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# Limnological survey of the warm monomictic lake Trichonis (central western Greece)

## *I. The physical and chemical environment*

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## Abstract

The physical and chemical status of Trichonis – the largest and deepest natural lake in Greece – is examined over two annual cycles (1985–86 and 1988–89). A correlation between lake nutrient patterns and phytoplankton biomass is attempted. Limnological features are compared with data from other warm and temperate lakes.

With regard to its thermal regime, Trichonis is classified as a warm monomictic lake. The lake's stratification pattern and annual heat budget resemble those of other temperate lakes. Trichonis is a carbonate type, low conductivity lake ('class II, low salinity' warm lake). Nitrogen and phosphorus concentrations were rather low. The inorganic nitrogen content fluctuated widely over the two annual cycles examined. On the contrary, phosphorus concentrations showed no significant changes. The limiting factor during 1985–86 was P, while N was limiting during stratification in 1988–89. A weak correlation was found between the plankton community features (species abundance, biomass, chlorophyll-*a*) and light penetration. At present the eutrophication process from oligotrophy towards mesotrophy has not been essentially accelerated.

## Introduction

The province of Aetoloakarnania in western Greece comprises a wealth of aquatic biotopes, including five natural lakes (Trichonis, Amvrakia, Lyssimachia, Ozeros and Voulkaria), three artificial lakes (Kremasta, Kastraki, Stratos), two rivers (Acheloos, Evinos) and the extensive coastal lagoon system of Messolongi-Aetoliko. While some limnological and biological characteristics of the above sites have already been presented (Economou-Amilli, 1979, 1982; Kristiansen, 1980, 1983; Overbeck et al., 1982; Overbeck & Anagnostidis, 1982, Anagnostidis et al., 1985, 1988a, b; Falniowski et al., 1988; Economou-Amilli & Spartinou, 1989a, b, 1991; Danielidis, 1991; Tafas, 1991; Tafas & Economou-Amilli, 1991; Spartinou, 1992; Danielidis et al., 1996), this is the first attempt of a more thorough limnological survey of Lake Trichonis.

*Table 1.* Morphometric characteristics of lake Trichonis.

| | |
|---|---|
| Max. length (km) | 18.2 |
| Max. width (km) | 7.5 |
| Max. depth (m) | 58 |
| Mean depth (m) | 30.45 |
| Lake volume ($m^3$) | $2.99 \times 10^9$ |
| Shore length (km) | 52.1 |
| Surface area ($km^2$) | 98.2 |
| Drainage area ($km^2$) | 215 |

Trichonis (long. 38°18′–38°51′ N; lat. 21° 01′–21° 42′ E, see Figure A) is the largest lake in Greece. According to Koeppens' system (in Karras, 1973),

