Observations suggested that a mixed tidal wave may be predominant. During minimal tidal forcing, up to three tidal cycles with irregular frequencies may prevail (Fig. 3), and during strongest tidal forcing, maximum

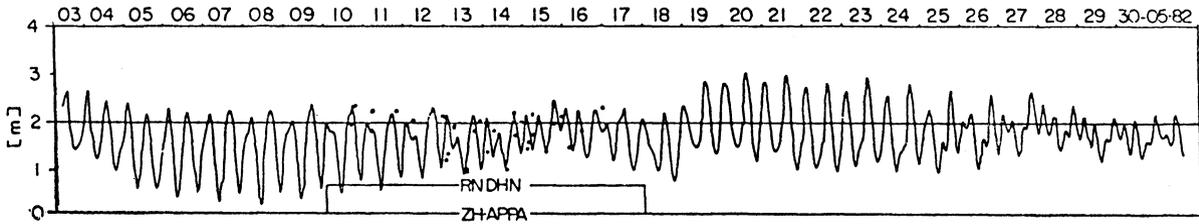


Fig. 3. Example of the tidal spectrum off the Port of Paranaguá City.
 (Source: APPA — Port authorities).

flow and slack water conditions may occur at a time difference up to one quarter of the tidal period from high or low tide. This is substantiated in Figure 4 which depicts a time-depth plot of current velocity obtained during one and a half tidal cycles at a fixed station in the middle section of Paranagua Bay. Maximum tidal amplitudes of 2m and calm meteorological conditions prevailed. Surface floodflow and ebbflow attained velocities between 100 and 125cm/s in turn of two ours before high and low tide respectively, and maximum mid depth and bottom flow was about two hours before surface peak flow.

The pattern of the tidal currents in Paranagua Bay is poorly understood. Information is restricted to a study conducted by the Brazilian Navy (IPqM, 1969) and some heterogeneous data from this study. Figure 5 portray tidal currents at ebb and flood flow (large arrows) and the residual flow (small arrows) recorded at 5m depth for several stations in the bay (IPqM, 1969). The residual flow at the mouth of the bay attained 9 cm/s and in the middle section 5 cm/s. Within the lower section of the bay, the residual flow inclined slightly towards Laranjeiras Bay, thus indicating a complex behaviour of the circulation pattern in this area. The data should only be regarded as a momentary example, as measurements were conducted below surface within the water level of maximum salt entrainment and during a period of unstable meteorological conditions.

The studies conducted by IPqM (1969) also revealed that water exchange between the middle section of Paranagua Bay and the open sea occurs accross both the southern and northern tidal channels. This was confirmed in more detail in the present study. Figure 6 exhibits the direction of surface flood and ebbflow obtained during a tidal cycle within the lower section of the estuarine system. During floodflow water enters both channels, flows past the northern and southern flanks of Mel Island and congregates within the lower estuary before entering the middle section of Paranagua Bay. A certain fraction of the water entering the northern channel also flows towards Laranjeiras Bay. At ebbflow a fraction of Laranjeiras Bay water is assumed to flow towards the southern channel after mixing with Paranagua Bay water within the lower section of the estuary.

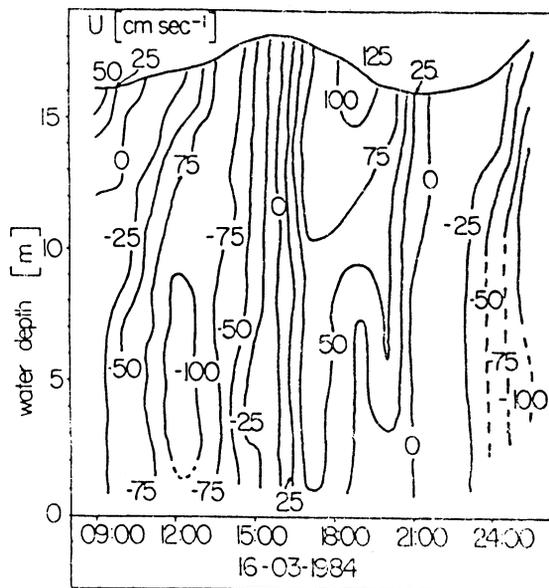


Fig. 4. Time-Depth plot of current velocity for the middle section of the bay.

