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Trophic Characteristics of the Sapanca Lake (Turkey)*

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Systematic measurements of optical properties, concentrations of major and minor chemicals and primary production throughout 1989–1992 enabled us to identify the oligotrophic state of Sapanca lake, Marmara region, Turkey. Lake waters which have low concentrations of major anions and cations (total = 49 μM) overturn every February–March, ventilating the bottom waters and enriching the surface waters with nutrients. Surface waters cool down to 6.5 °C by late winter and then warm steadily to 26 °C by late summer, while temperatures in deep waters range between 6.5 and 10.0 °C throughout the year. When the seasonal thermocline develops, the dissolved oxygen profiles exhibit a subsurface maximum in the thermocline, while in the hypolimnion water, the content varies seasonally from 11.5–12.0 ppm (350–375 μM) in March to 0.5–1.7 ppm (16–56 μM) in late autumn. Surface nitrate concentrations vary markedly with season, from < 0.15 μM in summer to 5.7 μM in early March, whilst the bottom water concentrations range from 13.5–14.0 μM in late autumn to 5.7 μM after the winter

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overturn. Phosphate concentrations are always less than 0.1 μM throughout the entire water column. Subsurface chlorophyll-a maximum descends in late summer to 20–25 m depths, where the light intensity is less than 1% of the surface value. Below 10–15 m depths, corresponding to the upper thermocline, primary productivity is very low. The range was from 35 to 93 mg C/ m^2 day^{-1} during 1989–1991, consistent with the values in other oligotrophic lakes.

INTRODUCTION

Lake Sapanca is located in the northeast of the Marmara region of Turkey (Figure 1). It has a volume of about 10^9 m^3 and a surface area of 49 km^2, which is nearly 5 times smaller than the catchment area (250 km^2). This freshwater lake, fed by several creeks (which are nearly dry in summer) and partly by groundwater,[1] has been used for years as a source of freshwater by the city of Adapazari and by some of the industries in the Izmit area. No estimate has been given for the mean residence time of lake waters. Though there is no direct discharge of waste into the lake, chemical pollutants of both domestic and agricultural origin find their way into the lake through surface-runoff.[2,3]

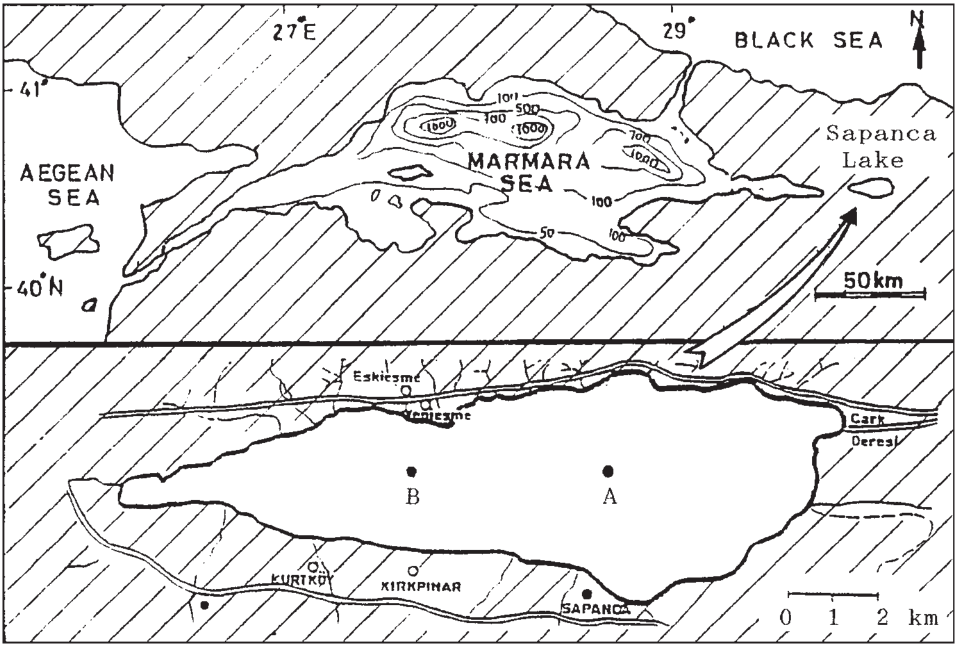

Figure 1. Location of the Sapanca Lake and sampling stations A and B.