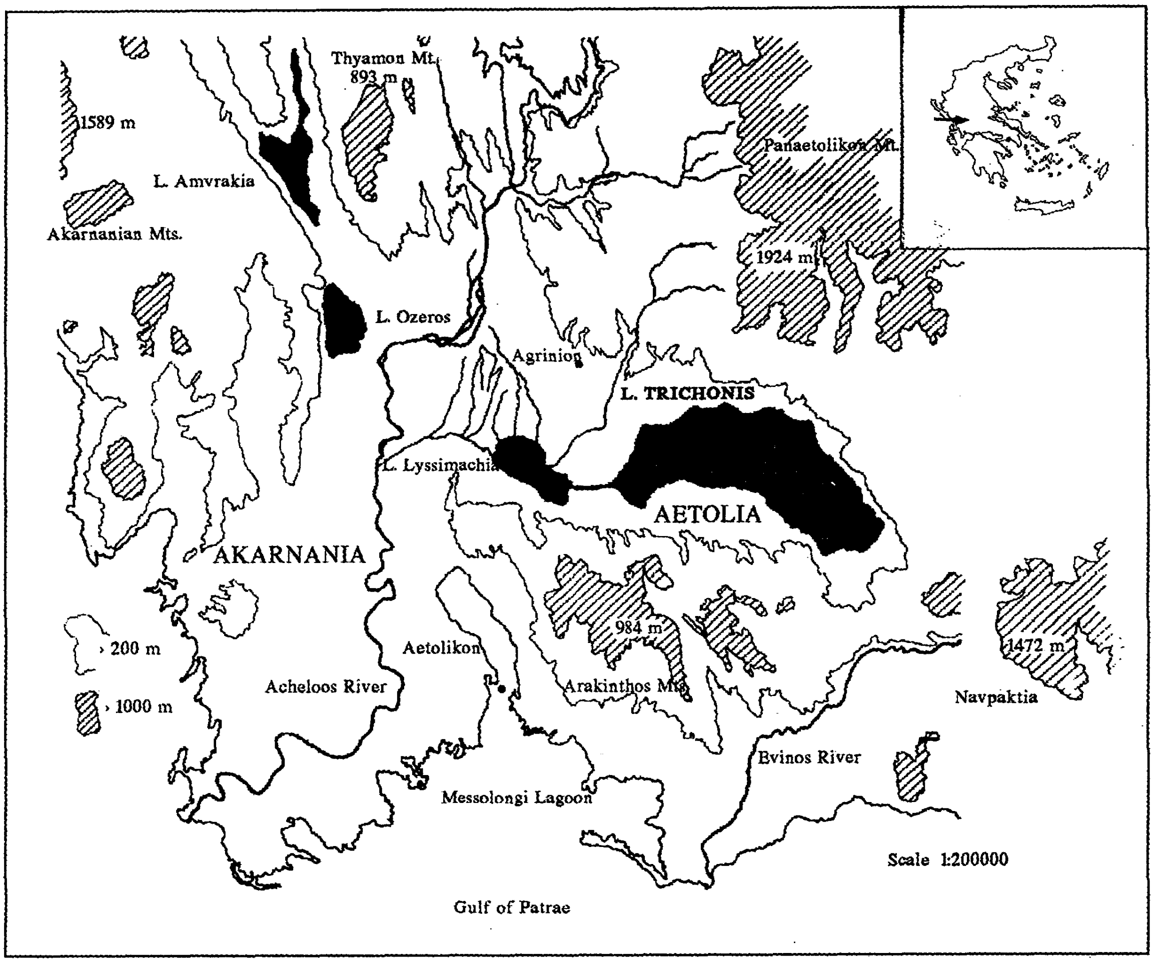

*Figure A.* Map of central western Greece.

the climatic type of the area is Csa, a temperate climate with summer drought (mean coldest month temperature >10 °C, mean warmest month temperature >22 °C; rainfall height during dry period <30 mm). The lake's morphometric characteristics are presented in Table 1. The mountainous surroundings of lake Trichonis form a drainage area of 215 km$^2$ of karstified calcareous rocks. Surface water input is low. The water level fluctuates ca. 1 m annually due to (a) the lake's hydraulic relation with karst aquifers, (b) extensive evaporation during the hot and dry summer and (c) the intensive irrigational use of the lake. For further geomorphological and hydrological data see Overbeck et al. (1982).

The phytoplankton and periphyton of Lake Trichonis include some interesting taxa (Economou-Amilli, 1979, 1982; Kristiansen, 1980; Anagnostidis et al., 1985, 1988a, b; Falniowski et al., 1988; Tafas, 1991). Another investigation has examined the correlation between the patterns of phytoplankton distribution and abiotic variables in this lake (Tafas & Economou-Amilli, 1991). The second part of this study (Tafas & Economou-Amilli, 1997) documents several community structure aspects of the lake microflora, including the seasonal phytoplankton periodicity.

Earlier attempts for a limnological survey of Trichonis have yielded sporadic data (Becakos-Kontos, 1971; Koussouris, 1981). Some other studies (Overbeck et al., 1982) were more detailed, however the latter were based on irregularly scheduled field trips. This paper examines the physical and chemical status of lake Trichonis over two annual cycles (April 1985 to February 1986, and October 1988 to September 1989) and presents a preliminary correlation between nutrient patterns with phytoplankton biomass. The continuous monitoring of basic limnological characteristics is necessary for a complete understanding of the lake's hydrobiological status. Besides its ecological importance Trichonis has been considered as a possible source for water supply of the city of Athens during summer shortages. The study of this typically warm monomictic lake can contribute significantly to the field of both regional and comparative limnology (Overbeck & Anagnostidis, 1982).

## Material and methods

Sampling was carried out at a site near the deepest point (58 m) of lake Trichonis from April 1985 to February 1986 for Annual Cycle I, and from October 1988 to September 1989 for Annual Cycle II. Using a Ruttner sampler water samples were collected from 10 to 20 different depths between 0–30 m depending on season with more samples obtained during stratification. Temperature and dissolved oxygen were measured *in situ* using a YSI-51B oxygen meter and probe. The depth of the euphotic zone was determined by Secchi disk. Light attenuation was measured using either an OSK-3174 submersible Lux meter or a LI-185B quantum radiometer. The annual heat budget ($\Theta_{ba}$) and the density difference between the epilimnion and the hypolimnion were calculated according to the methods given by Hutchinson (1957). Conductivity, pH and alkalinity were measured in situ. Conductivity readings were obtained using a YSI-33 SCT-meter. Alkalinity and the various forms of inorganic carbon ($HCO_3^-$, $CO_3^{2-}$, free $CO_2$) were calculated after titration with 0.1 N $H_2SO_4$ according to APHA (1980). Samples for nutrient estimation were preserved in accordance with the recommendations of APHA (1980). Calcium concentration was calculated by titration (APHA 1980). Ammonia nitrogen ($NH_4^+$-N) and chloride were measured by Orion's selective electrodes (no. 95-12 and 96-17B respectively). Total organic nitrogen was determined by Kjeldahl digestion and subsequent ammonia determination (Midgley & Torrance, 1978). Nitrate nitrogen ($NO_3^-$-N) was measured after reduction to nitrite with metallic Zn (Freier, 1974). Nitrite nitrogen ($NO_2^-$-N) was measured photometrically as red azide (APHA, 1980; Mackereth et al., 1978). Inorganic phosphorus ($PO_4^3$-P) and silica ($SiO_2$) were analysed photometrically according to Murphy & Riley (1962) and APHA (1980) respectively. Total phosphorus concentration was determined photometrically after wet digestion (APHA, 1980). Chlorophyll-*a* concentration was determined after filtration *in situ* through glass-fibre filters and extraction with methanol in the dark (Holm-Hansen & Reimann, 1978). Phytoplankton was counted with a Zeiss inverted microscope according to the Utermöhl's (1958) sedimentation method. Phytoplankton analysis was subject to the statistical criteria set by Lund et al. (1958). Phytoplankton biomass determination was based on the calculation of species volume using appropriate geometric formulae and assuming a specific gravity of one (Van Heusden, 1972; Willen, 1976).

