SEASONAL CHEMICAL CHANGES AND EUTROPHICATION OF A LAND-LOCKED COASTAL LAGOON (ST. ANDRÉ, SW PORTUGAL)

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With 7 figures and 1 table

ABSTRACT. Coastal lagoons are important reservoirs of continental material where, as a rule, exceptional conditions of primary production prevail. This exceptional primary production may itself disrupt these ecosystems, leading to dystrophic phenomena. Part of the accumulated allochthonous and autochthonous material is exported from lagoon to the sea, from which an important biological component is imported in return. It is known that interactions between sea and lagoon environments are of major importance to lagoonal biogeochemical and ecological cycles. St. André is an enclosed coastal lagoon, connected to the sea only for short periods of time (March/April) through a man-made channel. According to the magnitude of episodic freshwater and seawater inputs in winter, anoxic conditions in the stagnant bottom water may develop. High concentrations of nutrients, dissolved iron and dissolved manganese were measured in this water layer. It was found that the opening of the lagoon to the sea causes chemical modifications in the lagoon. Such changes appear to be related to hydrological and meteorological conditions over winter. As nutrients and other degradation products from the bottom are prevented from recycling within the lagoon, near-bottom reduced conditions may cause considerable damage, especially by eutrophication. Due to the strong reducing near-bottom conditions in 1986, sea-lagoon exchanges caused sharp chemical changes which in turn led to abnormal fish mortality in the lagoon.

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KEY WORDS: Coastal lagoon, nutrients, sediments, eutrophication, iron, fish mortality.

RESUMO. As lagoas costeiras são importantes receptáculos de material continental, sendo propícias a condições excepcionais de produção primária. Por outro lado, a intensa produtividade primária pode levar à ruptura destes ecossistemas, implicando fenómenos de distrofia. O material alóctono e autóctono acumulado nestas lagunas é, em parte, exportado para o mar e, por sua vez, uma parte relevante da respectiva componente biológica é importada da zona costeira. Vários estudos têm mostrado a grande importância das interacções entre os ambientes marinho e lagunar no que respeita aos ciclos biogeoquímicos e ecológicos lagunares. A lagoa de St.º André é uma lagoa costeira fechada em que geralmente a ligação com o mar apenas se estabelece por curtos períodos (Março/Abril) através da abertura de um canal artificial. Em virtude das quantidades de água doce e de água salgada que recebe durante o Inverno, e da consequente estratificação da coluna de água podem desenvolver-se condições de anóxia na água estagnada junto ao fundo, na qual se obtiveram concentrações elevadas de nutrientes, ferro e manganês dissolvidos. Foi verificado que a abertura da lagoa ao mar conduz a alterações químicas, as quais parecem estar relacionadas com as condições hidrológicas e meteorológicas prevalecentes ao longo do Inverno. A dificuldade na reciclagem dos nutrientes e de outros compostos de degradação com origem no fundo da laguna, é provavelmente devida a condições redutoras que se desenvolvem junto ao fundo podendo, em casos extremos, levar à eutrofização. As trocas mar-laguna que ocorreram em 1986, quando se registaram condições fortemente redutoras junto ao fundo, provocaram alterações químicas abruptas e uma mortalidade anormal de peixes nesta lagoa costeira.

PALAVRAS-CHAVE: Lagoa costeira, nutrientes, sedimentos, eutrofização, ferro, mortalidade de peixes.

INTRODUCTION

The ecology of coastal lagoons is determined to a large extent by freshwater inputs and the mixing and circulation processes with the adjacent sea (POSTMA, 1981). In shallow environments, such as in land-locked lagoons, nutrient cycling is strongly influenced by internal processes such as sediment-water exchanges (LOEFF *et al.*, 1981; MARTENS, 1982), pelagic-benthic biota (NIXON, 1980; NOWICKI & NIXON, 1985) and light-dark cycling (ESCARAVAGE, 1990). Episodic inputs of freshwater and seawater to enclosed lagoons tend to create vertical density stratification in the absence of strong mixing forces. This may promote the development of temporary anoxic conditions near the bottom, reflecting respiratory processes occurring in the sediment (SMETHIE, 1987).

Small rivers running towards the south-western coast of Portugal do not always reach the sea. Their discharge to the ocean is prevented by active beach-ridges, forcing their water to accumulate in small coastal lagoons. St. André (SW Portugal, with an area of 150 ha and an annual average depth of 1.8 meters) is one of these enclosed systems, except in late winter/early spring, when an inlet channel is artificially opened (Fig. 1). This exchange of water with the open sea is maintained for some weeks (usually 2-6 weeks), until tidal currents are no longer capable of destroying any incident barriers of sand created by wave action. The marine renewal and the maintenance of brackish characteristics are essential to the secondary productivity of the system (CANCELA DA FONSECA *et al.*, 1987a; CANCELA DA FONSECA, 1989; BERNARDO, 1990). As for most coastal lagoons, St. André lagoon is characterized by high vegetal biomass (mainly macrophytes) and by bottom sediments with high organic content (CANCELA DA FONSECA *et al.*, 1987b; CANCELA DA FONSECA, 1989). Ecological changes in summer generally referred to as dystrophic crises, have been observed (BERNARDO *et al.*, 1988).