Before 1980, a few studies of its principal limnological properties[3,4] showed the lake to contain low concentrations of dissolved inorganic ions and the water to be adequate for drinking, industrial usage and irrigation.[3] In 1989, we initiated a comprehensive study of the lake to determine its principal limnological characteristics and assess its trophic state. Concentrations of major anion and cation components of the lake water were determined only in the summer months of 1989 and 1992. By the end of 1992, other physical and biochemical parameters controlling primary production in the lake were studied systematically in the water columns of the two deepest locations. Data obtained between 1989–1992 were partly evaluated in technical reports.[2,5] Metal pollutants measured in surface sediments and biochemical data obtained in the water column in July–September 1989 have been published elsewhere.[6]

The present paper aims to describe the current limnological characteristics of Lake Sapanca, based on the physical and biochemical data obtained during 1989–1992. These findings are of critical importance, not only for defining the present trophic state of the lake but also for the development of both biological models and rational management plans.

EXPERIMENTAL

The deepest locations (maximum depths of 40 and 45 m), denoted as stations A and B in Figure 1, were visited regularly in the course of the study. Sampling dates and parameters measured during each field survey are given in Table I. Water samples were collected at depths of 0.5, 5, 10, 15, 20, 25, 30, 40, and 45 meters in horizontal-type Nansen bottles. Samples for measurements of primary production were collected at depths where solar irradiance was reduced to 75%, 50%, 25%, 10%, 3% and 1% of its surface value. Bioassay samples were collected at 3 m and 1% surface light depths at station B only.

Water samples for metal, anion and nutrient analyses were kept refrigerated or frozen according to the Standard Methods.[7] Samples for total organic carbon analysis were first acidified with 6 N HCl to a pH of less than 3 and then kept cool in the dark. Samples for phytoplankton production, bioassay and chlorophyll-a measurements were placed in ice-boxes and immediately transported to the Institute laboratory in Gebze for processing according to the measurement protocols. The chlorophyll samples were filtered immediately on Whatman GF/F filters, which were then kept frozen until analysis. Water samples taken for pH and alkalinity measurements were kept cool in an ice-box until processed in the laboratory.

Concentrations of major cations (Ca, Mg, Na, K) in the lake water were determined by a Hitachi flame-atomic absorption spectrometer. Sulphate, fluoride and chloride concentrations in lake water were measured by a Shimadzu model ion chromatography. Dissolved inorganic nutrients (nitrate + nitrite, ammonia, phosphate, reactive silicate) were determined colorimetrically using a two-channel Technicon auto-analyzer. The methods of analyzing nutrients were similar to those given in the Standard Methods[7] and Strickland and Parsons.[8] The total-phosphorus content of

TABLE I

List of sampling dates and parameters measured in Sapanca Lake at two stations between 1989–1992

Dates		Parameters
06 July '89	30 Apr. '91	Temperature, conductivity
23 Aug. '89	13 June '91	Major anions and cations (*)
25 Sep. '89	08 Aug. '91	Nutrient elements (N, P, Si)
30 Oct. '89	12 Sep. '91	Total organic carbon (TOC)
25 Dec. '89	21 Jan. '92	Dissolved oxygen (DO)
04 Apr. '90	30 Mar. '92	Chlorophyll-a (CHLA)
24 July '90	26 May '92	Primary production (PP)
27 Nov. '90	30 June '92	Limiting nutrients (**)
14 Jan. '91	08 Sep. '92	Light penetration
18 Feb. '91	06 Oct. '92	
13 Mar. '91		

* Measured in July 1989 – May 1992.