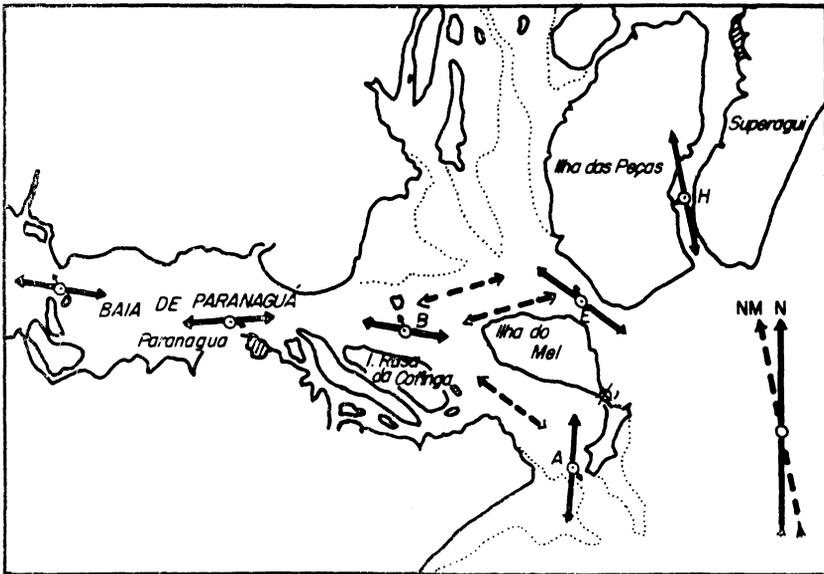


Fig. 5. Tidal currents at ebb and flood flow (large arrows) and the residual flow (small arrows) at 5m depth for several stations. (Source: IPqM, 1969).

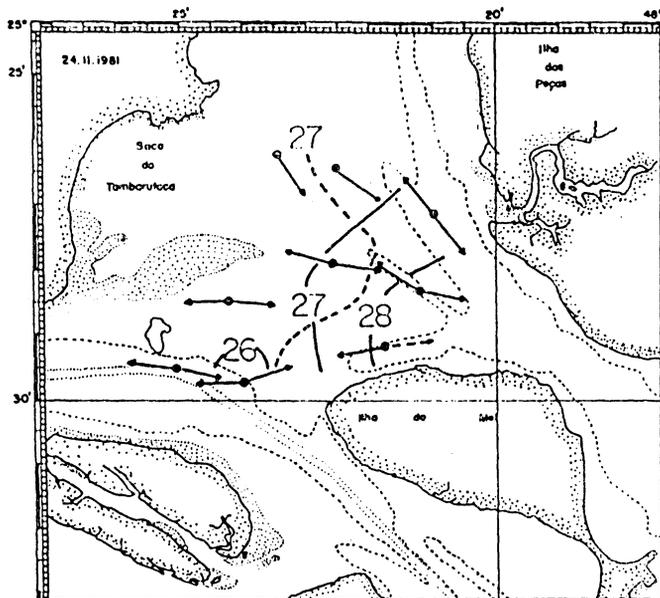


Fig. 6. Direction of surface ebb and flood flow and respective isohalines at ebb (broken lines) and flood (unbroken).

An indication to this mixing process was given by the inclination of the isohalines depicted in Figure 6 and the change in direction of the current vectors between ebb and flood conditions observed during this study.

These observations suggest that future studies on the water exchange of Paranagua Bay should first be conducted at the cross-sectional narrows between the lower and middle sections of the bay (Fig. 1), instead of at the southern tidal channel only.

As shown in Figure 4 beforehand, the pattern of flow in the middle section of Paranagua Bay is governed by vertical inhomogeneity. Lateral inhomogeneity in flow is also present as indicated by the inclination of the surface isohalines depicted in Figure 7. The salinity data were obtained during a quasi-synoptic assessment at more or less slack tide conditions. The results imply a stronger outflow at the southern flank of the middle section of the bay. This could be brought about by the presence of a higher fresh water inflow at the southern flank, than of the northern flank indicated by the larger number of rivers (Fig. 1). The presence of flow in form of a cyclonic gyre should also be considered as observed for other estuaries (Dyer, 1973; Ketchum, 1983).

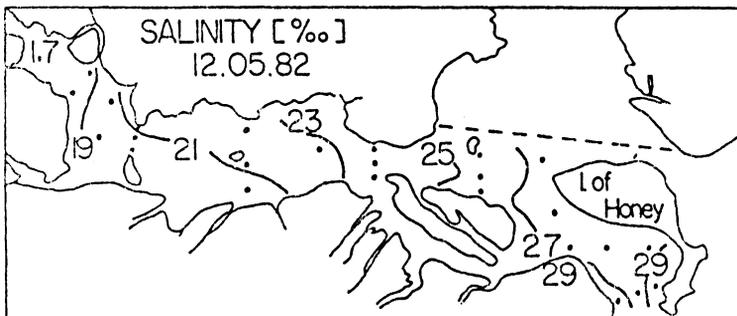


Fig. 7. Surface isohalines at approximately slack water conditions.

TEMPERATURE AND SALINITY

Horizontal and vertical temperature gradients do usually not surpass 3°C and thus, have little effect upon density stratification. However, temperature affects the seasonal variation in the density of water masses. Winter values lie around 20°C and summer values at 30°C.

Density stratification of water masses in the bay is primarily determined by salinity. Some examples of the vertical distribution of salinity, obtained along transects between the mouth and the upper section of the bay, are given in Figures 2.a — e. A situation at ebbflow is given in Figure 8a and conditions during slackwater or early floodflow are presented in the remaining figures. In general, the vertical gradient increases from the mouth towards the upper section and the surface gradient decreases towards the mouth of the bay, which is typical for a positive type estuary (Dyer, 1973).

