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Seasonal and spatial variability of the physicochemical characteristics of deep Maranhão Reservoir, south of Portugal

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With 11 figures and 1 table in the text

Abstract

The spatial variability of the physicochemical characteristics of Maranhão Reservoir, south of Portugal, was studied over one year period. Non algal turbidity was most likely the main factor controlling the water transparency of the reservoir. An hypolimnetic oxygen depletion developed during summer stratification and a relative oxygen deficit of 1.1 $mg\,cm^{-2}\,month^{-1}$ was quantified. Maximum values of nitrates (1.2—2.4 $mg\,l^{-1}$) and silicates (4.4—5.2 $mg\,l^{-1}$) were detected in winter, contrasting with phosphates which maximum concentrations (140—480 $\mu g\,l^{-1}$) were observed during summer/early autumn. The gross internal phosphorus loading detected from June to October corresponded to a calculated release rate of 18 $mg\,m^{-2}\,day^{-1}$. A new method of discriminant analysis based on a modification of Principal Component Analysis was developed, and applied to the physicochemical variables. This analysis showed to be an efficient method in summarizing the variability of the physicochemical parameters along the reservoir. The gradient-depth effects on temperature, oxygen, pH, silicates, nitrates and ammonia are evident along the factor I. Factor II is clearly related to a phosphorus enrichment in the central area of the reservoir. Significant differences in surface chlorophyll-a and primary production rates from two sampling sites were observed from May to September. Effects of local nutrients input on those parameters are discussed.

Introduction

Natural water resources in the south of Portugal are scarce and a large amount of water supply for agricultural, industrial, fisheries and recreational purposes is provided by man-made lakes. Deterioration of water quality of these systems is a public concern. The development of agricultural and industrial activities in Maranhão watershed stresses the importance of limnological study of this reservoir.

Influence of morphometry, stratification dynamics, water movements and discharge type on the physicochemical and biological conditions of reservoirs have been discussed by several authors (Hannan et al., 1979; Whalen et al., 1982; Tundisi, 1983). Different patterns of basic physicochemical and biological conditions are observed in relation to lakes.

Several methods of multivariate analysis have been applied to reservoirs and lakes to analyze interactions between physicochemical and biological pa-

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rameters (Estrada, 1978; Devaux, 1980; Whalen et al., 1985). In order to summarize the spatial variability of the physicochemical variables along the reservoir a new method of discrimination based on a modification of Principal Component Analysis was developed.

The purpose of the present paper is to describe seasonal and spatial variability of the physicochemical characteristics of the reservoir and to compare the different sampling stations under the standpoint of the relevant variables, using a discriminant analysis method. Furthermore, results of surface chlorophyll-a and primary production from two sampling sites, during growing season are presented. Effects of local nutrients input on those parameters are discussed.

Study area

Maranhão reservoir, situated in Alentejo south of Portugal, belongs to the hydrological system of the Tagus River (Fig. 1). The impoudement was built in 1957, on Ribeira da Seda. Morphometric and hydrologic data of the reservoir are given in Table 1. Impouded water is released mainly through an outlet located 22 m from bottom at maximum storage capacity (106 m above sea level, a.s.l.). The reservoir is subjected to large annual water fluctuations. During 1979 a decrease of 7.5 m was recorded from January to September, corresponding approximately to a decrease of 50 % in lake volume.

Total evaporation was about twice the total precipitation, although its contribution for the total outflow was only 4 % of the annual water loss from the reservoir. Maximum precipitation and evaporation occurred in February and June, respectively (Fig. 2).

Geologically the reservoir and drainage area are characterized by the presence of shales (approx. 50 %), clays (approx. 30 %) and limestones (approx. 20 %). The altitude of the area ranges from 100 to 200 m. Climate is submediterranean. Annual mean air temperature ranges from 15.0 °C to 17.5 °C and mean relative humidity is less than 65 % (CNA, Atlas do Ambiente).

Land uses of the catchment area are extensive agriculture (wheat)/dispersed forest (cork and olive trees) and grazing.

The reservoir is used for irrigation, fishing activities and power generation.

Non treated sewage and industrial effluents discharging directly into the middle and upper part of the reservoir, can constitute important sources of nutrients, specially during the summer period when no significant external loadings from streams occur. Phytoplankton studies carried out in the reservoir showed that dominance of Cyanophyceae is frequent and blooms of *Microcystis aeruginosa* occurred in 1979, during summer (Oliveira, 1984). Fish community is dominated by carp (*Cyprinus carpio*) and Iberian nase (*Chondrostoma*