## Results

### *Physical variables*

Temperature profile in lake Trichonis (Figures 1–2) showed a minimum of 9.5 °C in January during winter overturn. A stable metalimnion began to form at the beginning of April and lasted through November in both study periods. At the peak of the stratification period, the upper boundary of metalimnion was generally between 10–13 m of depth, while the lower was located between 18–20 m. At the end of stratification the metalimnion extended between 21 and 24 m. Mean temperature in the epilimnion was $>22$ °C from June to September. Maximum temperature values during both years (26.2 °C and 27.5 °C) were observed in August. The annual heat budget $\Theta_{ba}$ between January and August 1986 was 70 564 kcal $cm^{-1}$ $y^{-1}$. At the same period density difference between the epilimnion and the hypolimnion was high (2971 g $l^{-1}$).

The euphotic zone depth was $>20$ m throughout Annual Cycle I (Figure 3) and during stratification in Annual Cycle II (Figure 4). The light bands with the greatest penetration were green and blue. Measurements in October 1985 showed that red light was fully attenuated at 10 m of depth, whereas blue and green light penetrated equally, having values similar to the overall extinction coefficient value (c. 0.17 ln units $m^{-1}$). Phytoplankton characteristics (species abundance, biomass, chlorophyll-*a*) and light penetration during Annual Cycle I are correlated in Table 2.

### *Chemical variables*

The epilimnion and the upper layers of hypolimnion remained well oxygenated (Figures 5–6). In Annual Cycle I, oxygen saturation values higher than 100%