Near to homogeneously mixed conditions are encountered in the lower section of the bay during periods of strong tidal forcing and a fresh water input below 50m³/s. This is paired with a vertical salinity gradient between 2 and 4‰ in the middle and upper sections of the bay. A similar range in the vertical gradient was also observed for the study conducted during one and a half tidal cycles in the middle section of Paranaguá Bay (Fig. 9). Under conditions with a fresh water input greater than 90m³/s, the vertical salinity gradient may attain 8‰ (Fig. 8d). The surface mixed layer is not always well defined but varies in depth between 0,5 and 2,0m. It is most pronounced during periods of high rainfall in austral spring and summer.

The presence of a seasonal variation in salinity becomes clearly evident from figure 10, which depicts an annual cycle of surface isohalines between the mouth and the upper section of the bay. Lower surface values predominates in summer due to the increase in fresh water inflow. However, intra-annual variations may be marked due to irregular seasonal variability in precipitation. Knoppers & Opitz (1984) encountered exceptionally low surface salinity values during winter 1983 in the

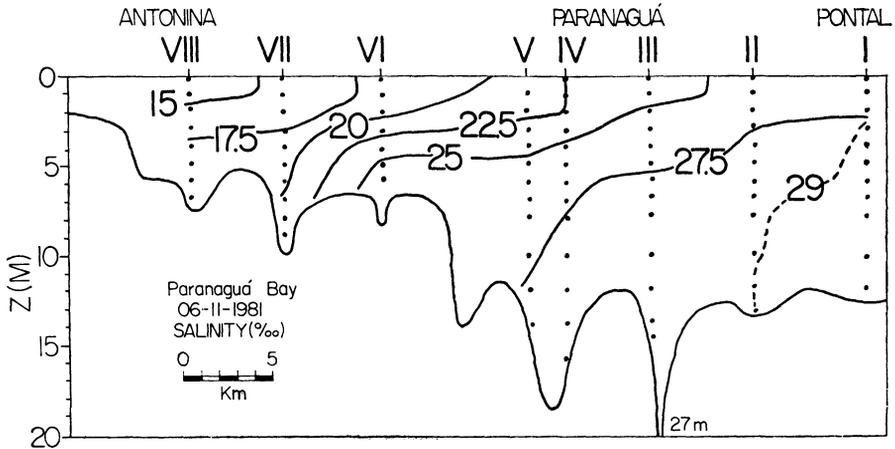


Fig. 8a. Vertical distribution of salinity at approximately slack water conditions for $Q = 60^3/s$.

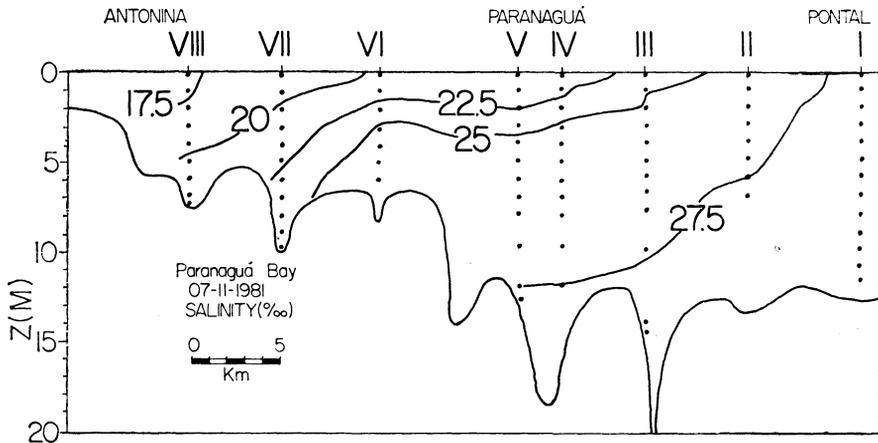


Fig. 8b. Vertical distribution of salinity at early flood flow for $Q = 60m^3/s$.

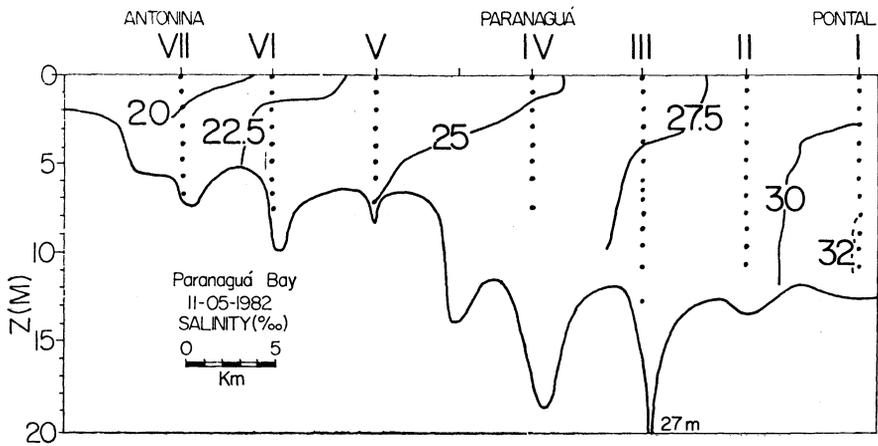


Fig. 8c. Vertical distribution of salinity at early flood flow for $Q = 40\text{m}^3/\text{s}$.