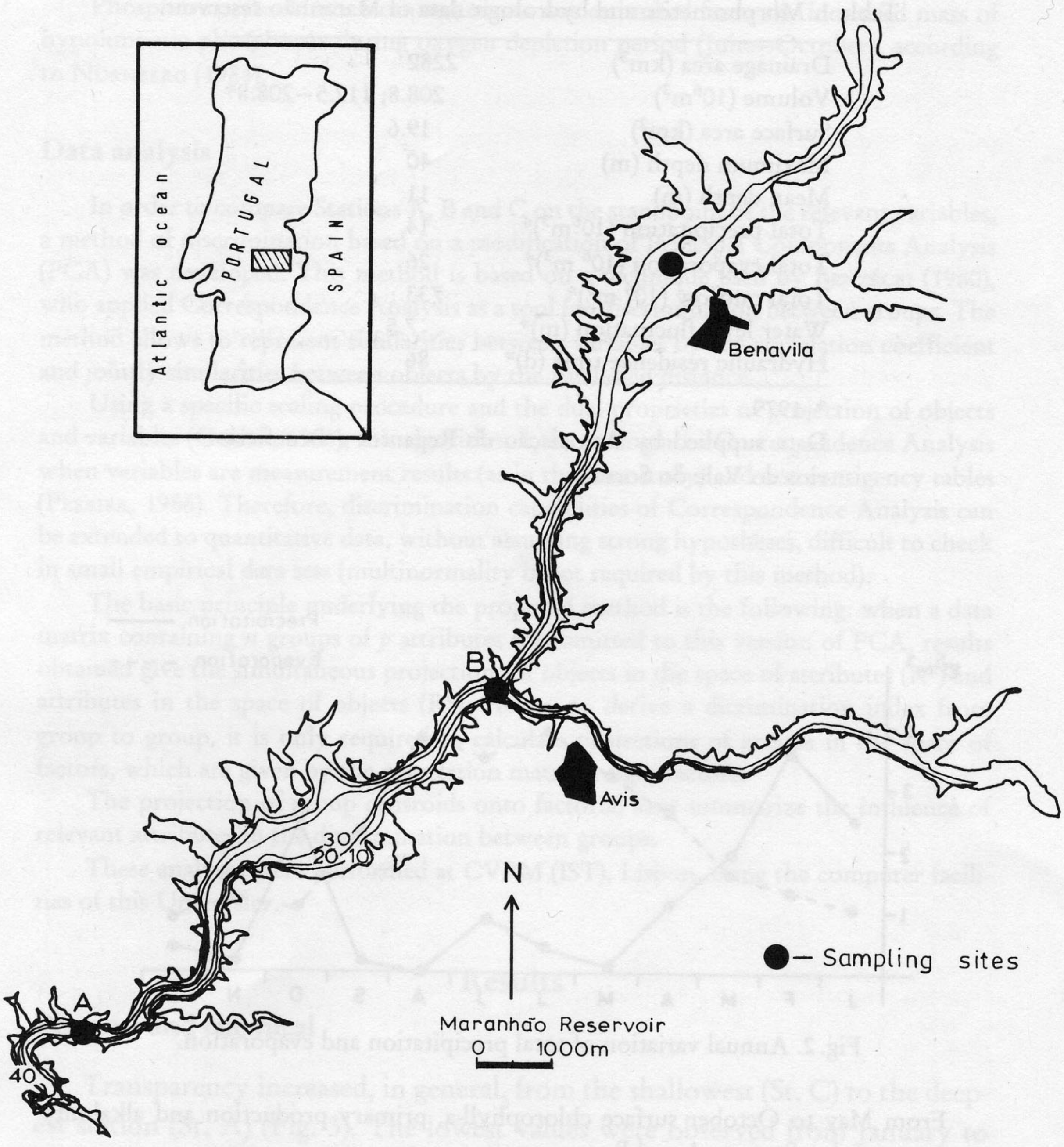

Fig. 1. Bathymetric map of Maranhão Reservoir showing sampling sites.

polylepis) (BRABRAND et al., 1986). Sporadic fish killing has been observed in the reservoir.

Material and methods

Physical and chemical

The study was conducted monthly, from January to December 1979. Sampling stations A, B and C are shown in Fig. 1.

Water samples were collected from fixed depths (0, 2, 5, 10, 15, 20, 30 m and bottom) with a 6 l Van Dorn bottle.

The following physical and chemical determinations were made: transparency, temperature, pH, dissolved oxygen (DO), nitrate + nitrite (NO), ammonia (NH), phosphate (IP), total phosphorus (TP) and dissolved silicate (SI).

Table 1. Morphometric and hydrologic data of Maranhão reservoir.

Drainage area (km^2)	2282
Volume (10^{6}m^3)	208.8; 112.5 – 208.8*
Surface area (km^2)	19.6
Maximum depth (m)	40
Mean depth (m)	11
Total precipitation (10^{6}m^3)*	14
Total evaporation (10^6 m^3)*	26
Total outflow (10^6 m^3)*	733
Water level fluctuation (m)*	7.5
Hydraulic residence time (d)*	86

* 1979.

Data supplied by Associação de Regantes e Beneficiários do Vale do Sorraia.

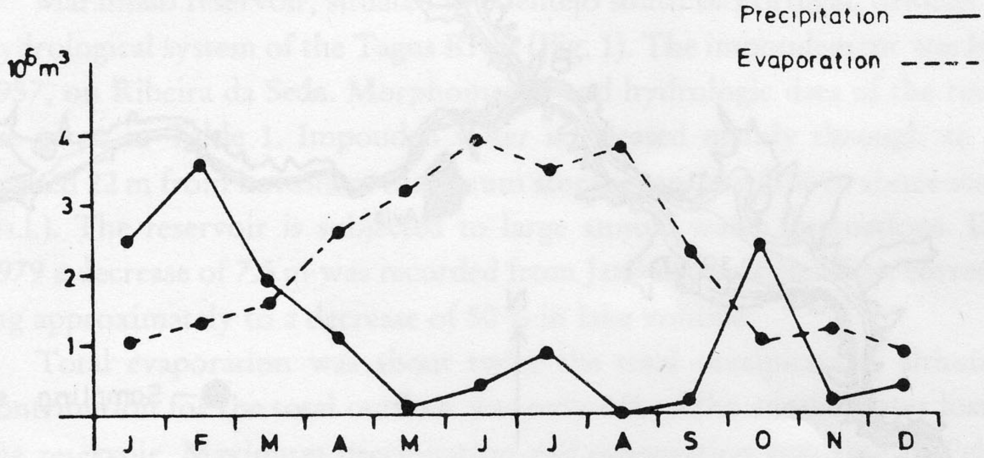

Fig. 2. Annual variation of total precipitation and evaporation.

From May to October surface chlorophyll-a, primary production and alkalinity were measured at Stations A and B.

Transparency was estimated from Secchi disc (20 cm ∅) measurements. Temperature was measured with a thermometer coupled to the Van Dorn bottle and pH with a pH meter E488 Methrom Herisau. Dissolved oxygen was determined by a modified method of the Winkler technique (Carrit & Carpenter, 1966). Inorganic phosphate was analyzed by a modified method of Murphy & Riley (FAO, 1975), ammonia by the indophenol blue method (Solórzano, 1969) and dissolved silicate by a modified method of Mullin & Riley (FAO, 1975). Nitrate + nitrite and total phosphorus were determined according to FAO (1975). Samples for chlorophyll-a determinations were filtered through Millipore membrane filters (0.45 μm). Chlorophyll-a was extracted in 90 % acetone and measured spectrophotometrically. SCOR-UNESCO (1966) equations were used for calculations. Primary production rates were measured in situ, using ^{14}C technique (Steeman Nielsen, 1952). Sampling method has been previously described (Cabeçadas & Brogueira, 1987), as well as the method for alkalinity analysis.

The relative areal hypolimnetic oxygen deficit (below 115 m a.s.l.) was calculated as described by Wetzel (1975).

Phosphorus release rate from sediments was estimated from the increased mass of hypolimnetic phosphorus during oxygen depletion period (June—October), according to Nürnberg (1984).

Data analysis

In order to compare Stations A, B and C on the standpoint of the relevant variables, a method of discrimination based on a modification of Principal Components Analysis (PCA) was developed. This method is based on a technique used by Benzécri (1980), who applied Correspondence Analysis as a tool for discrimination between groups. The method allows to represent similarities between variables by the correlation coefficient and jointly similarities between objects by the Euclidien distance.

Using a specific scaling procedure and the dual proprieties of projection of objects and variables (Gower, 1966), this algorithm is the analogue to Correspondence Analysis when variables are measurement results (as in this case study) and not contigency tables (Pereira, 1986). Therefore, discrimination capabilities of Correspondence Analysis can be extended to quantitative data, without assuming strong hypotheses, difficult to check in small empirical data sets (multinormality is not required by this method).

The basic principle underlying the proposed method is the following: when a data matrix containing *n* groups of *p* attributes is submitted to this version of PCA, results obtained give the simultaneous projections of objects in the space of attributes (R^p) and attributes in the space of objects (R^n). Hence, to derive a dicrimination index from group to group, it is only required to calculate projections of groups in the space of factors, which are given by the correlation matrix's eigenvectors.

The projection of group centroids onto factorial axes summarize the influence of relevant attributes in the discrimination between groups.

These analyses were performed at CVRM (IST), Lisbon, using the computer facilities of this University.

Results

Physical and chemical

Transparency increased, in general, from the shallowest (St. C) to the deepest station (St. A) (Fig. 3). The lowest values were observed from January to March, along the system, when the highest precipitation values were recorded (Fig. 2). This contrasts with the situation during spring/summer period, when the highest values of transparency (4 m, 2 m and 1.5 m at Sts. A, B and C respectively), were observed.

No significant relationship was found between transparency and surface chlorophyll-a from May to October. From September to October a decrease in transparency was observed, simultaneously with an increase of precipitation (Fig. 2) and a decrease of chlorophyll-a and primary production (Fig. 9). This suggest that transparency is mainly dependent on the amounts of suspended material carried to the reservoir during periods of high precipitation.