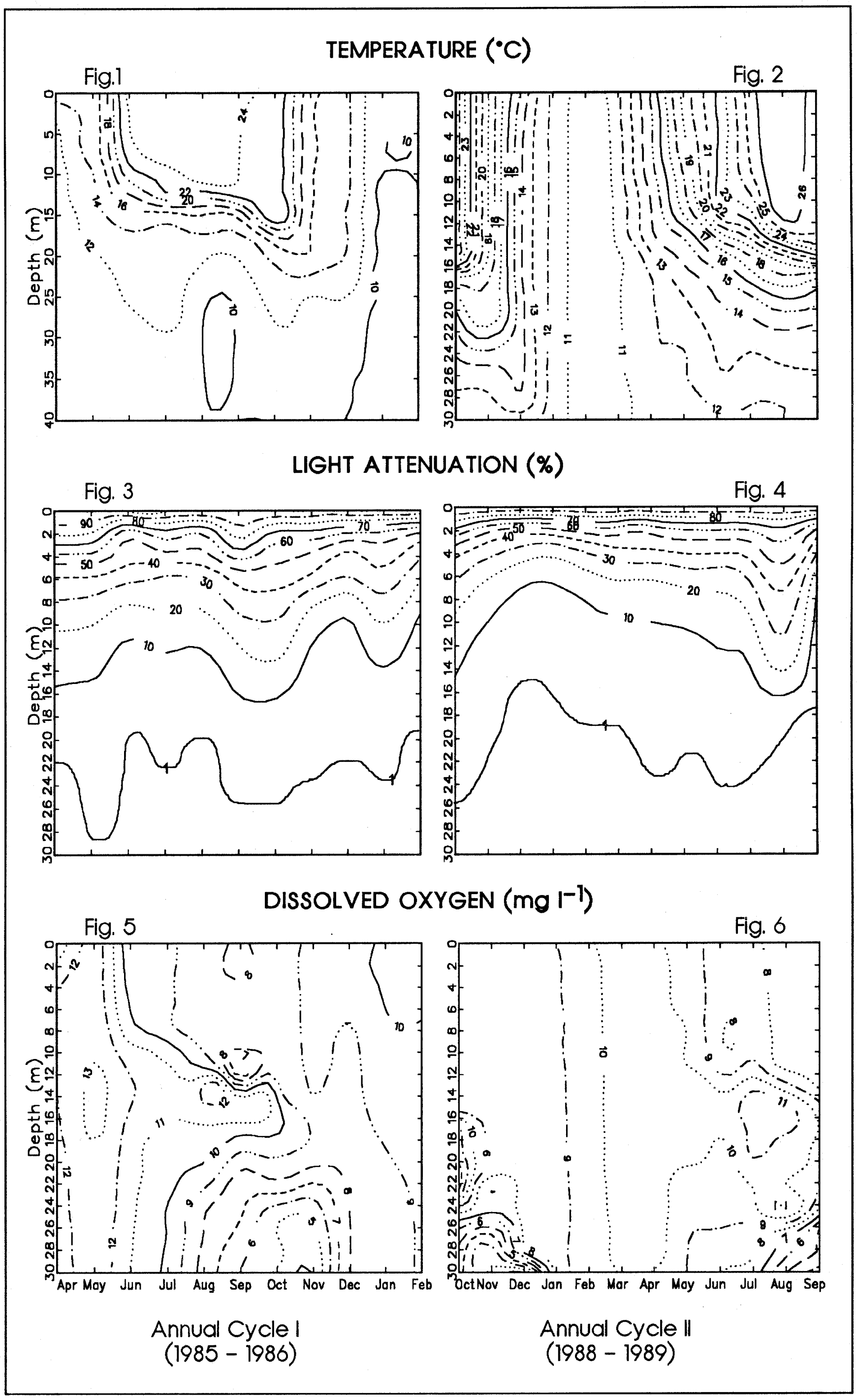

*Plate 1.* Vertical profiles of temperature, light attenuation and dissolved oxygen in lake Trichonis over the study periods.

*Table 2.* Spearman rank correlation coefficients between phytoplankton community characteristics and light penetration (probability levels in parentheses).

| | Mean chlorophyll-$a$ concentration | Maximum chlorophyll-$a$ concentration | Mean phytoplankton abundance | Mean phytoplankton biomass |
|---|---|---|---|---|
| Secchi disk depth | 0.25 | 0.21 | 0.19 | 0.05 |
| | (0.42) | (0.50) | (0.55) | (0.89) |
| Euphotic zone depth | −0.12 | 0.44 | 0.11 | 0.15 |
| | (0.70) | (0.16) | (0.73) | (0.63) |

were maintained at a depth of 30 m until the middle of stratification, with a subsequent decline with depth. Oxygen deficiency was not observed in the upper layers of hypolimnion. Lower oxygen saturation values were observed in the beginning of the stratification period during Annual Cycle II; oxygen saturation was 3.5% at a depth of 35 m, and slightly over 1% in the bottom layers immediately before the winter overturn. However, complete hypolimnetic anoxia was never reached.

The water was generally alkaline with pH ranging from 7.6 to 8.5. The high pH values ($>8$) in the epilimnion were sustained during stratification but gradually decreased to reach a minimum during overturn. A similar pH trend occurred in the hypolimnion to levels below 7.5 at a depth of 40 m. Conductivity ranged from 195 during overturn to 320 $\mu$S cm$^{-1}$ in the hypolimnion during stratification.

Calcium concentration was high (26–45 mg l$^{-1}$). Chloride concentration ranged from 12 to 24 mg l$^{-1}$. Inorganic carbon was abundant mainly as bicarbonates. Dissolved $CO_2$ was present during turnover (2–7 mg l$^{-1}$) when alkalinity reached values of 240 mg $CaCO_3$ l$^{-1}$ (Annual Cycle I) or just 135 mg $CaCO_3$ l$^{-1}$ (Annual Cycle II). At the onset of stratification dissolved $CO_2$ almost disappeared ($<1$ mg l$^{-1}$) from the epilimnion reaching gradually higher concentrations in the hypolimnion, whereas total alkalinity values gradually decreased (approx. 115 mg $CaCO_3$ l$^{-1}$).

Differences were shown in the inorganic nitrogen content between the two annual cycles (Figures 11–12). Inorganic nitrogen in lake Trichonis was mainly in the form of nitrate with a prominent accumulation in the hypolimnion during Annual Cycle I (Figure 7), but greatly reduced during Annual Cycle II (Figure 8). Nitrite nitrogen concentrations ranged between 0–5 $\mu$g l$^{-1}$ (Annual Cycle I) or remained below detection limits (Annual Cycle II). Ammonia nitrogen concentrations were generally low during Annual Cycle I (Figure 9), never exceeding 90 $\mu$g l$^{-1}$; in Annual Cycle II, ammonia values were almost below detection limit ($<10$ $\mu$g l$^{-1}$) in all strata, remaining below 50 $\mu$g l$^{-1}$ during overturn (Figure 10). Higher Kjeldahl N concentrations (100–300 $\mu$g l$^{-1}$) were measured in Annual Cycle I, in contrast to the distinctly lower values of Annual Cycle II (10–45 $\mu$g l$^{-1}$).