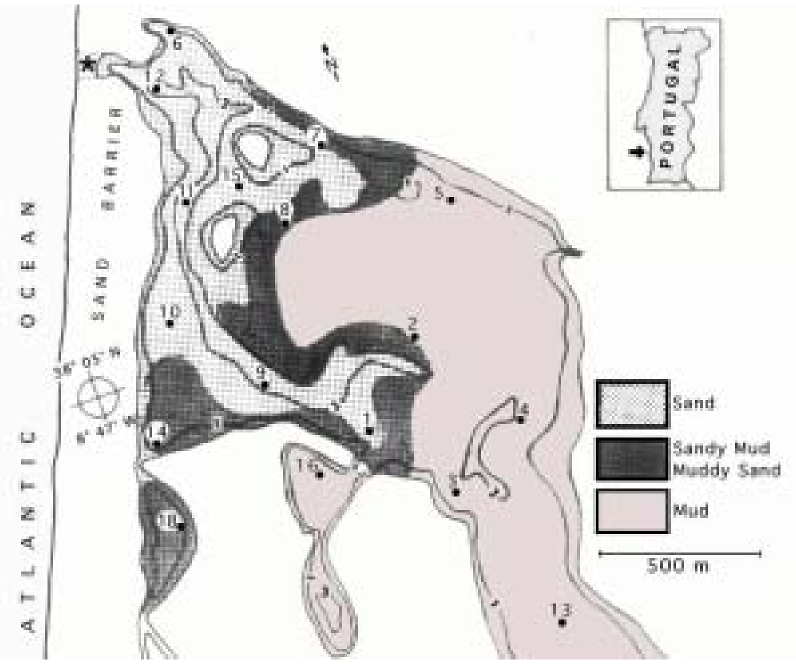

Fig. 1 - The St. André lagoon: bathymetry and sediment distribution. Monthly sampling stations (•) and April 1986 tidal cycle station (*) are indicated.

St. André is a sedimentation basin of mineral and organic terrestrial material, as is the rule in coastal lagoons. Also, significant macrophyte blooms develop each year in the inner lagoonal areas (CANCELA DA FONSECA, 1989). Both these materials promote and accelerate the organic enrichment of the sediment (CANCELA DA FONSECA *et al.*, 1987a and 1987b), endowing complex metabolic processes related to the recycling of nutrients. Decomposition of the bulk of settled organic material supplies nutrients to the lagoon, and very high nutrient concentrations are observed in the interstitial waters of the sediments (BERNARDO, 1990). Oxygen depletion in the sediment and overlying waters further enhances the nutrient release from the sediments (CANCELA DA FONSECA, 1989) thus increasing the eutrophication process. This paper describes the seasonal variation of water chemical characteristics at St. André lagoon over a two-year period, and reports on the sharp chemical modifications occurring during a brief opening of the beach ridge.

METHODS

The following surveys were carried out at St. André lagoon: (i) surface and bottom waters were collected monthly, from March 1984 to May 1986, at 17 stations distributed throughout the lagoon; (ii) inlet channel water was sampled hourly, over a 13-hour period in 4-5 April 1986; (iii) surface, bottom and pore waters were sampled, in March 1987, at stations 8, 9, 11 12 and 16.

Temperature, salinity, dissolved oxygen and pH were measured *in situ*. For chemical analyses water was collected with a 3-liter Van Dorn sampler. Turbidity was measured in the laboratory with a turbidimeter. Chlorophyll *a* and phaeopigments were determined spectrophotometrically in the filtered material obtained on Whatman GF/C filters, after extraction with 90% acetone in cool and dark conditions (LORENZEN, 1967). Analyses of nutrients were carried out in unfiltered water samples following the standard procedures described by STRICKLAND & PARSONS (1972) for phosphate, nitrate, nitrite and silicate, and by GRASSHOFF (1976) for ammonium. Nutrients of the March 1987 survey were determined on a Technicon Auto-Analyser. Pore water from the top sediment layer (0.5 cm) was separated by centrifugation and filtration (0.45 µm). Total dissolved iron and manganese were analyzed by direct atomic absorption spectrometry in filtered samples, previously acidified (pH = 2) and kept in nitrogen atmosphere.

In order to summarize the information, Principal Component Analysis (PCA) was utilized on the values of the physical-chemical water parameters for each sampling point. Data analysis was performed at Laboratório Marítimo da Guia (Tektronix 6130 Workstation), using programs by ANDRADE (1986).

RESULTS

Seasonal variation of salinity

Freshwater and seawater inputs occur mainly in winter and early spring. Monthly variations of salinity at the surface and on the bottom in the deepest zone of the lagoon (station 11) reflect the frequency and intensity of these inputs (Fig. 2). Lower salinities were observed in winter (February) when rainfall was higher. Salinities of 35‰ were recorded in March/April 1985 and in April/May 1986, due to the exchange of water with the sea. From the closure of the lagoon in April 1985 until late autumn, salinities at the surface and the bottom were similar, decreasing progressively with time from 35‰ to 15‰. In late autumn and winter, increases of both freshwater and seawater inputs resulted in a decrease of salinity near the surface (5‰), and in an increase near the bottom (25‰). Vertical density heterogeneity is then developed. Such stratification was observed throughout the lagoon in April 1986 (Fig. 3).