** Bioassay experiments carried out in July '90, November '90, April '91, June '91, August '91, September '91.

lake water was measured by the persulphate oxidation technique; after open digestion and adjustment of the pH to 8.0, phosphate concentrations were measured colorimetrically.[7] Total organic carbon in lake water was measured using a Shimadzu TOC-500 model analyzer whose oxidation efficiency was guaranteed by an intercomparison exercise.[9] Filter samples for chlorophyll-a and pheopigment analyses were extracted with 90% acetone; fluorescence intensities of the extracts were then determined with the Hitachi model instrument both before and after acidification.[7] For quantification, a chlorophyll-a standard (SIGMA) was used. Temperatures and dissolved oxygen concentrations were measured *in situ* using a YSI model probe and a deck unit. Conductivity was measured with a WTW model instrument, precalibrated with standard KCl solution.

Solar light penetration in the lake was measured with a portable quantameter. Phytoplankton production in samples taken from the selected depths was determined by the ^{14}C technique developed by Nielsen[10] and later modified by Gargas.[11] Briefly, 2.0 μCi was added to each water sample in 25 ml glass bottles, which were then incubated for 2 hours under artificial light at the *in situ* temperature. After incubation, the phytoplankton assemblage in the bottle was collected on a membrane filter (pore size: 0.2 μm) under suction of about 0.3 atm. The ^{14} C-labelled carbonate ions utilized in photosynthesis and converted to organic particulates were measured quantitatively with a Tri-Carb 1550 low-level, liquid scintillation counter. Values of potential production in incubated samples were converted to daily production at stations A and B using the Estimation of Daily Production Programme (EDP), originally developed by the Water Quality Institute, Denmark.

For bioassay experiments, ionic nutrients from stock solutions were added to the lake water either separately or in combination; the final concentrations of each element in each 25 mL lake sample, similar to those used by other workers,[12] are given in Table III.

TABLE II

Average concentrations of major cations and anions, conductivity (at 25 ºC) and pH measured in the water column of Sapanca Lake

Depth m	Conductivity µS cm^{-1}	pH	Ca^{2+} µM	Mg^{2+} µM	Na^{+} µM	K^{+} µM	CO$_3^{2-}$ µM	SO$_4^{2-}$ µM	Cl^{-} µM	F^{-} µM	Si^{4+} µM
0.5	245–277 (259)*	7.44–8.54 (8.25)	795–987 (891)	272–288 (281)	245–265 (255)	12–31 (25)	1742–2333 (1920)	169–188 (181)	110–169 (138)	6.3–8.4 (7.4)	23–58 (38)
5	248–264 (262)	8.07–8.57 (8.24)	835–927 (880)	283–288 (286)	249–262 (256)	12–32 (22)	1733–2293 (2151)	170–184 (179)	138–169 (158)	7.4–9.5 (7.9)	23–59 (38)
10	250–277 (260)	7.43–8.58 (8.24)	807–987 (912)	275–284 (279)	249–263 (256)	12–32 (25)	1690–2350 (2158)	173–185 (182)	135–175 (162)	7.9–10 (8.9)	27–59 (41)
15	255–278 (264)	7.95–8.66 (8.24)	–	–	–	–	1952–2303 (2182)	173–180 (176)	107–166 (138)	6.8–9.5 (8.4)	33–60 (45)
20	267–288 (279)	7.62–8.15 (7.79)	887–1037 (970)	272–283 (275)	251–261 (256)	14–33 (26)	2030–2333 (2213)	170–187 (179)	124–172 (159)	5.3–8.9 (7.4)	46–64 (55)
30	262–288 (279)	7.33–7.86 (7.53)	950–1087 (997)	280–288 (284)	249–265 (259)	13–32 (26)	2050–2450 (2305)	172–181 (176)	129–214 (166)	5.3–7.9 (7.4)	51–89 (62)
40	262–288 (280)	7.32–7.86 (7.53)	947–1040 (990)	280–284 (282)	243–265 (259)	13–31 (27)	2087–2483 (2283)	176–181 (178)	132–169 (153)	5.3–7.9 (6.8)	55–89 (64)

* The value in parentheses represents the arithmatic mean of measurements.