Inorganic phosphorus levels were low ($<20$ $\mu$g l$^{-1}$ $PO_4^-$-P) except during overturn when values as high as 70 $\mu$g l$^{-1}$ (Annual Cycle I) or 50 $\mu$g l$^{-1}$ (Annual Cycle II) were recorded. Total phosphorus concentrations remained below 70 $\mu$g l$^{-1}$ with lower levels prevailing during Annual Cycle II (Figures 13–14). The N:P ration shifted from $>20$ in Annual Cycle I to $<10$ in Annual Cycle II due to a decline of the epilimnetic nitrogen content.

Silica ($SiO_2$-Si) concentration in the epilimnion during both annual cycles was low (100–200 mg l$^{-1}$). Through constant accumulation in the hypolimnion silica reached high values (c. 4000 $\mu$g l$^{-1}$ at a depth greater than 30 m in Annual Cycle I) at the end of stratification (Figures 15–16).

Chlorophyll-*a* concentrations differed distinctly over the two study periods (Figures 17–18). During Annual Cycle I, epilimnetic chlorophyll-*a* concentrations did not exceed 4 $\mu$g l$^{-1}$ from April to September with higher values in the metalimnion (8.2 $\mu$g l$^{-1}$ at 12 m and 6.2 $\mu$g l$^{-1}$ at 14 m in June 1985), whereas lower values ($<2.5$ $\mu$g l$^{-1}$) occurred during overturn. During Annual Cycle II, chlorophyll-a concentrations were generally lower never exceeding 2.2 $\mu$g l$^{-1}$ with maximum values also in the metalimnion (c. 3.5 $\mu$g l$^{-1}$) by the end of turnover.

## Discussion

The thermal regime in Trichonis (minimum temperature 9.5 °C, a single turnover annually) is that of a warm monomictic nature of lake (see also Overbeck et al.,