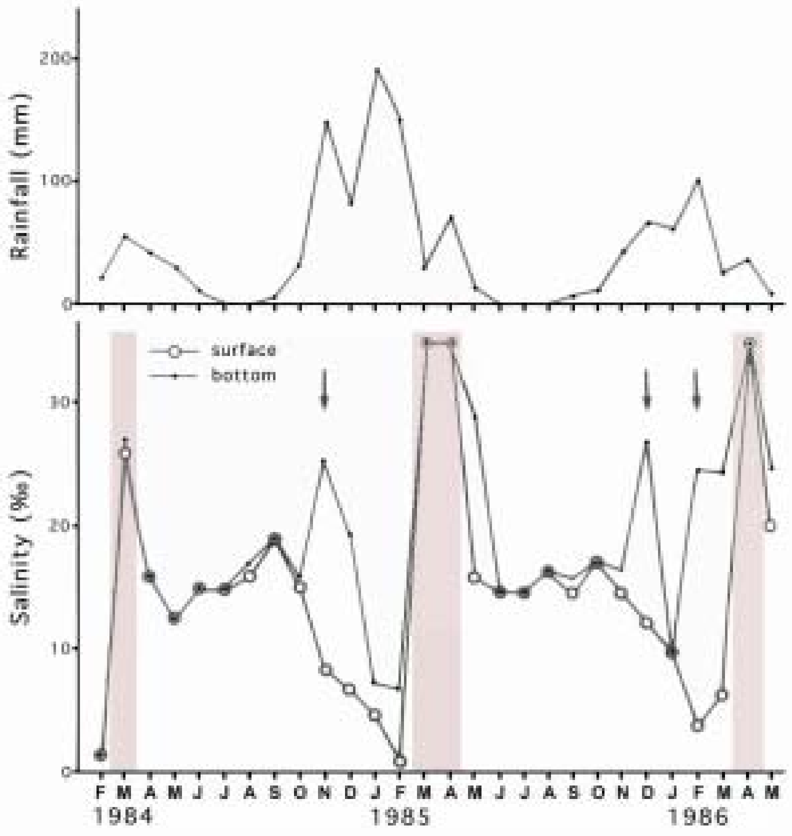

Fig. 2 - Salinity variation at station 11 (surface and bottom). Bars indicate sea connection periods and arrows indicate where seawater washes over the sand barrier. Monthly mean precipitation is also plotted.

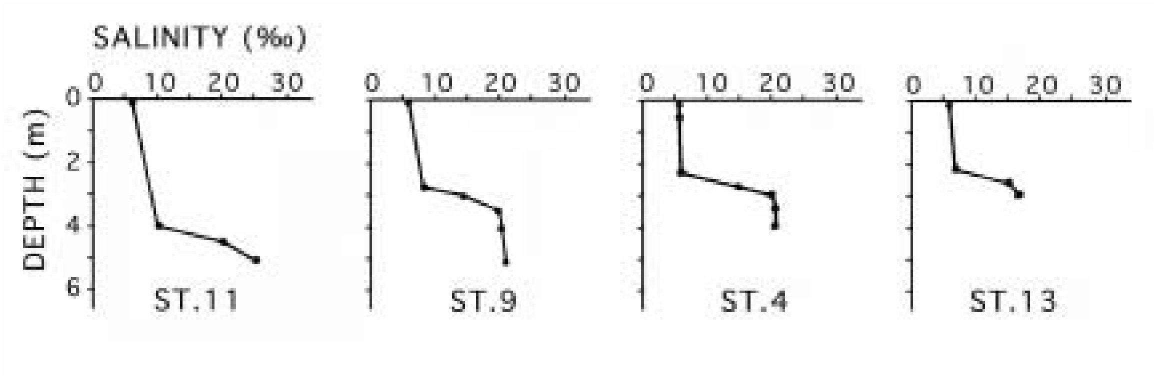

Fig. 3 - Vertical salinity profiles before the 1986 opening process (86/04/02).