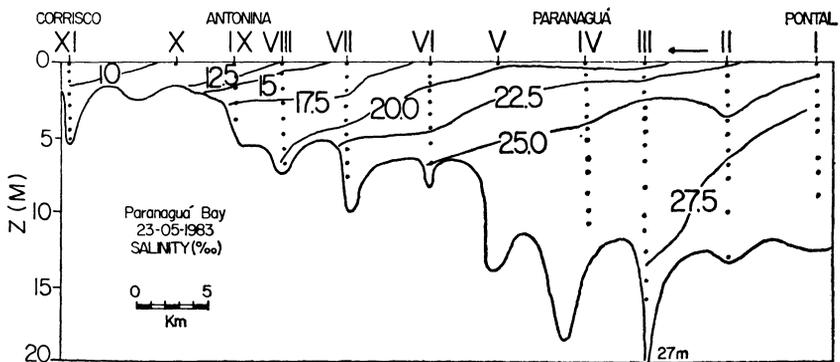


Fig. 8d. Vertical distribution of salinity at early flood flow for $Q = 90\text{m}^3/\text{s}$.

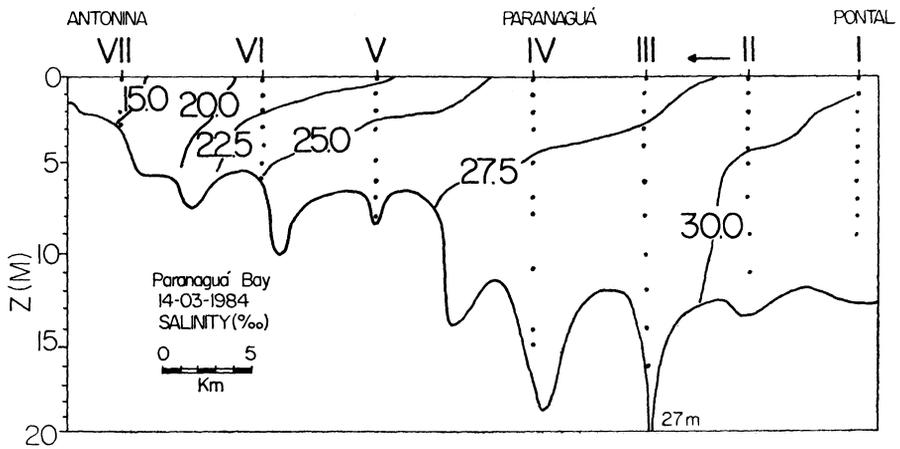


Fig. 8e. Vertical distribution of salinity at early flood flow for $Q = 50\text{m}^3/\text{s}$.

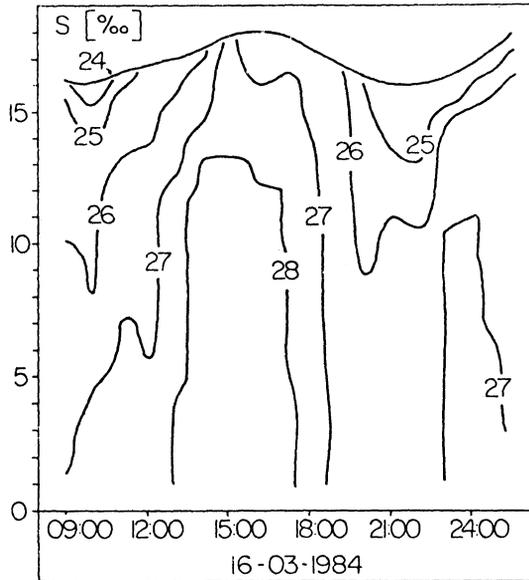


Fig. 9. Time-depth plot for salinity for the middle section of the bay.

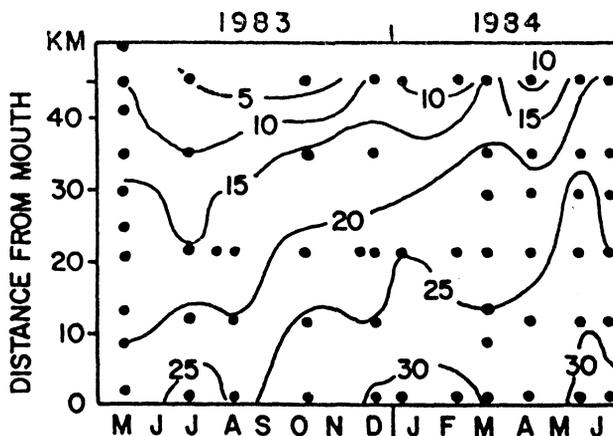


Fig. 10. An annual cycle of surface isohalines between the upper section and the mouth of the bay.

adjacent Bay of Laranjeiras. An annual cycle obtained by Sinque *et al.* (1982) revealed the presence of higher salinity values throughout the bay during winter because annual precipitation was lower in comparison to the present study period.

On the whole, water masses of higher densities prevail in winter than in summer. This is not only brought about by the seasonal variation in precipitation but also due to temperature as already described above.