Depth isotherms of the three stations are presented in Fig. 4. It can be observed that Stations A and B have a well defined period of stratification from June to October, starting in April. From the end of July to September (St. A)/

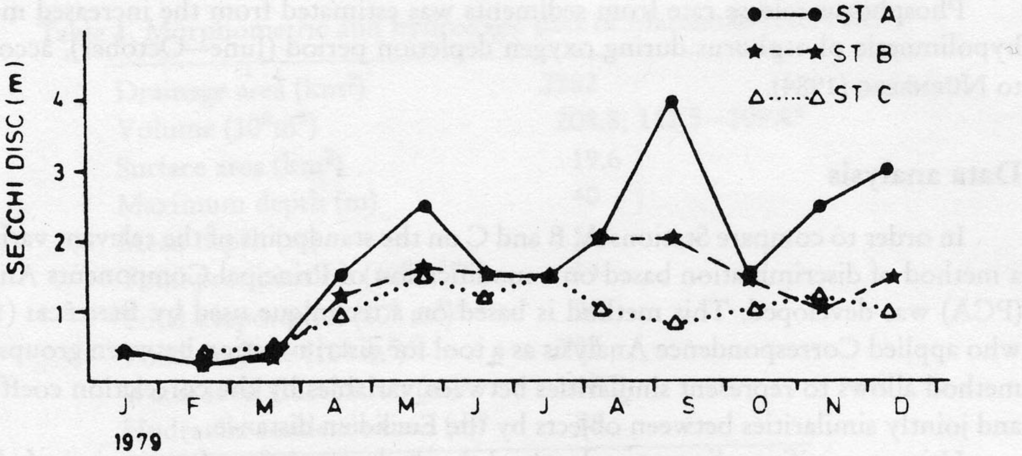

Fig. 3. Secchi disc fluctuation at Stations A, B and C.

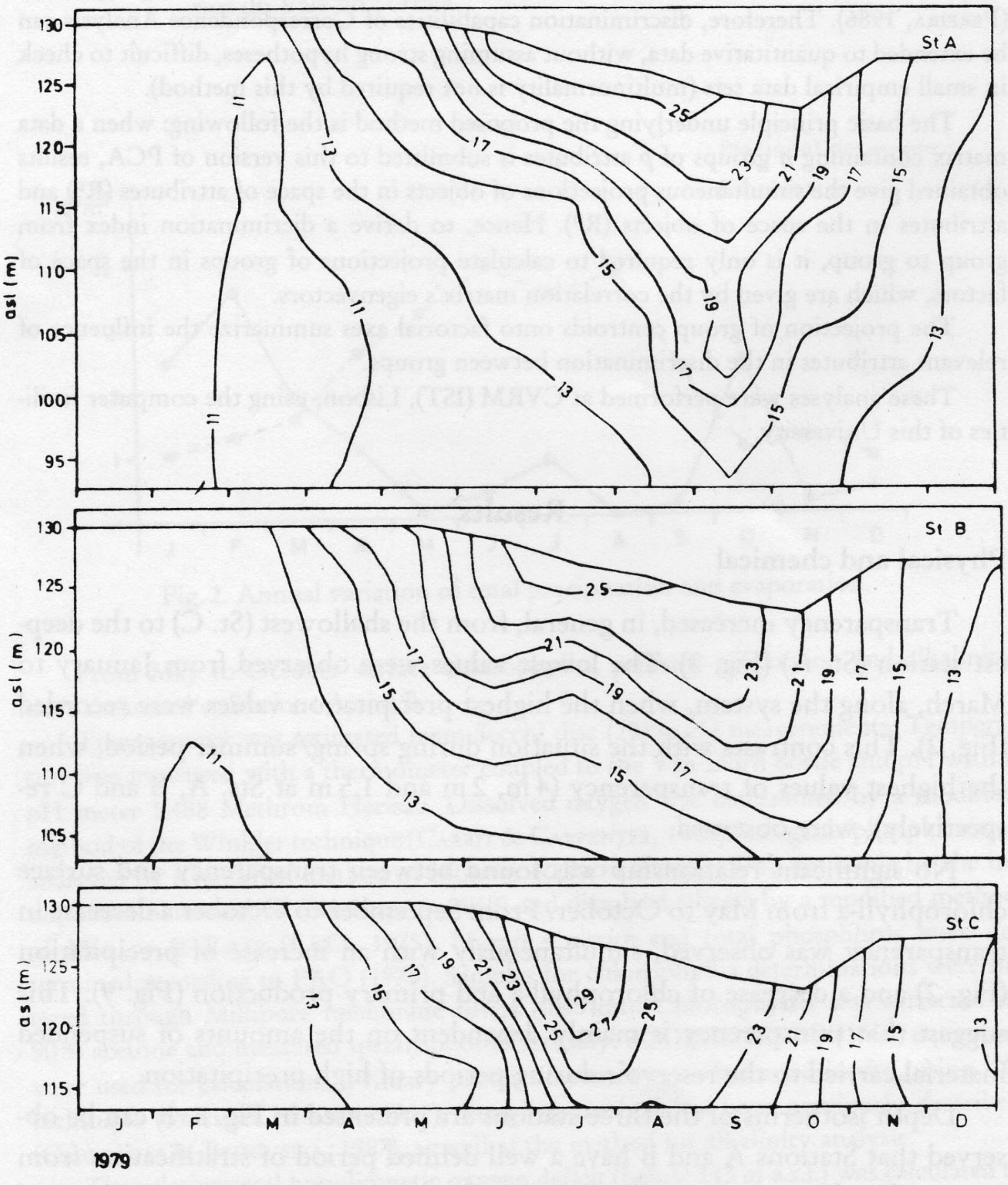

Fig. 4. Depth-time distribution of isotherms (°C) at Stations A, B and C.

October (St. B), a sinking of the thermocline was detected. Such effect was enhanced at Station A, probably due to the hydraulic functioning of the reservoir. The withdrawal of the water comes from a deep layer close to this station. Such occurrence has been reported from other bottom or hypolimnion draining reservoirs (Hannan et al., 1979; Tundisi, 1983). Overturn started in October. During November a complete mixing of the water column and isothermy were established. Thermal stratification at Station C (the shallowest station) was less pronounced, starting in April and remaining until July, when a maximum of 30 °C was detected in the reservoir. By August, stratification was disrupted and a temperature of 25 °C was observed throughout the water column.