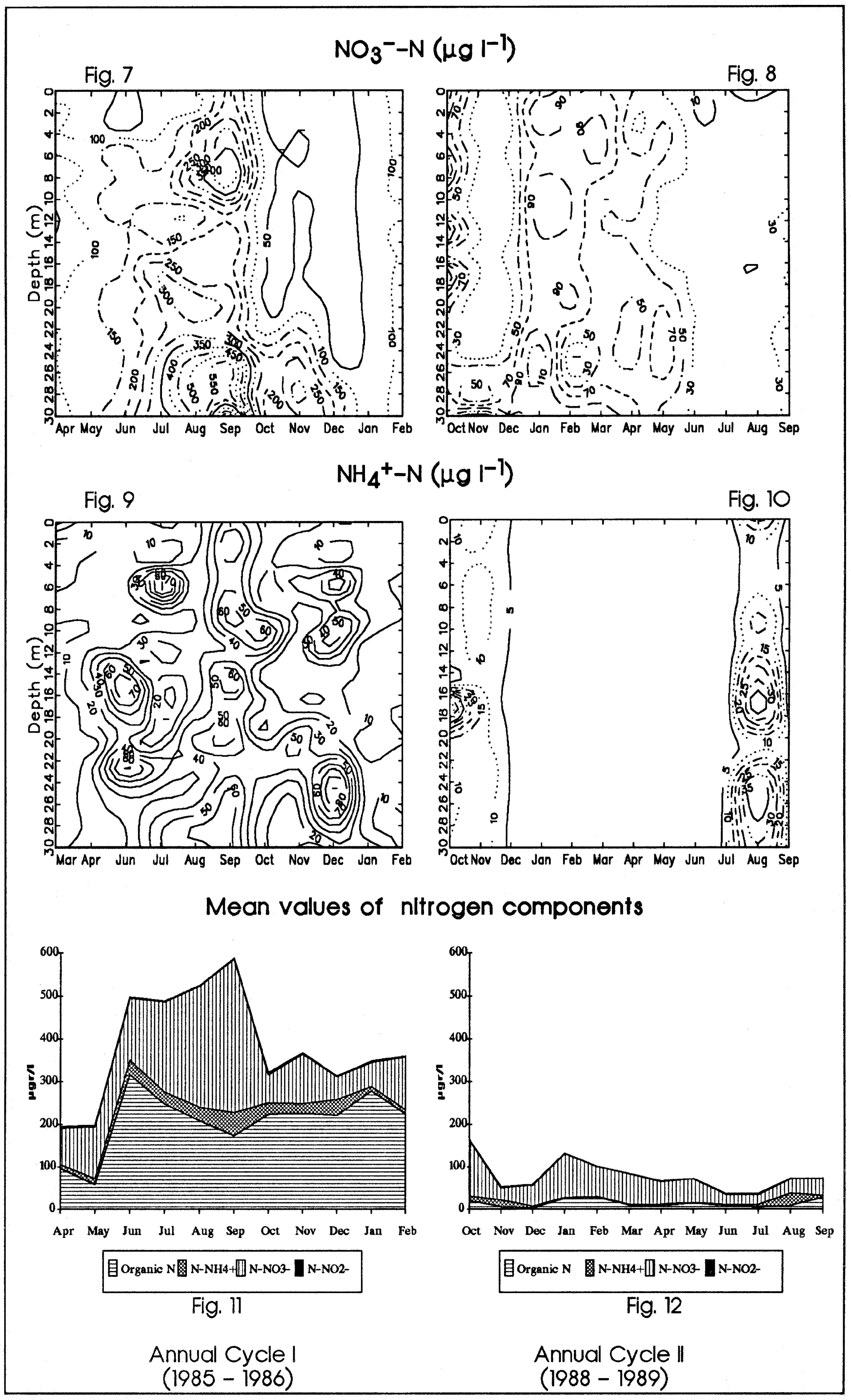

*Plate 2.* Vertical profiles of nitrate and ammonia concentrations, as well as the mean values of inorganic nitrogen components in lake Trichonis over the study periods.

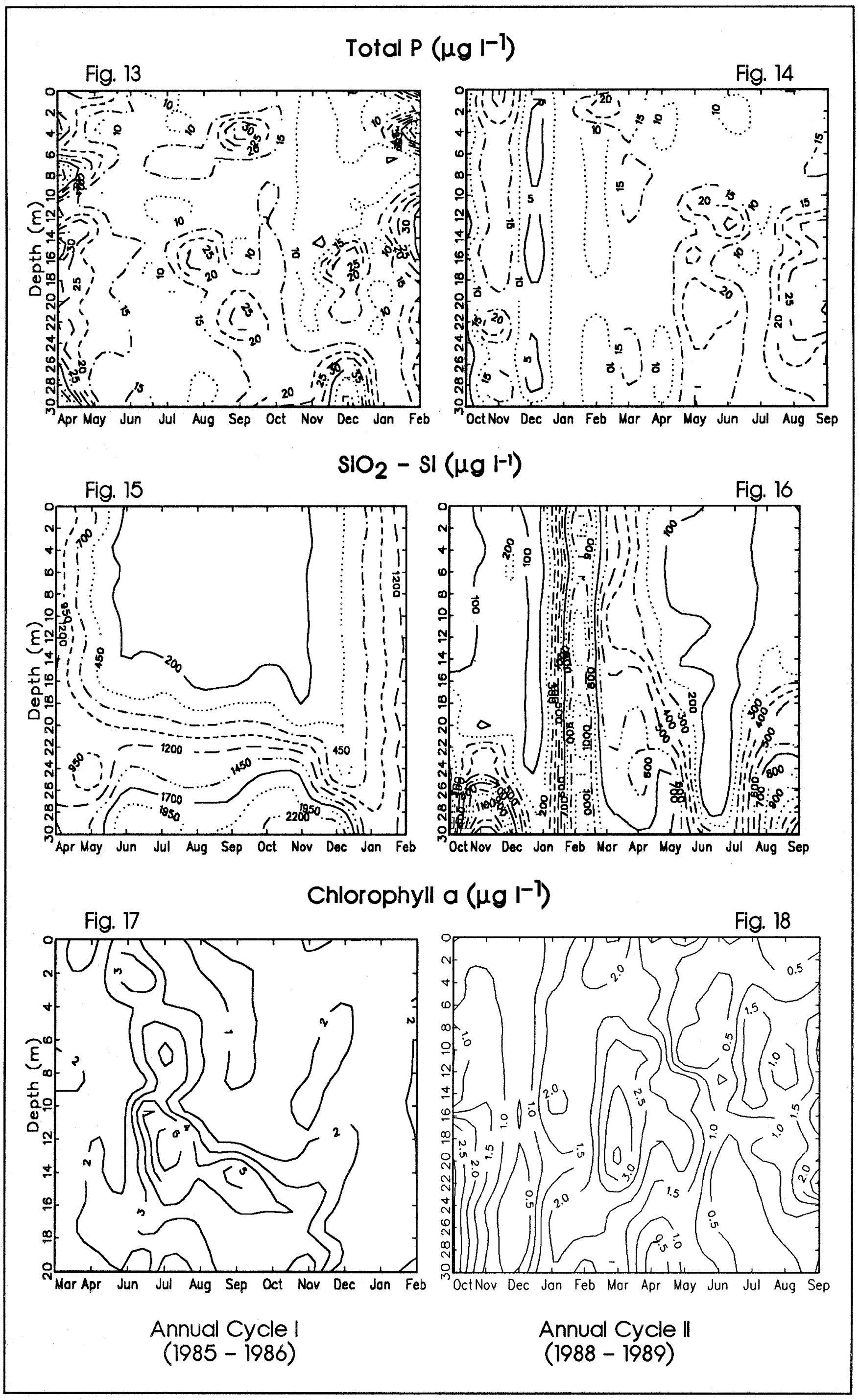

*Plate 3.* Vertical profiles of total phosphorus, silica and chlorophyll-*a* concentrations in lake Trichonis over the study periods.