Recently, sporadic shelf-break upwelling has been detected off Paranaguá Bay (Mesquita *et al.*, 1983; Brandini, 1986) its influence upon coastal watermass characteristics within the bay has not yet been detected, probably due to the lack of intensive time series studies. The importance of sub-surface inflow of higher density upwelled water in estuarine systems has been well documented for other areas (Blanton, 1981; Atkinson, 1982 and others cited therein). This process may, in addition to the fresh water source, furnish essential nutrients to primary production and also cause seeding of plankton resting spores and non-endemic species to the bay.

CLASSIFICATION

The most common classification schemes in use are based upon the pattern of distribution of salinity (Pritchard, 1952) and the type of salinity structure related to circulation as in the stratification circulation diagram (Hansen & Rattray, 1966). The former scheme tends to be more qualitative and is thus more suitable for the present results.

The salinity data presented beforehand portray Paranaguá Bay as a partially mixed Type B estuary with lateral inhomogeneity. However, on some occasions during short periods of extreme precipitation a strongly prevail due to short-term and seasonal variations in meteorological forcing.

The current speed and salinity results presented in Figures 4 and 9 respectively, obtained during a tidal cycle at a fixed station in the middle section of the bay, were computed in order to attempt a preliminary quantitative classification within the scheme of the stratification-circulation diagram. The average salinity difference between the bottom and the surface ($\bar{S}_b - \bar{S}_s$) was 2.4‰ and the watercolumn depth averaged ($z=16\text{m}$) salinity $\langle s \rangle$ was 26.9‰. The stratification parameter, i.e. the ratio between the former and the latter ($\bar{S}_b - \bar{S}_s / \langle s \rangle$), thus being 8.9×10^{-2} . The net surface velocity was computed at $v_s = 14.4 \text{ cm/s}$ and the watercolumn averaged flow at $\langle v_x \rangle = 1 \text{ cm/s}$. The circulation parameter v_s / v_x was in turn of 14.4. Henceforth, the dimensionless parameters yielded a classification in the 2nd category. This implies that the middle section of the bay portrayed a partially mixed estuary with net flow reversal at depth. At this stage, it must be borne in mind that the obtained result is merely a rough estimate because lateral measurements over the entire cross section of the bay were not conducted.

Nevertheless, the results coincide with the classification based upon the structure of salinity. Further time series studies during several tidal cycles under consideration of lateral variability should be conducted to substantiate the present classification.

FLUSHING TIME

An approximation of the flushing time is attempted for the middle section of Paranagua Bay with the "freshwater fraction method and the simple "tidal prism method" (Dyer, 1973; and others cited therein). The "modified tidal prism method" introduced by Ketchum (1951) may not be applied due to the lack of knowledge on the bathymetry and tidal regime in the upper reaches and, particularly, the head of the estuary. In contrast, these features are known for the middle section, for which it is also easier to conduct volume calculations as it closely resembles a triangular basin.

The flushing time T calculated via the "freshwater fraction method" expresses the relationship between Q , the amount of freshwater accumulated in the section, and R the river flow. Q can be obtained by multiplying the freshwater concentration "f" by the total water-volume of the section, and "f" is obtained from $f = \frac{S_s - S_n}{S_s}$, where S_s is the salinity of seawater (=34‰) and S_n the mean salinity of the section.

Henceforth, the flushing time T , evaluated for five occasions (see topic on salinity), varied between 13 and 24 days with values of R from 84 to 40 m³/s, respectively. Values of R represent two week means prior to the salinity measurements.

The "tidal prism method" assumes that the seawater and riverwater volume introduced correspond to the volume between the low tide and P the intertidal volume within the section during flood flow all seawater is mixed with estuarine water. The flushing time T in tidal cycles equals $V + P/P$, where V is the volume at low tide and P the intertidal volume within the section. This method harbours many uncertainties, particularly, in the presence of a mixed tidal wave and stratification. Both factors seem to be present in Paranagua Bay. However, the tide gauge utilized is situated within the middle section of the bay and calculations are conducted for situations with salinity gradients below 3‰, which represents the most common conditions in the area. The artefact introduced by incomplete mixing may be roughly corrected by multiplying the flushing time with the

ratio between the average depth of the section ($z= 4.4\text{m}$) and the average depth of the mixed layer, which in most cases oscillates around 1 m.

The flushing time T with a maximum and minimum tidal amplitude of 2 m and 0.5 m corrected for the tidal frequencies per day, were computed at 13.4 and 35 days, respectively. The flushing time evaluated for the mean tidal amplitude of a fortnightly tidal sequence amounted to 24 days. In all, the results obtained by the two independent methods coincided fairly well with each other.

CHEMICAL PROPERTIES

A practical first approach to understand the behaviour of dissolved inorganic nutrients in estuaries is given by plotting these properties against the salinity gradient. In positive estuaries where the fresh water source usually supplies more nutrients than the marine source, the property vs. salinity plots may reveal three basic mixing patterns: A negative linear relationship implies that properties introduced by the fresh water source are diluted upon their descent in the estuary in proportion to the mixing of fresh and salt water. This is denominated as conservative mixing. A negative concave upward plot shows that the estuary serves as a sink and a convex upward plot as a source for the properties. The two latter patterns are denominated as non-conservative mixing (Liss, 1976; Head, 1985).