TABLE III

Final mass concentrations (γ/μM) of nutrient ions added in each sub-sample (750 mL) before the incubation

1. Control	Nothing added
2. γ_{N} (KNO_3)	25 μM
3. γ_{P} (KH_2PO_4)	1.6 μM
4. γ_{N} (NO_3^-) + γ_{P} (HPO_4^{2-})	25 μM + 1.6 μM
5. γ_{Si} (Na_2SiF_6)	28.5 μM
6. γ_{Mo} ($NaMoO_4$)	0.05 μM

RESULTS AND DISCUSSION

Concentrations of major anions and cations were determined during stratification to assess the total dissolved inorganic matter content in water. The conductivity data obtained systematically in 1989–1992 permit one to collate inter-annual changes in total major components of lake water. The biologically-related parameters listed in Table II, which control primary production or give information on algal biomass in the water column, were determined systematically at selected depths at station A or B, or both, in 1989–1992. We discuss these data here in order to determine the current water quality of the lake and parameter variations with both depth and season.

Average concentrations of major dissolved inorganic ions, measured in July 1989 and May 1992 at selected depths of stations A and B, are given in Table II. Not surprisingly, the major cation in the lake water is calcium, with concentrations of 930–960 μM in the surface layer (0–10 m) and 1020–1040 μM below 30 m. Other major cations, though of secondary importance, are magnesium (Mg), sodium (Na) and potassium (K); their concentrations remained almost constant throughout the entire water column, varying only between 280–290 μM for Mg, 260–270 μM for Na and 37–38 μM for K. Major anions present in lake water were found to be carbonate (1920–3000 μM), sulphate (220–230 μM), chloride (160–170 μM) and reactive silicate (28–75 μM). It appears that calcium and carbonate ions dominate the total dissolved inorganic matter content of the Sapanca Lake waters.

Figure 2a depicts measurements of conductivity, normalized to 25 °C, indicating variation with both season and depth due to changes in the total dissolved ion content of the Sapanca Lake water. In the summer-autumn period before the overturn of the entire water column, the conductivity ranges between 245 and 280 μS/cm in the surface mixed layer (epilimnion); it increases by about 15% to levels of 265–285 μS/cm in deep waters below the seasonal thermocline. In late winter-early spring, when lake waters are mixed thoroughly from top to bottom, the entire water column possesses a nearly uniform conductivity profile with a value of 280–285 μS/cm.

Vertical distributions of temperature in lake water are displayed in Figure 2b, indicating an apparent seasonality in the upper mixed layer (epilimnion). Figure 2c illustrates the monthly variation of temperature in the epilimnion and at the 40 m depth between 1989 and 1992. Surface water starts warming in spring and the temperature increases steadily from nearly 6.5 °C in March to 27.5–28.0 °C in August. Later, with the beginning of surface cooling in autumn, the upper mixed layer temperature decreases again to around 21.0–22.0 °C in September, 7.0–10.0 °C in January and 6.8 °C in February. In contrast, deep water temperatures range between 6.5–7.0 °C in February–March and 7.8–8.0 °C in summer In February–March, the thorough mixing of the water column from top to bottom leads to an isothermal depth profile of 6.5–6.8 °C. The seasonal thermocline, lying between 10 and 20 meters in summer, weakens in late autumn – early winter and disappears in February–March due to the overturn. Lake Sapanca, with one overturn per year is a typical example of a warm-monomictic lake.[13]