*Table 3*. Annual heat budget (*sensu* Hutchinson, 1957) of lake Trichonis compared with various temperate and warm lakes at different latitudes north of equator. Sources: in (1) Lewis 1973, (2) Hutchinson 1957, (3) Stanhill & Neumann 1978, (4) Tafas 1991.

| Lake | Latitude | Annual heat budget (kcal $cm^{-1}$ $y^{-1}$) |
|---|---|---|
| Lanao(1) | 8° 00′ | 4,500–7,250 |
| Amatitlan(2) | 14° 25′ | 8,510 |
| Titicaca(2) | 16° 00′ | 18,900 |
| Kinneret(3) | 32° 42′ | 40,000–67,000 |
| TRICHONIS(4) | 38° 35′ | 70,500 |
| Geneva(2) | 42° 34′ | 32,300 |
| Michigan(2) | 44° 00′ | 52,400 |
| Baikal(2) | 53° 00′ | 65,500 |

1982; Tafas, 1991). Due to the climate conditions and latitude of the lake district, there is a rapid warming of the surface layers and moderate thickness of the drift current layer (see Serruya & Pollingher, 1983) resulting in a shallow thermocline (thickness of epilimnion 10–13 m at the peak of stratification); in this sense Trichonis resembles more closely to temperate lakes than the tropical ones. It is worth noticing that shallow metalimnia characterize lakes of higher latitudes (e.g. in lake Geneva located 42° 34′ N and with max. depth 310 m, the thermocline starts at 15 m depth; Hutchinson, 1957), whereas in warm lakes of lower latitudes deeper metalimnia were recorded (e.g. in lake Kinneret with 32° 42′ N and max. depth 43 m, the thermocline starts at 18 m of depth at the peak of stratification; Serruya, 1978). The same stratification pattern with a shallow and stable thermocline was observed in Amvrakia, a lake located in the vicinity of Trichonis (Danielidis et al., 1996), whereas in the warm monomictic lake Volvi located in northern Greece a weaker thermocline was recorded (Moustaka-Gouni, 1988).

Additionally, stratification in lake Trichonis is considered highly stable with a density difference between epilimnion and hypolimnion reaching a maximum of 2971 g $l^{-1}$, and is comparable to lakes of lat. 20°–30° N with a high thermal stability (lake Kinneret 32° 42′ N, 3.75 g $l^{-1}$; lake Nasser 22° N, 4.67 g $l^{-1}$ in Serruya & Pollingher, 1983; and lake Geneva 42° 34′ N, 1.77 g $l^{-1}$ in Hutchinson, 1957). Although classified as a typical warm lake, Trichonis more closely resembles temperate lakes with regard to its annual heat budget (see Table 3).

Because of the high water transparency, the euphotic zone extends to 15–29 m. This euphotic zone depth is greater than that of the adjacent lakes Amvrakia (12–20 m: Danielidis et al., 1996) and Lyssimachia (less than 5 m: Overbeck et al., 1982) or lake Volvi in northern Greece (c. 4 m; Moustaka-Gouni, 1988). The spectral properties of the water are similar to those of distilled water (sensu Wetzel, 1983), with the green and blue wavelengths having the highest penetration (see also Overbeck et al., 1982; Tafas, 1991). A weak correlation was found between the phytoplankton community (species abundance, biomass, chlorophyll-*a*) and light penetration during Annual Cycle I (Table 2). The high water transparency implies an oligotrophic status for lake Trichonis.

Nutrient concentrations during Annual Cycle II show a dramatic decline at the onset of stratification. At this period phosphorus is still present but nitrogen depleted, leading to the observed decrease of the N:P ratio; as a result phytoplankton growth was restricted, and chlorophyll-*a* concentrations never exceeded 2.2 $\mu$g $l^{-1}$, despite the favourable temperature and light conditions. The chlorophyll-*a* pattern is typically monoacmic. Based on the chlorophyll-*a* concentrations – especially the recorded values in Annual Cycle II – Trichonis is classified as an oligotrophic lake (sensu Ogawa & Ichimura, 1984). Both the lower chlorophyll-*a* content and the large depth of the euphotic zone imply that the lake does not follow an obvious transition to eutrophication. Phytoplankton biomass levels, even during the July bloom, did not exceed 7000 mg $m^{-3}$. The biomass ranged between 44–241 mg $m^{-3}$ from March to April, while in July it had a mean value of 4295 mg $m^{-3}$ (Tafas, 1991). Two additional parameters, indicating that Trichonis can be classified among the oligotrophic lakes with mesotrophic tendencies, are the phytoplankton periodicity and biomass distribution patterns (Tafas & Economou-Amilli, 1997).