A variety of physical, chemical, and biological processes are responsible for non-conservative behaviour of nutrients in estuaries. For example, evidence for the removal of orthophosphate and, to some extent also silicate by chemical precipitation within the lower salinity range (0-10‰) has been presented by Morris *et al.* (1981). Other abiological processes for the retainance of nutrients in an estuary are the adsorption onto suspended matter, particularly within the regions of turbidity maxima (Lis, 1976; Biggs *et al.*, 1982), and flocculation of inorganic with organic matter during mixing of fresh and salt-water (SHOLKOVITZ, 1976). Biological removal of inorganic nutrients is brought about via uptake by primary producers and libera-

tion via biological decomposition (Wollast, 1975; Sharp *et al.*, 1982).

In the present study, the behaviour of the properties are only presented for the salinity range between about 10 and 34‰ as nutrient data related to the fresh water source and the head of the estuary were not obtained. No extrapolation from the plots to estimate the nutrient concentrations in the fresh water source is attempted, due to the possibility of nutrient removal within the salinity range below 10‰ by the above mentioned processes, and also because the numerous fresh water sources spiked at the upper section of the estuary are assumed to vary in their quantitative and qualitative input of nutrients.

Dissolved oxygen — In general, the bay exhibited only minor deviations of D.O. concentrations to levels of saturation. However, particularly during austral summer cruises, the middle section of the bay served as a source to D.O.. Super saturation attained 120%. This was probably the result of enhanced autotrophic activity. Brandini (1985a) has shown that the middle section of the bay exhibits the highest primary production rates within the entire estuary.

Silicate — Throughout the estuary, silicate demonstrated more or less a conservative mixing (Fig. 11). A minor sink was however detected on two occasions in the lower estuarine region within the salinity range between 27 and 33‰. A clear seasonal variation in the behaviour of silicate, as detected in temperate estuaries (Simpson *et al.*, 1975; Peterson, 1979; Sharp *et al.*, 1982) and tropical estuaries (Van Bennekom *et al.*, 1978) could not be detected, probably due to the low sampling frequency of silicate in this study. Temporal variations in the behaviour of silicate are however expected, as phytoplankton blooms consisting of diatoms have been detected (Brandini, 1985b).

Orthophosphate — The composite plot of orthophosphate and salinity is depicted in Figure 12. A tendency towards a negative convex upwards plot for most sampling occasions becomes evident. Highest concentrations, with $1 \mu\text{mol. dm}^3$ of $\text{PO}_4\text{-P}$, were encountered within the middle section of the bay. This section thus seems to represent a source to orthophos-

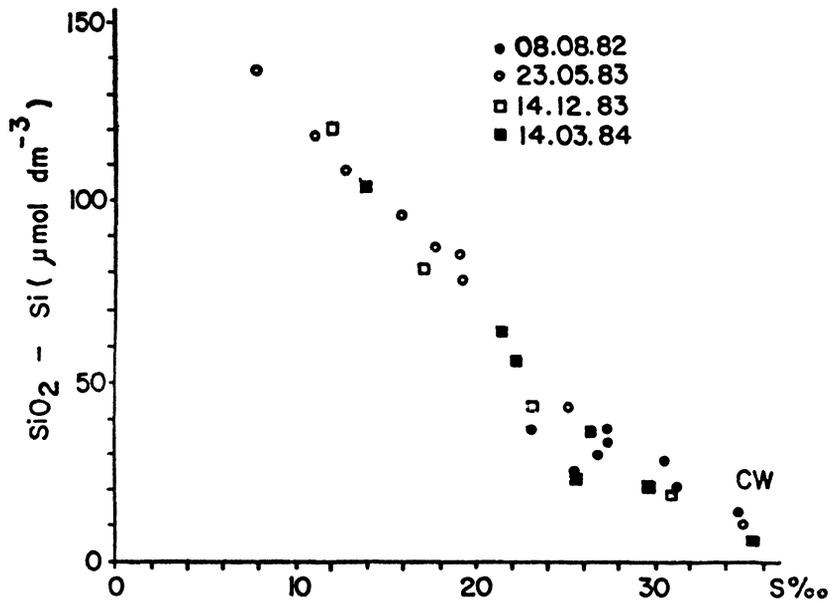


Fig. 11. Composite plot of salinity vs. silicate.

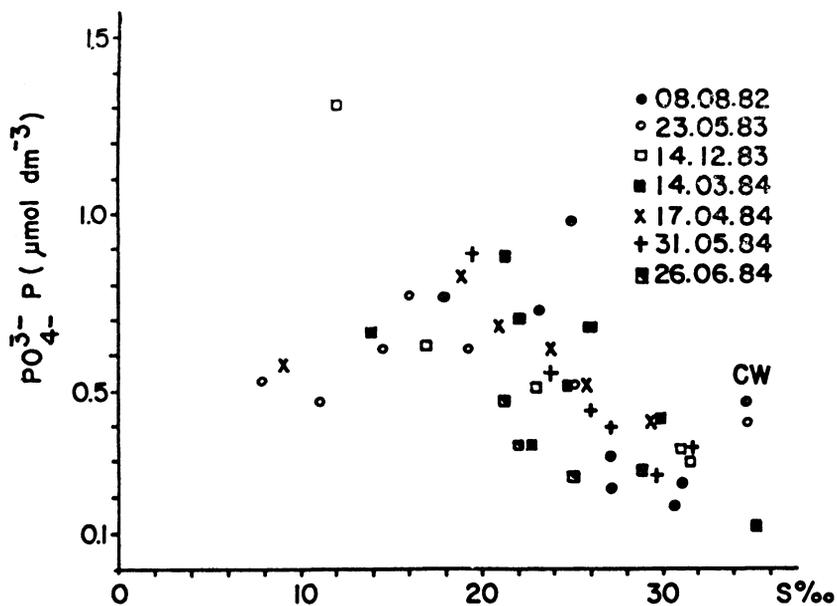


Fig. 12. Composite plot of salinity vs. orthophosphate.