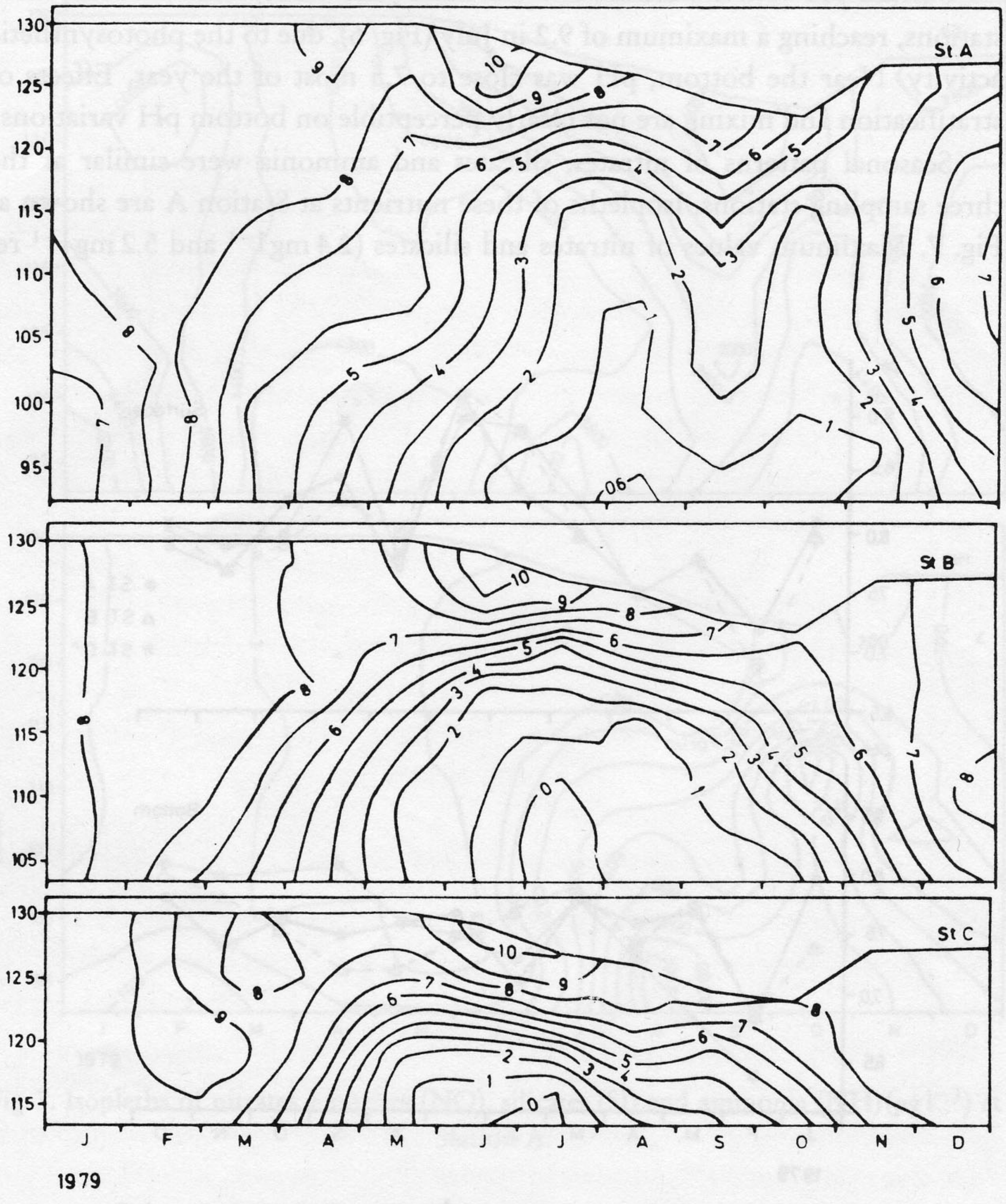

Fig. 5. Isopleths of dissolved oxygen (mg l^{-1}) at Stations A, B and C.

An hypolimnetic oxygen depletion developed shortly after starting of thermal stratification and lasted until the fall overturn at both Stations A and B (Fig. 5), where minimum values of 0.6 $\mathrm{mg\,l^{-1}}$ and 0.0 $\mathrm{mg\,l^{-1}}$ were observed, respectively. At Station C concentrations lower than 1.0 $\mathrm{mg\,l^{-1}}$ were detected earlier. However oxygen depletion remained during a shorter period of time and was discontinuous.

Surface dissolved oxygen was at saturation levels from June to September at the three stations. By November a value as low as 40 % was observed at Station A, obviously caused by the mixingup of hypolimnetic water to surface. From April to August a value of relative areal hypolimnetic oxygen deficit of 1.1 $\mathrm{mg\,cm^{-2}\,month^{-1}}$ was determined, which places Maranhão reservoir in the mesotrophic category according to Hutchinson's criterion (1957).

Surface pH values were around 8.5 from June to September at the three stations, reaching a maximum of 9.2 in July (Fig. 6), due to the photosynthetic activity. Near the bottom, pH was close to 7.5 most of the year. Effects of stratification and mixing are not clearly perceptible on bottom pH variations.

Seasonal patterns of nitrates, silicates and ammonia were similar at the three sampling stations. Isopleths of these nutrients at Station A are shown at Fig. 7. Maximum values of nitrates and silicates (2.4 $\mathrm{mg\,l^{-1}}$ and 5.2 $\mathrm{mg\,l^{-1}}$ re-

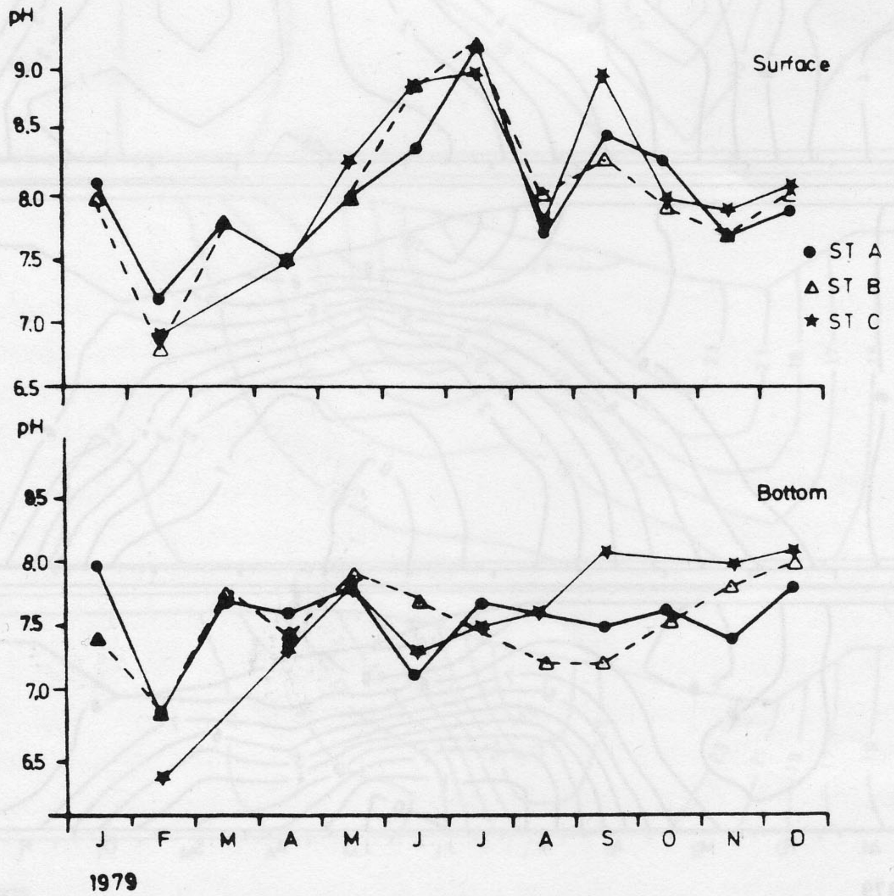

Fig. 6. pH variation at surface and bottom at Stations A, B and C.