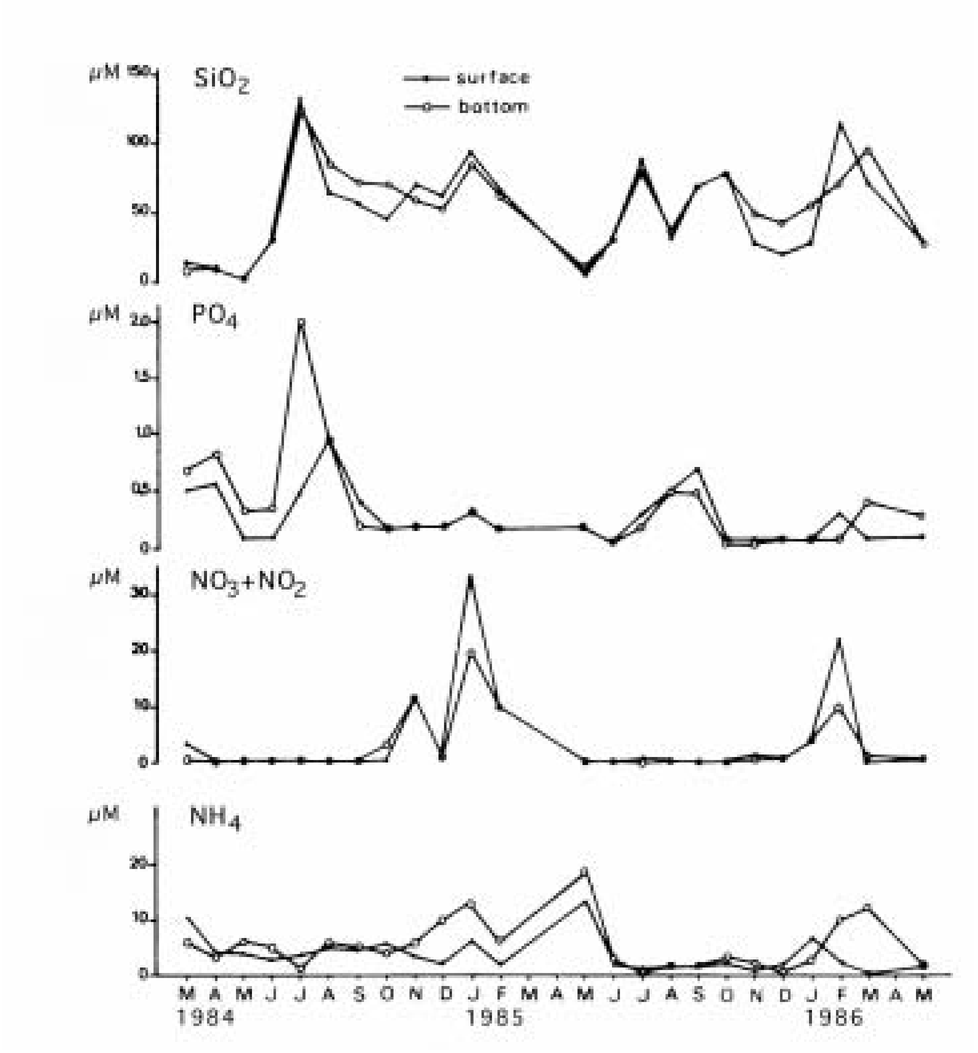

Fig. 4 - Surface and bottom monthly average values (17 stations) of silicates, phosphates, nitrate + nitrite and ammonium (μM).

Seasonal variation of nutrients

The mean concentrations (17 stations) of nitrates + nitrites, ammonium, silicates and phosphates, from March 1984 to May 1986, are shown in Fig. 4. A broad range of values were found: PO_4 from 0.1 to 2.1 µM, SiO_2 from 1 to 133 µM, NH_4 from 1 to 18 µM and NO_3 + NO_2 from 0,1 to 33 µM. Seasonal peaks may be discerned for all the parameters. Sharp increases of NO_3 + NO_2 were observed particularly at the surface during the periods of high precipitation. Though enhanced values of SiO_2 occurred during the rainy season, similar high values were also recorded in summer. In contrast sharp increases of PO_4 occurred only during the summer, particularly in July 1984 in the bottom waters. This indicates that run-off led to an increase in NO_3, while the sediment appears to be the major source of PO_4. For SiO_2 both external and internal sources produced seasonal peaks. The mean concentration of NH_4 also displayed a seasonal variation: higher values being recorded in winter and spring.

The near-bottom gradients of nutrients (NH_4, NO_2, NO_3, PO_4, SiO_2), dissolved oxygen, dissolved iron and dissolved manganese, developed in March 1987 under conditions of strong salinity gradient at station 11, are presented in Fig. 5. The low oxygenated near-bottom water is enriched with PO_4, NH_4, dissolved SiO_2, dissolved Fe and dissolved Mn, stressing the importance of the sediment as an internal nutrient source.

Inter-annual variation of the lagoon winter characteristics

The density stratification occurring in late autumn and winter in the lagoon, varied from year to year. In February 1985, salinity varied within a narrow range, from 1‰ at the surface to 7‰ at the bottom. In March 1986, salinity reached 25‰ in the deepest zone, in contrast with a 6‰ near the surface (Fig. 2). These inter-annual differences reflect different freshwater-seawater inputs from year to year and may lead to modifications of the nutrient concentrations.

Principal component analysis (PCA) was used to describe the variability of water chemical characteristics found in February 1985, March 1986 and March 1987, *i. e.*, the pre-opening periods. The results of this multivariate method of analysis are presented in Fig. 6. Surface and bottom samples of all the surveyed stations correspond to a point on the plots. A general pattern may be discerned from these plots: surface samples remained closely associated, while bottom samples are spread along axis I. In 1985, a group including surface and shallow-bottom samples was close to that embracing deeper bottom samples. However, in 1986, the distance between positions of these groups was greater, and another group, corresponding to intermediate depth-bottom samples, can be discerned.