phate. Non-conservative behaviour of orthophosphate in estuaries has earlier been reported by Liss (1976), Morris *et al.*, (1981) and Sharp *et al.* (1982), who attributed the phenomena to a "phosphate buffering system" brought about by the exchange between particulate and dissolved phases. In this study, the origin of excess orthophosphate in the middle section of the bay is attributed to the input of domestic discharge via the river Itibere from the harbour city of Paranaguá. Highest concentrations were always recorded in the vicinity of the river plume close to the harbours.

Nitrate and nitrite — On most occasions, these properties behaved in a non-conservative manner (Fig. 13). The middle section of the bay represented a moderate sink to nitrate. Concentrations varied considerably over time, the non-conservative behaviour of nitrate may be attributed to biological uptake and the temporal variations in concentrations also to changes in riverine input. On one occasion (23.05.83), a near to conservative behaviour under conditions of high fresh water inflow and marked water column stratification, was detected. The upper and, to a certain extent, also the middle section of the bay represented even a slight source to nitrate, which may be attributed to enhanced lateral riverine input. Low residence times of surface water, caused by strong outflow and maybe also marked turbulence, must have suppressed biological uptake of nitrate during these occasions.

In general, nitrate concentrations within the upper section of the bay (S ‰ 10-18), i.e. in the region prior to the area of the maximum nitrate sink, did rarely exceed $10 \mu\text{mol dm}^{-3}$. This suggests that nitrate is introduced into the estuary at relatively low concentrations and should thus not be regarded as a critical factor enhancing eutrophication. This is surprising as higher input levels were expected due to the presence of acute deforestation in the upper drainage system (Bigarella, 1978). A clear pattern of nitrate behaviour in not-polluted estuaries as is generally found for orthophosphate, i.e. in terms of the phosphate buffering system, does not seem to persist. Each estuary exhibits its specific behaviour in nitrate. Both conservative and non-conservative behaviour has been observed in tropical and

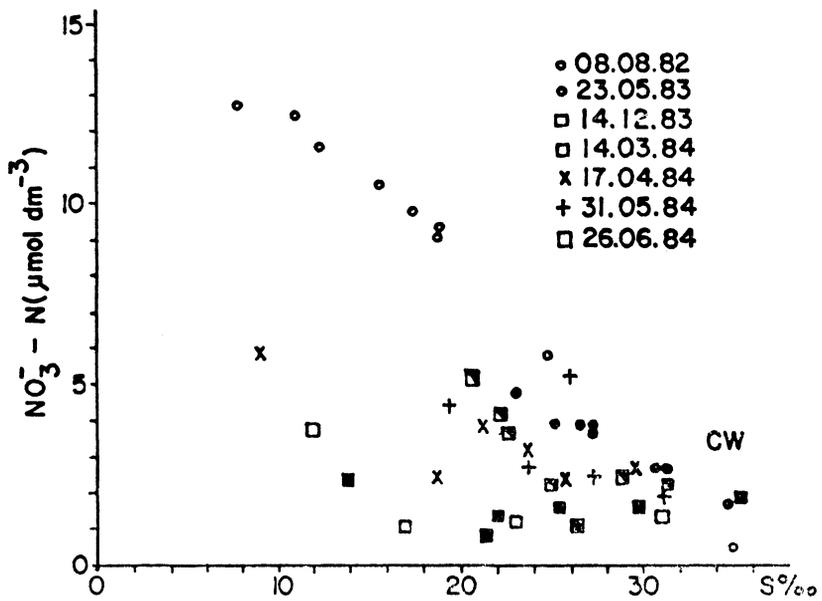


Fig. 13. Composite plot of salinity vs. nitrate.

temperate estuaries (De Souza *et al.*, 1981; Morris *et al.*, 1981; Sharp *et al.*, 1982; Tanning & Maynard, 1978; Van Bennekom *et al.*, 1978). Thus, nitrate seems to be the nutrient that is best suited to characterize differences in estuarine functioning as its behaviour is most sensitive to changes in both the physical regime and biological processes.

Ammonia — Information on the behaviour of ammonia in Paranaguá Bay is scarce (Fig. 14). However, its contribution to the dissolved inorganic nitrogen pool seems to attain near to equal proportions as nitrate. On some occasions, ammonia was clearly retained within the middle section of the bay and on other occasions (15.07.83 and 21.10.83) concentrations remained stable irrespective of the salinity gradient. The latter pattern resembled the behaviour of phosphate in other estuaries (Liss, 1976).