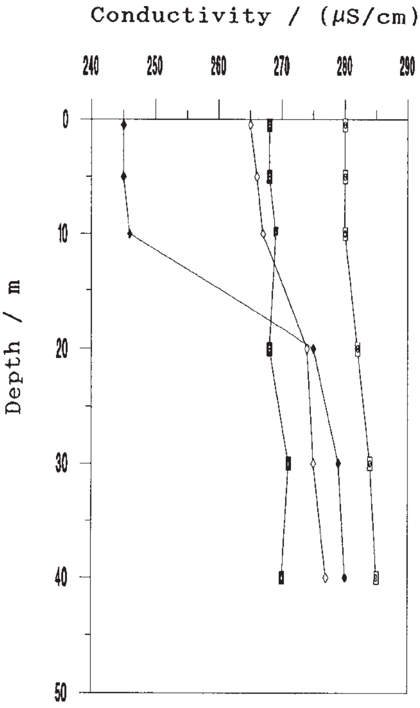

Figure 2a. Conductivity profiles at station A.

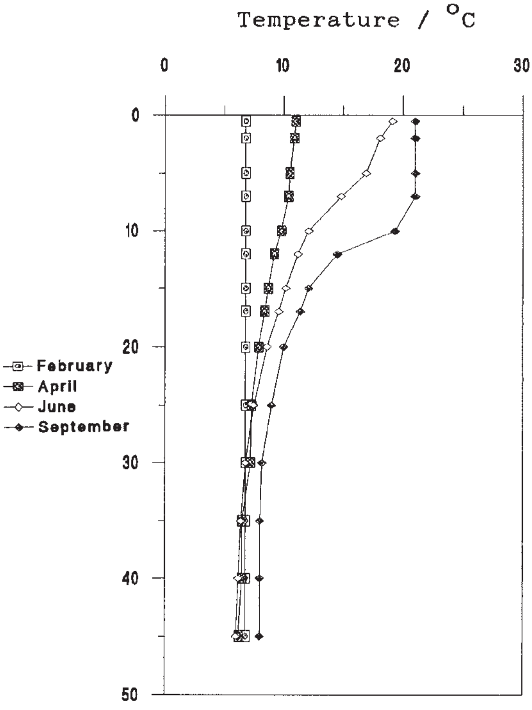

Figure 2b. Temperature profiles at station A.

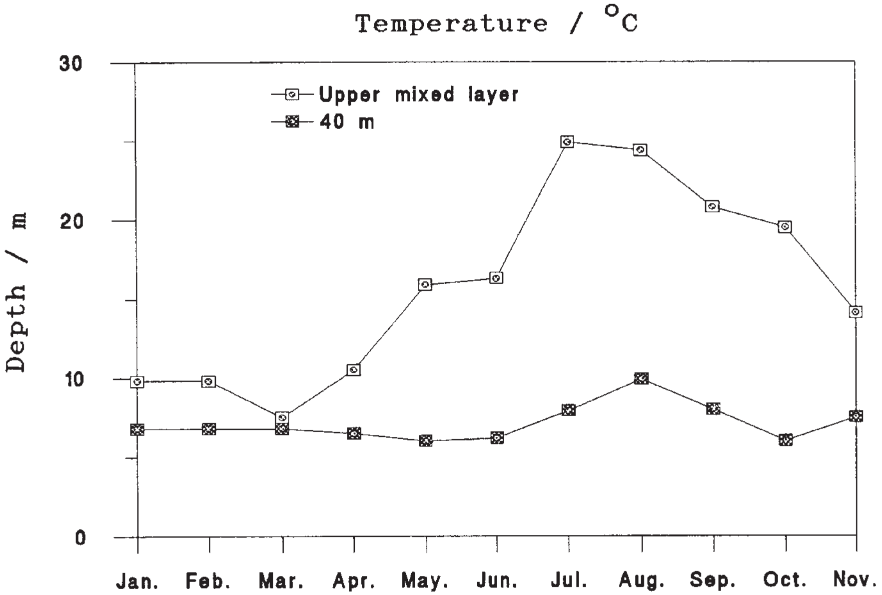

Figure 2c. Seasonal temperature variation in the epilimnion and at the 40 m depth.