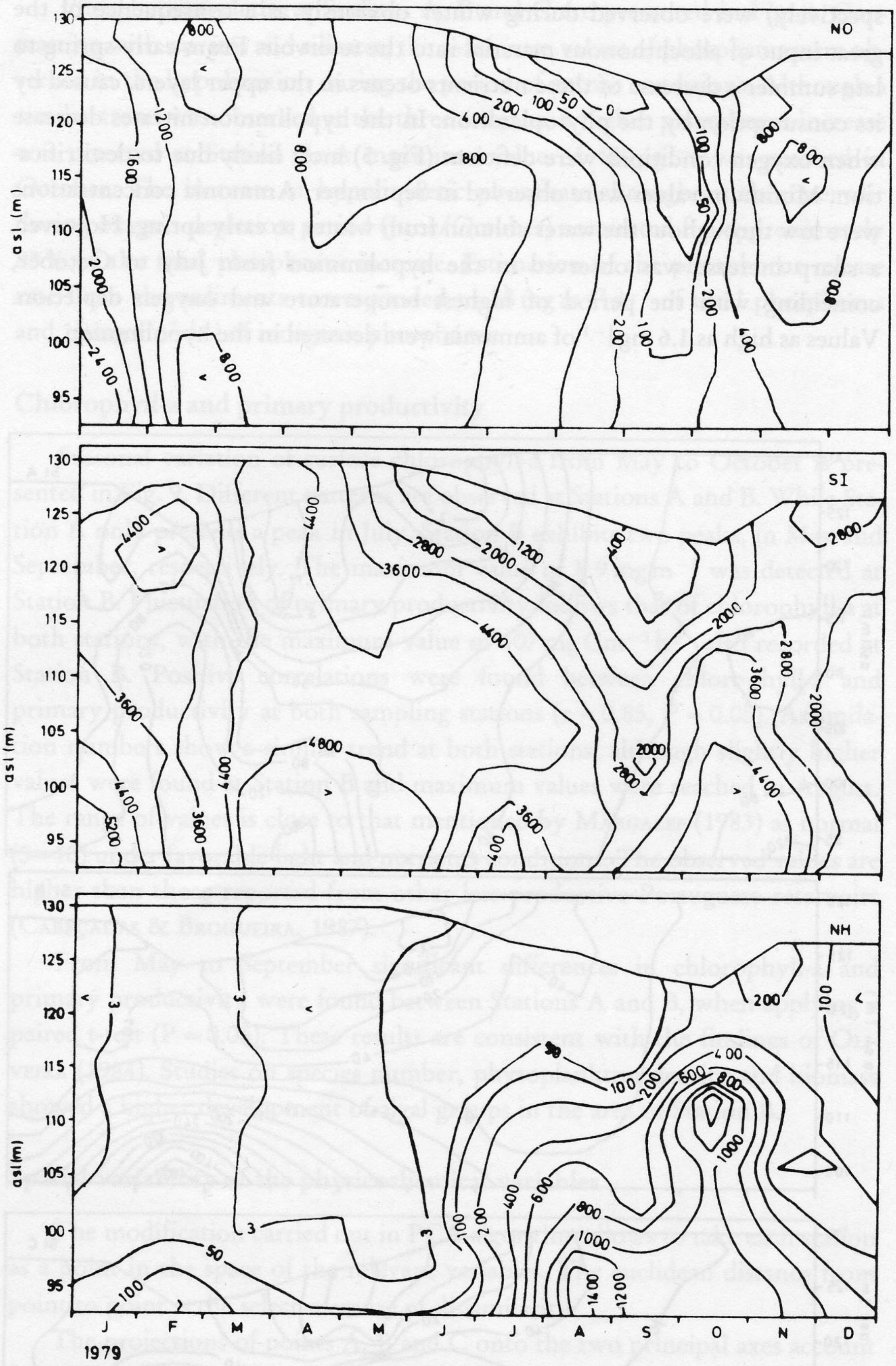

Fig. 7. Isopleths of nitrates + nitrites (NO), silicates (SI) and ammonia (NH) ($\mu g\,l^{-1}$) at Station A.

spectively) were observed during winter obviously as a consequence of the great input of allochthonous material into the reservoir. From early spring to late summer a decrease of these nutrients occurs in the upper layers, caused by its consumption by the phytoplankton. In the hypolimnion nitrates decrease when oxygen conditions were deficient (Fig. 5) most likely due to denitrification. Minimum values were observed in September. Ammonia concentrations were low throughout the water column from winter to early spring. However, a sharp increase was observed in the hypolimnion from July to October, coinciding with the period of highest temperature and oxygen depletion. Values as high as 1.6 $mg\,l^{-1}$ of ammonia were detected in the hypolimnion.