Ammonia in Paranaguá Bay should be regarded as important as nitrate for the sustenance of primary production. Its origin is difficult to assess due to the scarcity of data. Unpublished data on the vertical distribution of ammonia indicated that concentrations at the bottom were up to 30% higher than at the surface, particularly within the middle section of the bay, which suggest that the sediments are an important source. No direct evidence may be given that lateral input from domestic discharge of the City of Paranaguá via the Itibere river prevailed.

CONCLUSIONS

1. The mean annual fresh water input to Paranaguá Bay was estimated at approximately 75 m³/s.

2. The study area was characterized according to its pattern of stratification as a Type B estuary and, based upon preliminary results, according to the stratification-circulation diagram (Hansen & Rattray, 1966) as a 2a estuary. Under conditions above a mean fresh water input of about 75 m³/s strongly stratified conditions may sporadically prevail. The estuary is characterized by regional differences in stratification, the lower section of the bay exhibits a near to homogeneous water

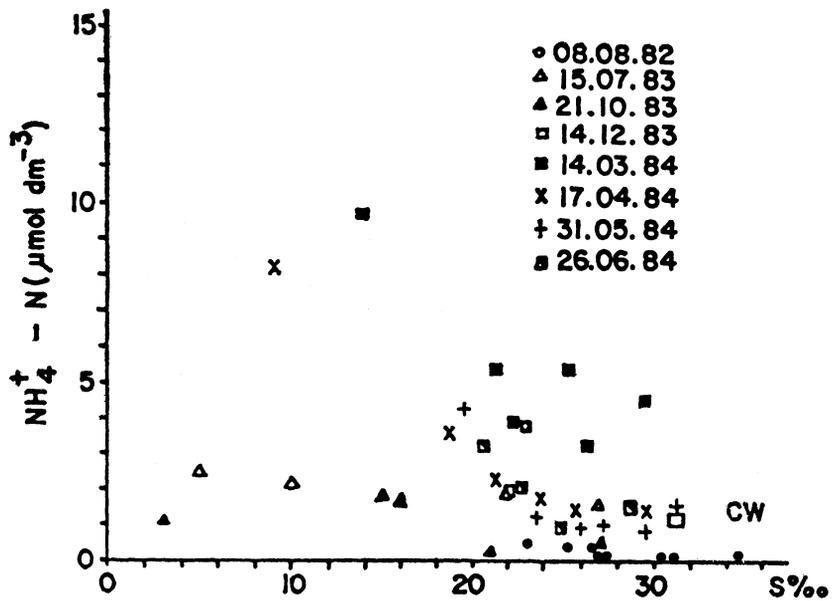


Fig. 14. Composite plot of salinity vs. ammonia.

column at conditions of fresh water inflow below 40 m³/s. The middle section of the bay was characterized by lateral inhomogeneity.

3. Flushing times of the middle section of the bay, estimated by the "fresh water fraction method", varied between 13 and 24 days. Estimations conducted by the "simple tidal prism method" corrected for the magnitude of the surface mixed layer and in accordance to the variation of the tidal regime yielded a similar range of the flushing times as above. An estimation of the flushing time by the more appropriate "modified tidal prism method" was not feasible due to the lack of basic information on the bathymetry and the tidal regime of the uppermost region of the bay and the extension of the tidal river.

4. Substantial studies on the pattern of circulation and water exchange in the bay are still lacking. Future studies on the water exchange in Paranaguá Bay should be conducted at the cross-sectional area between the lower and the middle section of the bay as the northern and southern tidal inlets at the mouth of the estuary are subject to water exchange from both Paranaguá and Laranjeiras Bays. The pattern of circulation within the lower section of the Paranaguá estuary is highly complex due to the interaction of water masses which originate from the bays of Paranaguá or Laranjeiras but should be regarded as a specific functioning physical unit between the sea and both bays.

5. Spatial and temporal variations in the behaviour of dissolved inorganic nutrients characterized the bay. with the exception of the element silicate, all properties exhibited a non-conservative behaviour under mean fresh water inflow rates. The middle section of Paranaguá bay served as the main sink to nitrate and ammonia and as a source to orthophosphate and dissolved oxygen. The excess in orthophosphate has most likely its origin via domestic discharge from the City of Paranaguá and supersaturation of dissolved oxygen from autotrophic activity. Conservative behaviour of most properties was sporadically detected under conditions of extreme high fresh water inflow and strong stratification. Under such conditions resi

dence times of surface waters were probably too low to enable a substantial biological uptake of nutrients.

6. The concentrations and the behaviour of dissolved inorganic nutrients in Paranaguá Bay revealed that minor cultural eutrophication exists due to activities of the City of Paranaguá. Excess input of nutrient properties due to acute deforestation into the upper section of the bay was not evident. However, Brandini (1985a) detected significant rates in primary production and phytoplankton biomass levels in terms of chlorophyll *a* in this area, resembling mesotrophic to eutrophic conditions. In order to obtain a better understanding of the physical and chemical characteristics of the bay, a profound assessment of the fresh water sources, the head and of the upper section of the bay should be conducted in the future.

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