Figures 3a and b show seasonal and vertical solar light penetration into the lake. Figure 3a shows that the 0.1% surface light depth was reached at about 15 m in June and at 25–30 m in January–February; the summer 0.1% light depth corresponds (15–20m) closely to the base of the seasonal thermocline and the onset of the nitracline. The 1% light depth, which is assumed to define the euphotic zone boundary, was as shallow as 10 m in June (Figure 3c) when surface waters were enriched with nutrients and suspended particles of photosynthetic origin. However, the euphotic zone extended to 18–22 m in summer when productivity was low in the upper mixed layer waters having very low concentrations of inorganic nutrients as discussed later. A similar seasonality appeared at the 10% light depth, ranging from 6.0 m in May to 12 m in February (Figure 3a). The light extinction coefficients, calculated from the collected data at station B, ranged seasonally between 0.4 m^{-1} in March and 0.29 m^{-1} in August, with an annual mean for the lake of 0.32 m^{-1}. These values are consistent with those reported for other oligotrophic lakes.[13] In order to estimate the 1% light depth in Sapanca Lake from each measurement of the Secchi disc depth (SDD), the ratios of the 1% light depth to the SDD were calculated for different months, based on the data depicted in Figure 3a; the ratio ranged from 1.18 in September to 4.16 in April, yielding an annual mean of 2.46.

Typical profiles shown in Figure 3c indicate that during stratification, the productive upper layer waters extend down to the lower thermocline

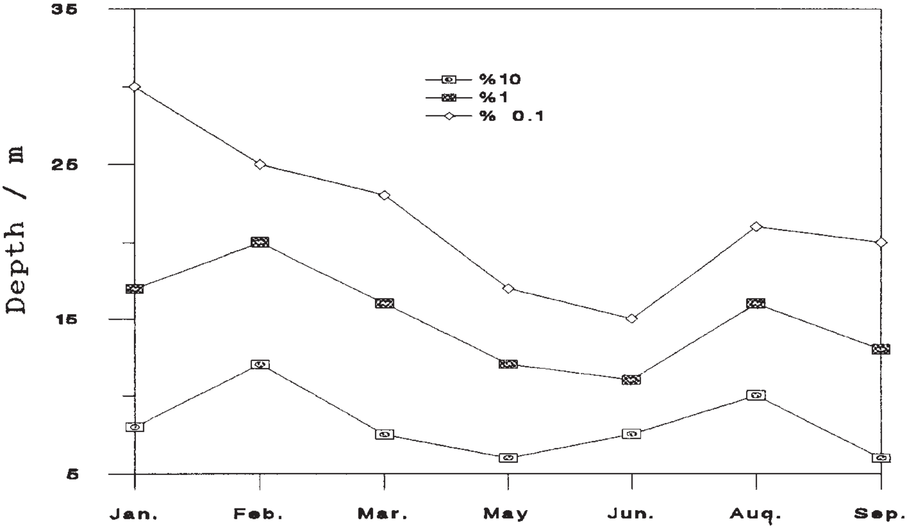

Figure 3a. Seasonal variation of light penetration depth to 10%, 1% and 0.1% of the surface value.

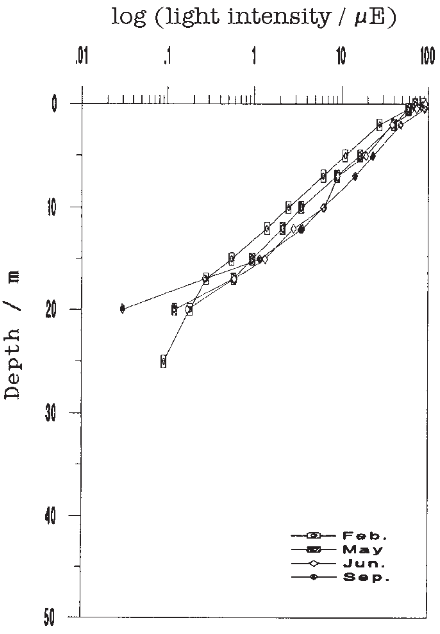

Figure 3b. Log of light intensity at station A.