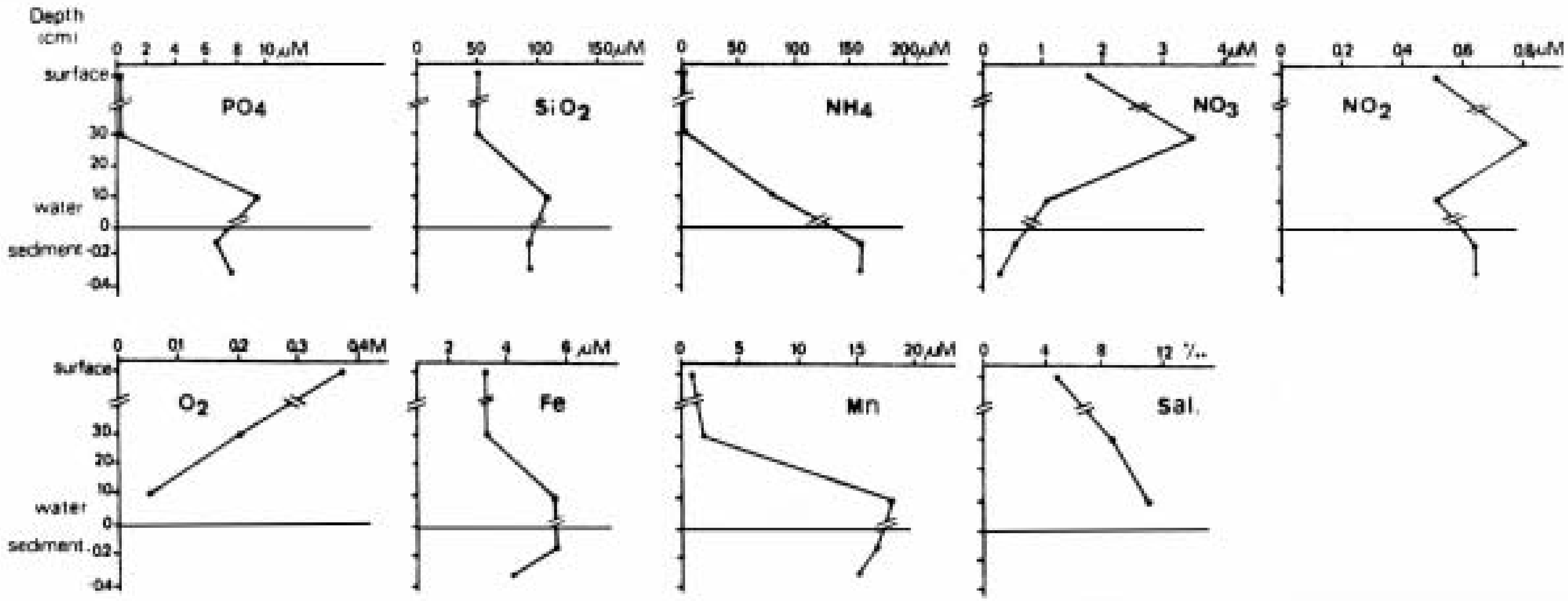

Fig. 5 - March 1987 vertical profiles of phosphates, silicates, ammonium, nitrate, nitrite, dissolved oxygen, iron, manganese (µM) and salinity (‰) at station 11.