Both the high transparency of the lake water (euphotic zone generally over 20 m) and the recorded phytoplankton productivity of 0.9–3.9 mg C $m^{-3}$ $h^{-1}$ (Overbeck et al., 1982; Tafas, 1991) would have been expected to support high whole-lake biomass values. However, the recorded low biomass values per volume are justified since temperature was found to be the governing factor for community succession in lake Trichonis (Tafas & Economou-Amilli, 1991). Therefore, the low standing phytoplankton crop may be due to (a) the accelerated decomposition combined with the generally high metabolic rate induced by the temperature increase (Overbeck, unpubl. data) and (b) the possible grazing impact by zooplankton (Dumont, unpubl. data).

The high dissolved oxygen levels of both the epilimnion and the upper layers of hypolimnion throughout stratification, might be explained (a) by the lake morphometric characteristics (large, deep lake) combined with the high transparency of the water, (b) by the water circulation due to wind and current action and (c) by the relatively low total plankton biomass resulting to a positive net oxygen production (Tafas, 1991; Dumont, unpubl. data). Even in the hypolimnion, dissolved oxygen was low, but anoxic conditions were never recorded. On the contrary, both adjacent lakes, i.e. the deep Arnvrakia and the shallow Lyssimachia with higher productivity levels, showed hypolimnetic anoxia and are considered mesotrophic and eutrophic respectively (Overbeck et al., 1982; Danielidis et al., 1996).

Due to its carbon chemistry (determined by alkalinity and pH) Trichonis belongs to the ‘carbonate type’ of lakes with relatively low conductivity (Overbeck et al., 1982), while with regard to salinity and temperature it is a ‘class II low salinity’ warm lake (*sensu* Serruya & Pollingher, 1983). The slightly lower conductivity values recorded in the epilimnion during Annual Cycle II could be attributed to biological and physical removal of CaC03 (Otsuki & Wetzel, 1974; Wetzel, 1983), a process intensified at warmer and drier climate conditions. Alternatively, the low conductivity might also be due to the reduced precipitation resulting to lower limestone dissolution of the karstic environment, a phenomenon observed during the preceding overturn. The alkaline lake water shows a clear seasonal pH pattern with peak values occurring in the epilimnion during and following the plankton bloom. In this context, the high pH values of the upper layers of the hypolimnion indicate intense photosynthetic activity at the onset of stratification.

Nutrient concentrations and availability were maintained at low levels during both study periods in lake Trichonis. Inorganic nitrogen content distinctly differed over the two annual cycles. The nitrogen content was distinctly higher during Annual Cycle I. Lower $NO_3^-$-N concentration during Annual Cycle II is attributed to the reduced nutrient input from lower surface runoff due to drought. The lower organic nitrogen content of the lake resulting from the lower productivity during Annual Cycle II, contributed to the observed nitrogen deficiency. The phosphorus content did not change substantially during both annual cycles. Inorganic phosphorus was generally low with minimal values recorded in the epilimnion especially after the summer algal bloom. The low $PO_4$-P concentration is due to the low inorganic phosphorus input to the lake; $PO_4$-P concentration in several incoming waters during Annual Cycle I ranged from 20 to 50 $\mu$g $l^{-1}$.

The N:P ratio showed that P was a limiting factor during Annual Cycle I. The same ratio shows N-limitation during Annual Cycle II. This change can be attributed to the decline of the nitrogen content, rather than an increase in the phosphorus content which remained low with insignificant variation between the two years studied. Sakamoto (1966) characterized Japanese lakes with N:P ratio >15–17 as P-deficient, while lakes with N:P <9–10 were considered N-deficient. According to Chiaudani & Vighi (1974) nitrogen becomes a limiting factor at N:P ratios below 5, a view shared also by Schindler (1977). Vollenweider (1982), on the other hand, suggests that N:P ratios <7 show nitrogen deficiency and ratios >15 indicate phosphorus deficiency. Many temperate lakes exhibit phosphorus deficiency (Schindler, 1977), while tropical lakes are usually deficient in nitrogen (Talling & Talling, 1965; Vincent et al., 1984). However, this distinction has been disputed (see Melack et al., 1982; Canfield, 1983).

Based on the total P and N concentrations and chlorophyll-*a* content, lake Trichonis is classified either as an oligotrophic to mesotrophic lake according to the measurements of Annual Cycle I, but oligotrophic according to data from Annual Cycle II (Vollenweider, 1979, 1982; USEPA 1974; NAS/NAE 1972).

In conclusion, lake Trichonis seems to be an oligotrophic lake with mesotrophic tendencies based on its physical and chemical characteristics. This is corroborated by findings on biological indices (Tafas & Economou-Amilli, 1997). Small differences were discerned over the two annual cycles in the four-year period of 1985–1989. The present study, along with measurements from random sampling by Overbeck et al. (1982), shows that the eutrophication process in recent years has not been essentially accelerated at least in the pelagic zone. The homeostatic capacity of Trichonis against anthropogenic impact has not been exceeded yet.

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