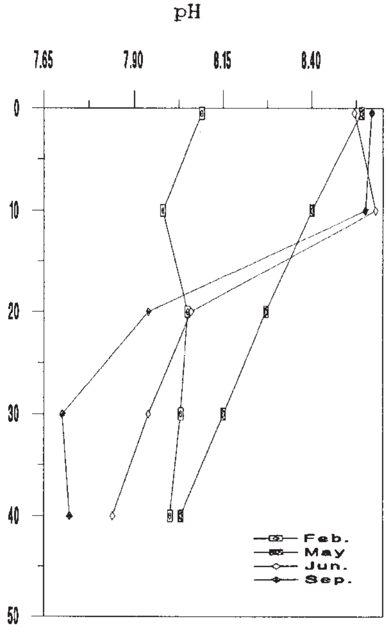

Figure 3c. Ph profiles at station A.

with pH values from 8.1 to 8.6, similar to pH values in other fresh water lakes. Below the seasonal thermocline, the pH decreased to 7.7–8.1 due to CO_2 released by the biochemical oxidation of organic matter sinking from the productive surface layer. Not unexpectedly, in February–March 1991, when the whole Lake water overturned, almost uniform vertical pH distributions were obtained throughout the entire water column with pH values ranging from 8.0–8.1 in the surface to 7.95–8.0 near the bottom.

Typical seasonal profiles (Figure 4a) and monthly averages of dissolved oxygen (DO) concentrations computed for the upper mixed layer and for the deep (below 40 m) water of the lake (Figure 4b) indicate remarkable variations of DO with both time and depth. It appears that the DO concentrations in the epilimnion water vary seasonally between 266 and 387 μM; the magnitude of the seasonality is primarily determined by the water temperature and the DO fluxes between the atmosphere and the surface water. Accordingly, the highest DO concentrations (381 μM, corresponding to 100% of the saturation value) were recorded in February–March when the surface water temperature was as low as 7 °C. Parallel to the warming of the sur-

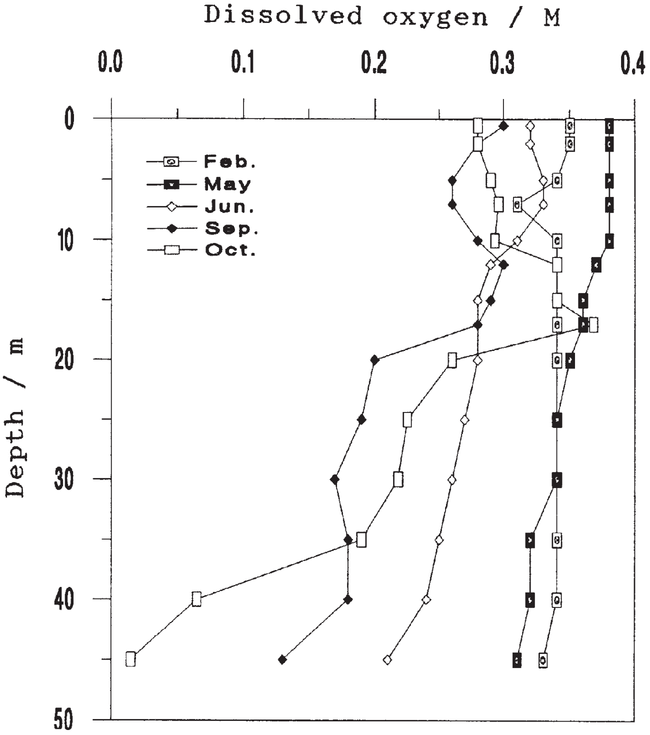

Figure 4a. Typical dissolved oxygen profiles at station A.