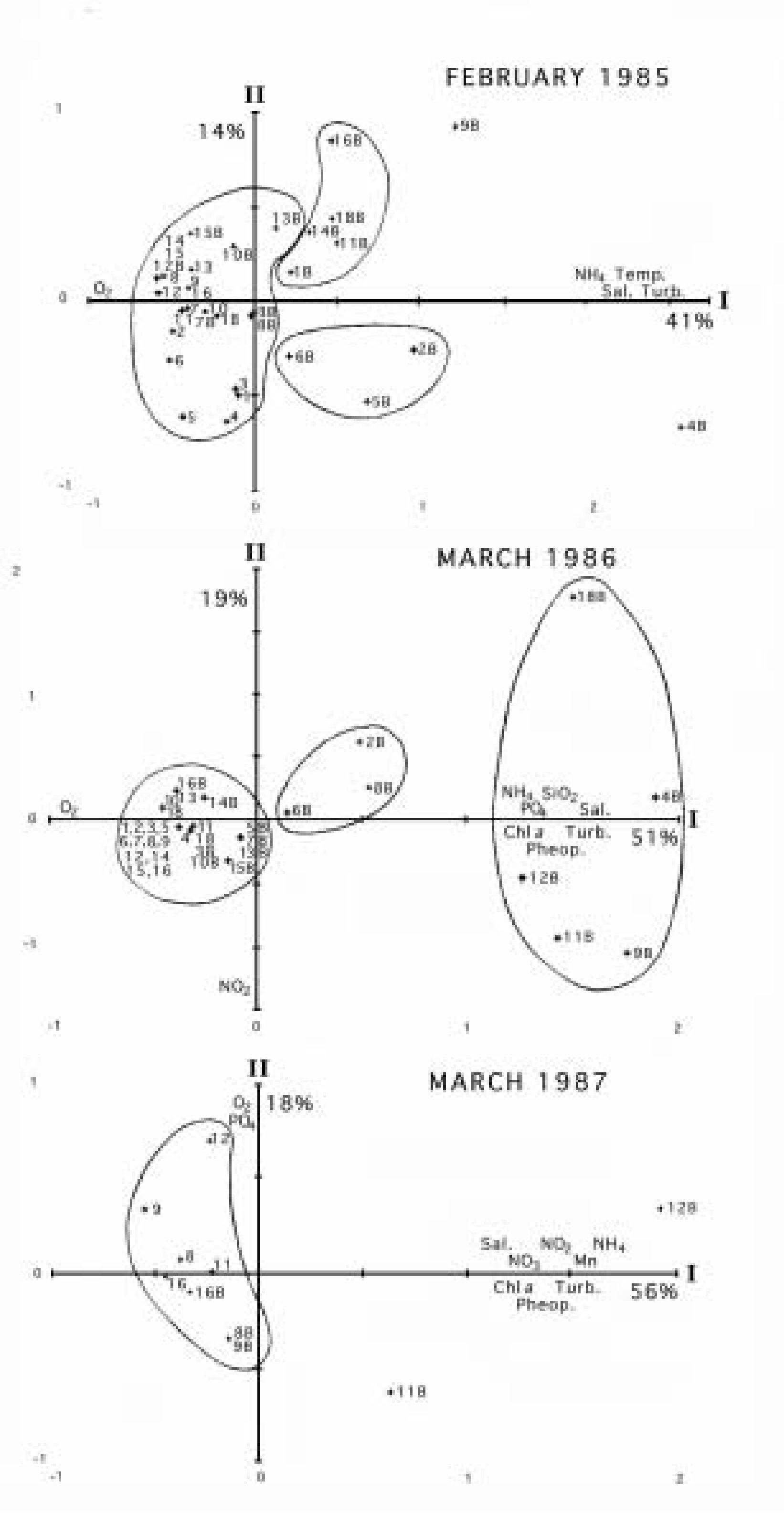

Fig. 6 - Principal component analysis for surface and bottom (B) water characteristics: (February 1985; March 1986; March 1987).

Different associations between parameters also can de discerned. While in 1985 and 1986, O_2 was the major contributor to the negative part of axis I, in 1987 this negative axis I was defined by opposition to the major contributors to its positive side. Only NH_4, Salinity, and Turbidity contributed constantly to the definition of the positive axis I. In February 1985, temperature was the other major contributor to this axis, while PO_4, SiO_2, and phytopigments (Chlorophyll *a* and Phaeopigments) in 1986, and NO_2, NO_3, Mn and phytopigments in 1987, were the new major contributors to the positive axis I.

Thus, multivariate analysis emphasizes the different characteristics between upper layer waters and the stagnant water stored in deep locations. In March 1986, water characteristics were different from the other pre-opening periods: the stronger vertical stratification conditioned the influence of the sediment-water exchange and consequently the composition of the bottom stagnant water.

Based on the PCA, lagoon water in March 1986 may be divided in four layers and their average composition estimated (Table 1): surface water and three groups of bottom waters with depth varying from 2.5 to 3 meters, 3 to 3.5 m and deeper than 3.5 m. The first two groups showed similar chemical characteristics, meaning that nutrients in the shallow areas of the lagoon (depth < 3 m) tend to be uniform. As water depth increases, dissolved oxygen decreased while salinity, nutrients, turbidity, chlorophyll *a* and pheopigments increased. The increments were particularly sharp for ammonium (3.5 µM) and phosphates (0.37 µM). Water remaining below 3.5 m depth contained low oxygen (< 38 µM) and was extremely nutrient rich, mainly with ammonium (42 µM) and phosphates (1.27 µM). These values are two orders of magnitude above those found in the upper layer. Standard deviations increase with depth, probably resulting from the spatial variability of sediment-water exchanges. This in turn may be due to the variation in organic matter content and grain-size distribution of the sediments (CANCELA DA FONSECA *et al*., 1987b).