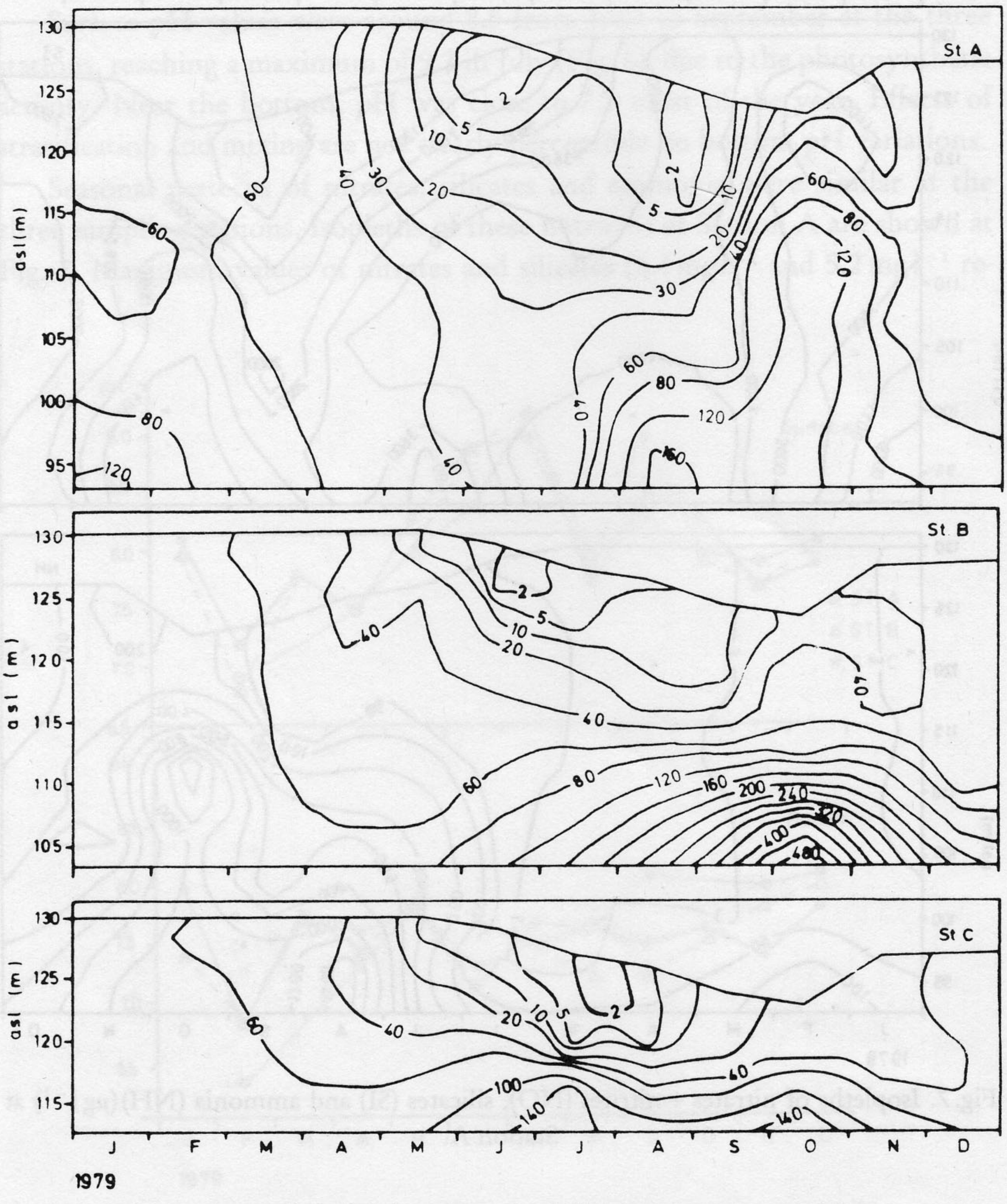

Fig. 8. Isopleths of phosphates ($\mu g\,l^{-1}$) at Stations A, B and C.

Phosphate isopleths at Stations A, B and C are presented in Fig. 8. Contrasting with nitrates and silicates, the maximum values of phosphates were observed in the hypolimnion during the period of anoxic conditions. Although a similar trend was observed at the three stations, a higher phosphorus increase was detected at Station B. A maximum value of $480\,\mu g\,l^{-1}$ was reached in October. The increase of hypolimnetic phosphate throughout the reservoir during oxygen depletion period (June/October) accounted for approximately 83 % of the total phosphorus increase. Estimation of the phosphorus release rate from the sediments corresponded to $18\,mg\,m^{-2}\,d^{-1}$ of total phosphorus and $15\,mg\,m^{-2}\,d^{-1}$ of inorganic phosphorus.

Chlorophyll-a and primary productivity

Seasonal variation of surface chlorophyll-a from May to October is presented in Fig. 9. Different patterns are observed at Stations A and B. While Station A only presents a peak in July, Station B exhibits two peaks, in May and September, respectively. The maximum value of $8.9\,mg\,m^{-3}$ was detected at Station B. Fluctuation of primary productivity follows that of chlorophyll-a at both stations, with the maximum value of $107\,mg\,C\,m^{-3}\,h^{-1}$ also recorded at Station B. Positive correlations were found between chlorophyll-a and primary productivity at both sampling stations ($r = 0.85$, $P = 0.05$). Assimilation numbers show a similar trend at both stations, although slightly higher values were found at Station B and maximum values were reached in August. The range of values is close to that mentioned by MARGALEF (1983) as normal (5—10) under favorable light and nutrients conditions. The observed values are higher than those reported from other less productive Portuguese reservoirs (CABEÇADAS & BROGUEIRA, 1987).

From May to September significant differences in chlorophyll-a and primary productivity were found between Stations A and B, when applying a paired t-test ($P = 0.05$). These results are consistent with the findings of OLIVEIRA (1984). Studies on species number, phytoplankton density and biomass showed a higher development of algal groups in the area of Station B.

Spatial variability of the physicochemical variables

The modification carried out in PCA algorithm allows to take each station as a point in the space of the relevant variables. The euclidean distance from point to point is the select measure of dissimilarity.

The projections of points A, B and C onto the two principal axes account for 100 % of the total inertia. Hence, in Fig. 10, the dissimilarity from station to station can be measured directly on the graph. Maximum discrimination occurs from Station A to Station C, along the factor I. Station B takes an intermediate position, linked to variables related to factor II (IP and TP). Two

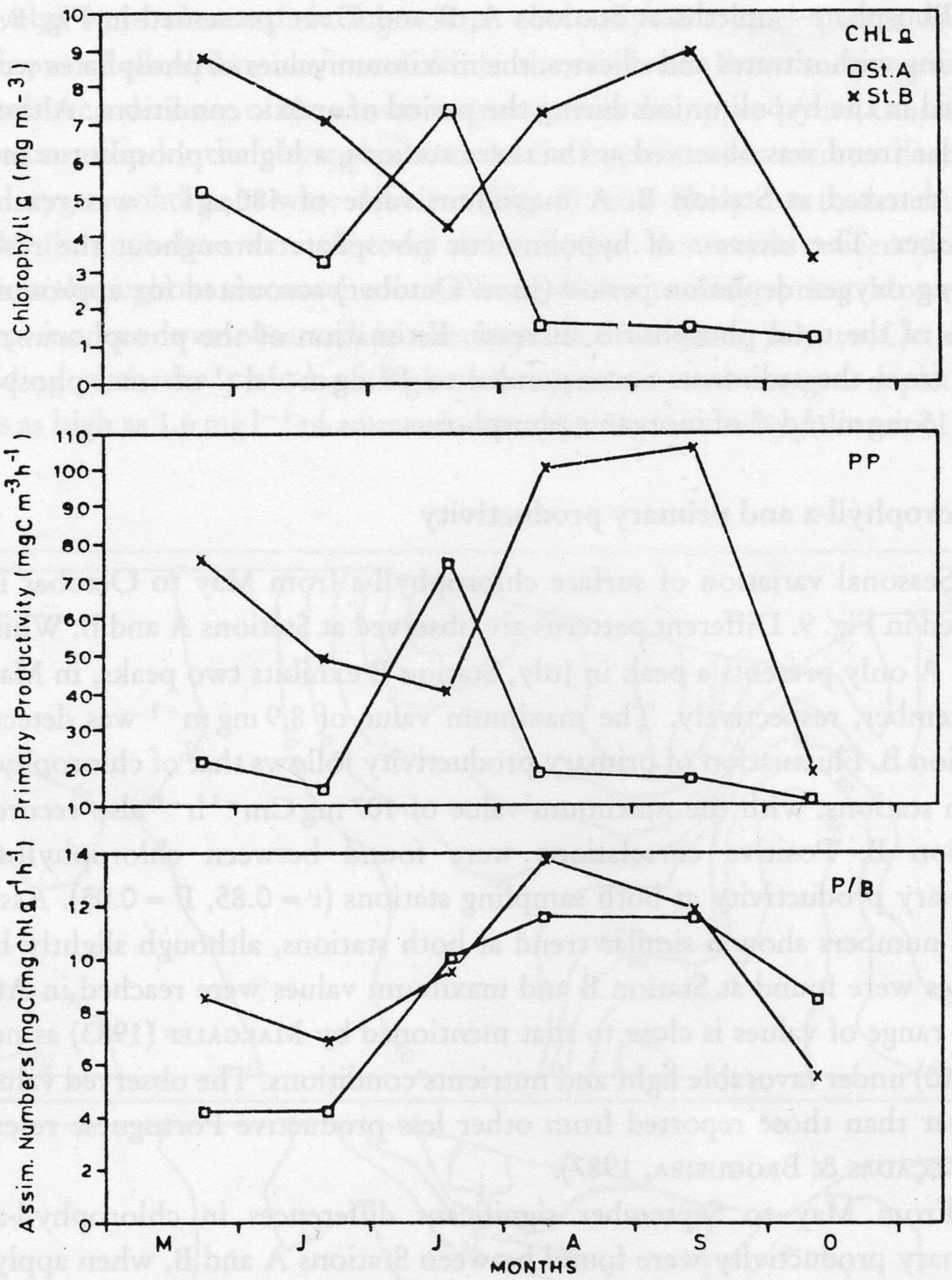

Fig. 9. Surface chlorophyll-a, primary production and assimilation numbers at Stations A and B.

groups of variables are associated with Stations A and C respectively, suggesting factor I to be related to the spatial variability of the physicochemical characteristics along the reservoir.