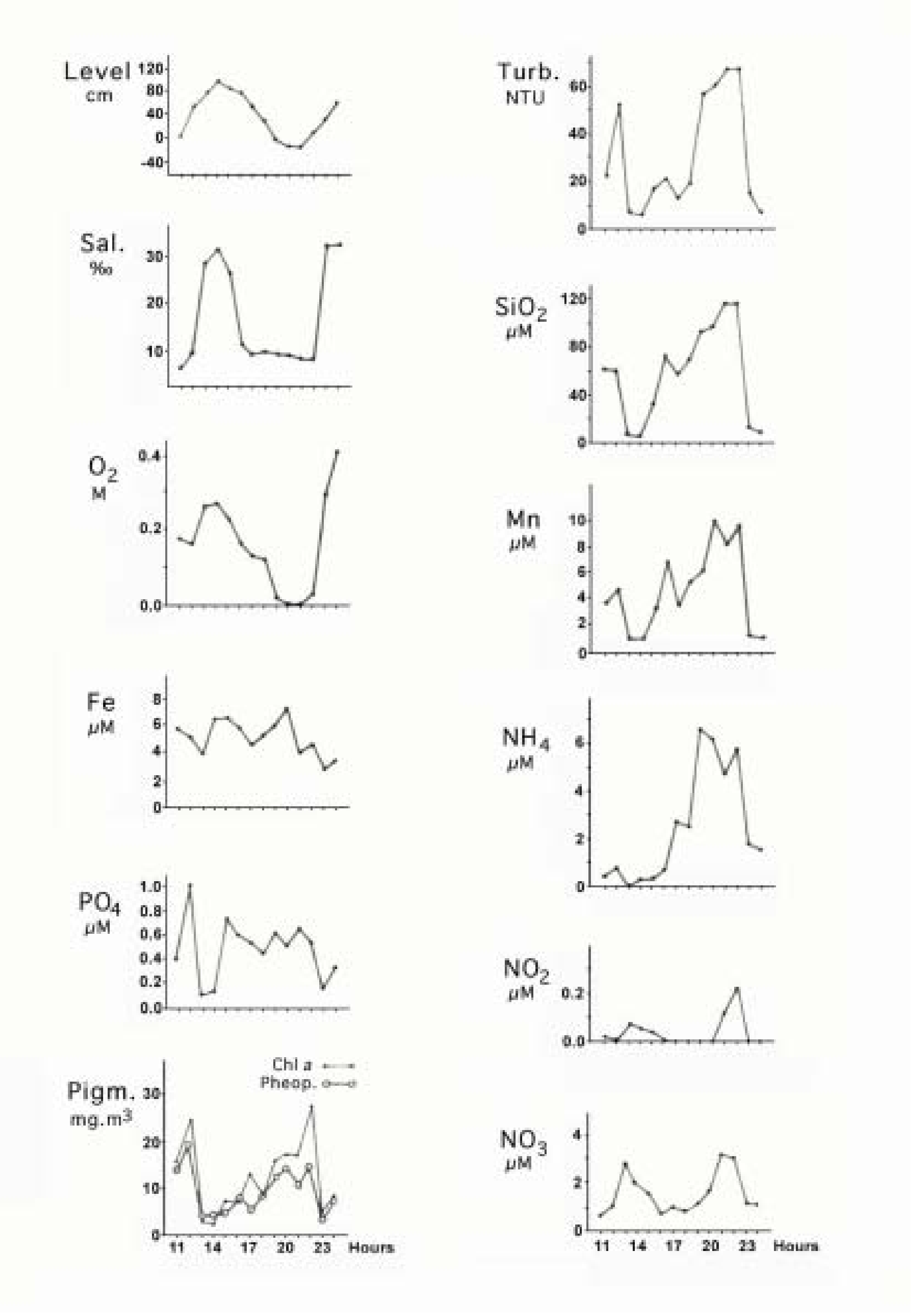

Fig. 7 - Tidal cycle variations of water characteristics at tidal cycle station (*) in April 1986.

TABLE 1 - Mean values and standard deviation of salinity (‰), O_2 (µM), T (°C), ph, Turbidity (NTU), Chlorophyll *a*, Pheopigments (µg. l^{-1}), NO_3^-, NO_2^-, NH_4^+, SiO_2, PO_4^{2-} (µM) of surface (< 0.2 m) and three bottom water layers (2.5-3; 3-3.5 and > 3.5 m). Number of samples were 17, 8, 4, and 5, respectively, collected in 2 April 86.

Depth	S‰	O_2 µM	T (°C)	pH	Turb NTU	Chl a µg L^{-1}	Phaeo µg L^{-1}	NO_3 µM	NO_2 µM	NH_4 µM	SiO_2 µM	PO_4 µM
< 0.2 m	6.4±0.2	278±16	16±0.5	8.1±0.2	4.5±1.0	4.1±2.2	2.0±1.4	0.2±0.1	0.04±0.05	0.44±0.14	72±6	0.07±0.07
2.5-3 m	11.7±5.3	260±28	16±0.2	8.0±0.7	5.0±1.0	4.6±1.8	2.4±1.4	0.3±0.1	0.04±0.06	0.45±0.25	70±8	0.07±0.09
3-3.5 m	19.3±1.3	209±56	16±0.0	8.2±0.1	22±17	11±5.5	14±8.9	0.5±0.2	0.07±0.14	3.5±2.7	91±12	0.37±0.25
> 3.5 m	24.4±5.6	38±31	15±1.1	7.4±0.6	29±28	15±20	27±34	1.4±1.5	0.06±0.13	42±18	154±50	1.27±1.11

A tidal cycle survey in the inlet channel

On 4th April 1986 the sand barrier channel was opened and for a 20 hours period, lagoon water was continuously discharged. Based on water level variation and bathymetry a water discharge of 4.85 x 106 m^3 (87% of the initial volume) was estimated. Subsequently, the sea-lagoon exchanges were driven by the tide and were surveyed over a 13-hour period (Fig. 7). At the beginning, influxed water showed low salinity (6-10‰) and high silicates (62 µM), phosphates (0.4-1.0 µM), turbidity (22-50 NTU), chlorophyll *a* (13 µg. l^{-1}) and pheopigments (15 µg. l^{-1}). Salinity values indicate the return of the lagoonal water (*e. g.* Table 1). Based on salinity and water level, the return of 0.35 x 106 m^3 water was estimated. At the third hour of the survey, salinity increased to 32‰, dissolved oxygen reached saturated values and turbidity, chlorophyll *a*, phaeopigments, phosphates and silicates decreased sharply (Fig. 7). This corresponds to the input of 0.55 x 106 m^3 of seawater.

When the lagoon started to spill again a sharp decrease in salinity, a gradual decrease of O_2 and an increase of nutrients were recorded. High values of pheopigments (27 µg. l^{-1}), ammonium (7 µM), nitrates (3 µM), silicates (120 µM), dissolved manganese (9 µM) and turbidity (65 NTU) were measured again. At the end of this period only 0.48 x 106 m^3 of water remained in the lagoon, about 35% corresponding to the seawater influx. Very low dissolved oxygen levels (< 10 µM) and a sulphide odor was noticed.

DISCUSSION

St. André lagoon is connected to the sea once a year in the same period – March/April. Though this connection always causes abrupt chemical changes and ecological modifications in the lagoon, an abnormal fish mortality was observed for the first time in 1986 (CANCELA DA FONSECA, 1989; BERNARDO, 1990). This event was presumably related to the particular internal conditions developed in the lagoon during the winter of that year.

Water characteristics of isolated lagoons are greatly influenced by climatic and hydrological winter conditions (BARNES, 1980). In St. André due to the long dry seasons, most freshwater enters the lagoon in periods of rainfall, while the seawater influx follows two principal processes: (i) seawater overtopping the low sand barrier during storms is sinking to the bottom and (ii) exchange through the inlet channel opened in late winter and spring. Thus, in this lagoon the frequency and magnitude of the volume of seawater overtopping the sand barrier are ruled by wind and winter storms. Salinity variation of the lagoonal water during the closure indicates that overtopping is the major process of seawater input and that percolation through the sand barrier plays a minor role. Seawater settles on the bottom of the lagoon, eventually leading to vertical density stratification. This stratification starts in the deep main channel but can gradually extend to other zones as the seawater influx progresses (CANCELA DA FONSECA, 1989; BERNARDO, 1990).

When seawater inputs are smaller than the freshwater run-off, as occurred in 1985 and 1987, only a weak stratification occurs which tends to be destroyed by the effects of wind before the opening of the lagoon in early spring. High seawater influx, as occurred in winter 1986, leads to the development of different conditions. Wind-driven mixing did not act so efficiently, and strong density stratification in deeper zones was maintained for a longer period. Its destruction occurred only with the seawater renewal through the inlet channel. The strong vertical density stratification led to changes in the bottom water chemical characteristics. Under these conditions consumption of oxygen near the bottom by the oxidation of the abundant vegetal biomass (CANCELA DA FONSECA *et al.*, 1987b) was insufficiently balanced by production and diffusion of O_2. As a result, a reduced bottom water layer enriched in silicates, phosphates and reduced forms of nitrogen, dissolved iron and dissolved manganese developed. In other years of weaker density stratification, nutrients were mixed through the entire water column and eventually consumed by the organisms.

At the 1986 opening, lagoonal water being discharged showed very low O_2 and high concentration of nutrients (Fig. 7). A simple mass balance calculation for a conservative constituent as salinity indicates a complex mixing of water layers. The high values of nutrients in low-salinity water (9‰), must result from the mixing with rich-nutrient water. Low and uniform salinity values recorded at the second ebb discharge (9‰) might indicate the mixing of stagnant deep lagoonal water (24‰) with the previous upper layer waters (6-7‰). However, mixing to a final salinity of 9‰ would lead to nutrient concentrations quite below the observed values (Fig. 7). Drainage of the nutrient-enriched overlying/pore water from recently air-exposed sediments to the water retained in deeper parts of the lagoon is the most probable cause for the high nutrient concentrations, as it was described elsewhere (POSTMA, 1988). In fact, about 80% of the sediments became exposed by the end of the second ebb period. Though such an area is also uncovered in other opening periods, drained water, enriched in dissolved iron and dissolved manganese (Fig. 5) coming into contact with oxygenated seawater may result in the flocculation of dissolved organic and inorganic matter (SHOLKOVITZ, 1976). In addition to the fresh material resulting from the precipitation of soluble iron and manganese, physical perturbation of the unconsolidated sediments may result in strong re-suspension. The overall result is the presence of large quantity of colloidal and particulate material in the water column. The observed fish mortality occurring during this opening may be due to all these factors. A large number of eels left the water, climbing over the sand where most eventually died. This reaction may come from the fact that they survive better in air than in poorly oxygenated or polluted water (TESCH, 1977). In water, 90% of the oxygen is absorbed across the gills, while in air about 2/3 of the oxygen absorption is cutaneous (BERG & STEEN, 1965). All specimens presented clear signs of stress apparently caused by asphyxiation. Beyond other stressing factors, such as low oxygen and a somewhat high ammonium, colloidal material, causing reduction of gas exchanges at the gills surface, may be the major cause for the observed mortality. A hypothesis concerning iron induced mortalities may also be stressed: precipitation of dissolved iron, alone or complexed to colloidal organic composites (MONTANI & OKAICHI, 1982), may obstruct the gills of fishes (MACHADO CRUZ, 1969) quickly leading to dead by exhaustion and asphyxia.

To prevent eutrophication and maintain a “steady state”, the renewal of the lagoonal environment has a relevant role. By annually connecting the lagoon to the sea, man promotes a “sediment-wash” and a release of materials from the lagoon to the sea, which decreases its trophic state, maintains a brackish system and prevents its rapid transformation towards a eutrophicated freshwater pond. This is also essential to the main species important for local fisheries (CANCELA DA FONSECA, 1989; BERNARDO, 1990). However, in spite of the recognized benefit of marine renewal, dramatic ecological modifications may occur during the short-time period of exchange to the sea. The key-factors controlling the intensity of such changes seem to be the hydrological and meteorological conditions of winter. As nutrients and other degradation products from the bottom are prevented from re-cycle in the lagoon, near-bottom reduced conditions may result in considerable damage. With this in mind, one may suspect that St. André lagoon is under severe environmental stress, and it becomes hard to assess whether the changes are reversible.

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