Monthly mean values of the variables have been projected on the space determined by the two axes previously defined. We selected the following parameters: DO and NO plus NH as representative of the variables having, respectively, positive and negative loadings with the first axis and IP as representative of the variables presenting negative loadings relatively to the second axis (Fig. 11). Although a steadily decrease of nitrates and a simultaneous increase of ammonia and oxygen consumption occur in all the stations, from winter to

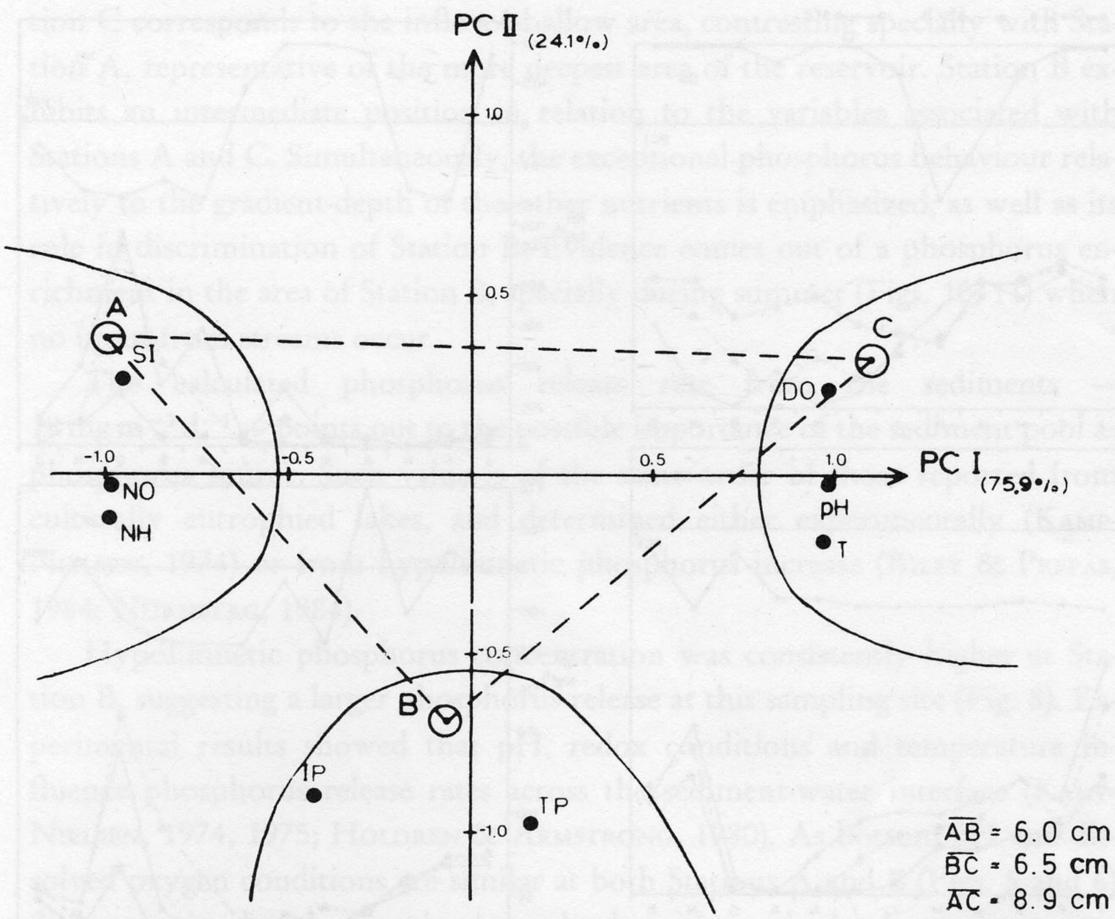

Fig. 10. Position of Stations A, B and C and variables (DO, pH, T, SI, NO, NH, IP and TP) in the space of the two first axes.

summer, a gradient is observed from Station A to Station C. Mean values of nitrates increase gradually from Station C to Station A, contrasting with oxygen concentration that presents in general the highest mean values at Station C, decreasing along the reservoir. On the other hand, mean values of ammonia increased from Station C to Station A. As can be observed both largest positive (DO) and negative (NO and NH) loadings reflect respectively, the contribution of the sampling stations C and A. Phosphorus doesn't exhibit the same depth-gradients as the other nutrients. The highest mean value usually observed at Stations B contributes to the largest negative loading of this variable with the second axis, allowing clearly to individualize this station from the other two. Discrimination of sampling stations takes place mainly during summer, when differences in the physicochemical and biological processes from the shallowest (St. C) to the deepest station (St. A) are enhanced.

Discussion

Although fluctuations in transparency during spring/summer period may be related with changes in phytoplankton concentration, no significant relationship was found between surface chlorophyll-a and transparency from May

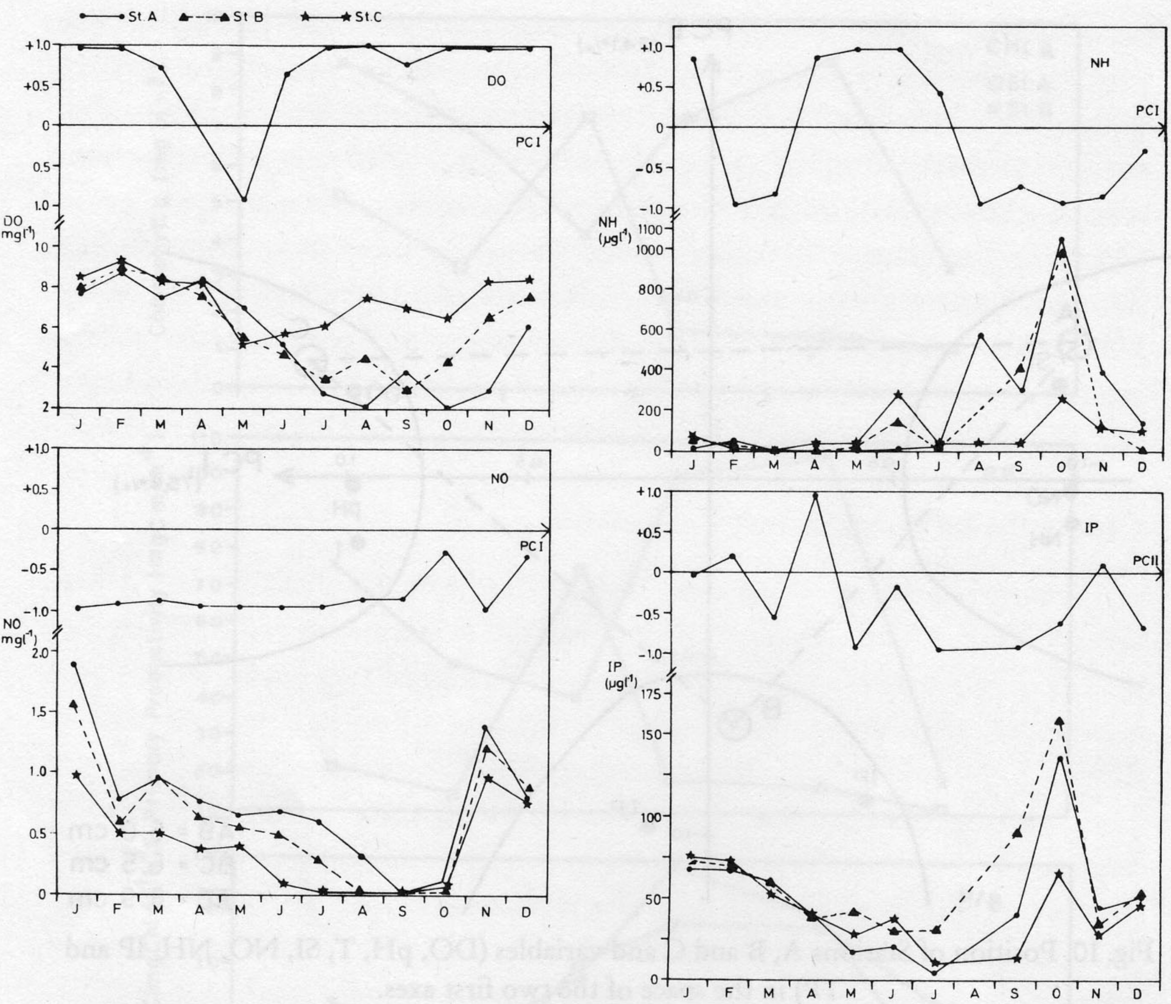

Fig. 11. Seasonal variation of the correlation coefficients of the variables DO, NO, NH and IP with the two first axes and integrated mean values of the same variables.

to September. Non-algal turbidity is likely the main factor controlling transparency of Maranhão Reservoir. Lind (1986) analyzing data from reservoirs of different trophic state, found that in the mesotrophic reservoirs Secchi depth was entirely determined by non-algal turbidity. He concluded that in such cases Secchi depth data were inappropriate to estimate algal biomass for trophic state classification or other management practices. Low transparency of Maranhão Reservoir during periods of high precipitation is obviously consequence of the sedimentary characteristics of the watershed as well as the rainfall wash-out.

The importance of the gradient-depth effect relatively of the physicochemical characteristics along the reservoirs has been discussed by several authors (Baxter, 1977; Whalen et al., 1982). Downstream effects of impoundment on nutrients contribute, in general, to its accumulation in the deepest part of the reservoir. Simultaneously, an increase of oxygen consumption occurs in this area, due to the microbial oxidation of organic matter. The applied discriminant analysis showed to be an efficient method in summarizing the spatial variability of the physicochemical variables along the reservoir (Fig. 10). Station C corresponds to the inflow/shallow area, contrasting specially with Station A, representative of the more deepest area of the reservoir. Station B exhibits an intermediate position in relation to the variables associated with Stations A and C. Simultaneously, the exceptional phosphorus behaviour relatively to the gradient-depth of the other nutrients is emphasized, as well as its role in discrimination of Station B. Evidence comes out of a phosphorus enrichment in the area of Station B, specially during summer (Figs. 10, 11) when no input from streams occur.

The calculated phosphorus release rate from the sediments — 18 mg $m^{-2} d^{-1}$ — points out to the possible importance of the sediment pool as phosphorus source. Such value is of the same order of those reported from culturally eutrophied lakes, and determined either experimentally (KAMP-NIELSEN, 1974) or from hypolimnetic phosphorus increase (RILEY & PREPAS, 1984; NÜRNBERG, 1984).

Hypolimnetic phosphorus concentration was consistently higher at Station B, suggesting a larger phosphorus release at this sampling site (Fig. 8). Experimental results showed that pH, redox conditions and temperature influence phosphorus release rates across the sediment-water interface (KAMP-NIELSEN, 1974, 1975; HOLDREN & ARMSTRONG, 1980). As bottom pH and dissolved oxygen conditions are similar at both Stations A and B (Figs. 5 and 6) differences in phosphorus release may be due either to higher bottom temperature (Fig. 4) or phosphorus saturation level of the sediment (BÖSTROM et al., 1982).

Studies from NÜRNBERG (1985) indicate that upwelling hypolimnetic phosphorus can be available to phytoplankton from the starting of the thermocline erosion. From August to November concentration of phosphate in the water surface increased at the three sampling sites (Fig. 8). It seems likely that hypolimnetic phosphorus fertilizes the epilimnetic layers of Maranhão Reservoir.

No apparent differences in surface nutrient concentration seem to justify the significantly higher values of surface chlorophyll-a and primary production detected at Station B from May to September. *Microcystis aeruginosa* was the dominant species during summer (OLIVEIRA, 1984). Experimental results (SAKSHAUG & OLSEN, 1986) show that this species is more efficient than other ones in accumulation phosphate when exposed to high concentrations. These facts suggest that a rapid uptake of phosphorus supplied by the wastes discharging near Station B takes place.

Zooplankton biomass and structure in the area of Station B (MONTEIRO, in press) also indicate that a larger contribution of recycling processes on local nutrients supply is not to be excluded.

The present work shows that the existence in Maranhão Reservoir of nutrient point sources is susceptible to modify either direct or indirectly the effects of depth-gradient on the nutrient distribution, particularly phosphorus.

Summary

Physicochemical characteristics of Maranhão Reservoir, south of Portugal were studied over one year period.

Transparency of the reservoir was most likely dependent on non-algal turbidity (Figs. 2, 3). It seems that changes in phytoplankton concentrations have a reduced influence on transparency (Fig. 9).

A relative oxygen deficit of 1.1 $\mathrm{mg\,cm^{-2}\,month^{-1}}$ was determined during summer stratification, which places Maranhão Reservoir in the mesotrophic category according to Hutchinson's criterion (1957).

A new method of discriminant analysis applied to the physicochemical parameters clearly summarizes the gradient-depth effect. Maximum discrimination occurs from Station A to Station C. Two groups of variables are associated with Station A (NO, SI, NH) and C (pH, T, DO) respectively, suggesting factor I to be related to the spatial variability of the physicochemical characteristics along the reservoir. Station B takes an intermediate position, linked to variables related to factor II (IP and TP) (Fig. 10). A phosphorus enrichment of the central area of the reservoir is emphasized.

Hypolimnetic phosphorus is likely to fertilize the epilimnetic layers of the reservoir from the beginning of destratification (Figs. 5, 8).

Significant differences in surface chlorophyll-a and primary production between the deepest (St. A) and the mid-reservoir sampling site (St. B), during growing season (Fig. 9) were apparently related with a rapid uptake of phosphorus supplied by the wastes discharging near the surface in the area of Station B.

Effects of depth gradient on nutrient distribution, particularly phosphorus, are susceptible to be influenced by nutrient point sources. Additionally, spatial plankton distribution seems also to be affected.

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