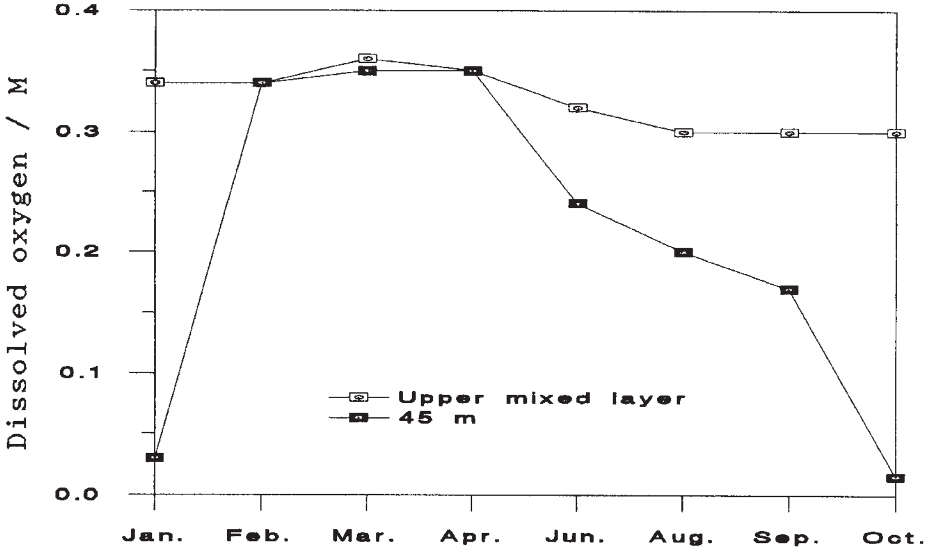

Figure 4b. Seasonal variation of dissolved oxygen in the surface mixed layer and at the 45 m depth of station A.

face waters, the DO decreased to levels of 272 μM in late summer, corresponding to 105% of its saturation value (see Figure 3b).

Below the surface mixed layer, DO profiles display a sub-surface maximum at 12–16 m depths, coinciding with the upper thermocline. This results from the increasing solubility of oxygen at lower water temperatures and the penetration of solar light down to the base of the thermocline, permitting photosynthesis and accumulation of DO at these depths. Steep DO gradients (oxycline) are located at the base of the seasonal thermocline, where the DO declines from 250–280 μM to 15–60 μM in autumn.

The DO contents of the hypolimnion water vary substantially with the season, as it is shown in Figure 4b. The DO declines to 15–63 μM in September-October and then increases to near saturation, 360–375 μM, in February–March when the entire water column becomes thoroughly mixed from top to bottom and an almost uniform vertical DO profile is generated (Figure 4a). With development of the seasonal thermocline, the hypolimnion concentrations decrease again from spring till the beginning of the winter overturn. The DO depletion in deep water is determined both by input of biogenic particles from the surface waters and by oxygen diffusion across the thermocline. Moreover, as clearly seen in Figure 4b, the hypolimnion concentration drops to hypoxic (< 50 μM) levels in autumn. The minimum is not reached at the same time from one year to another due to interannual changes in the nutrient supply from external sources, the rate of primary productivity and the duration of the surface water cooling/warming. For instance, in January 1991, only the upper 25 m were well-oxygenated by the wind-induced mixing event, while the bottom water still had 30 µM of DO due to insufficient ventilation.

The nitrate + nitrite concentrations (NO_x^-; mainly in nitrate form) of the lake surface water remain very low (< 0.15 µM) in summer and in autumn (Figure 5). With the beginning of vertical mixing, the surface NO_x^- concentrations reach only 1.5–2.0 µM in January and then peak to about 4.7 µM in February–March after the thorough mixing of the lake water. A steep nitracline is formed seasonally at the base of the thermocline, appearing at 10 m in June and deepening to 20–30 m in September–January (Figure 5a). The NO_x^- content of the bottom water increases from spring until the beginning of the winter overturn which dilutes the deep water with nitrate-poor surface waters of the lake (Figures 5a, b). Accordingly, the deep water concentrations, as high as 12–13 µM in late autumn, decrease to 5.7 µM in March when the entire water column has nearly constant NO_x^- concentrations. Throughout the year the concentration of dissolved ammonia in the lake water was always less than 0.35 µM, though some values of 0.5–0.7 µM were obtained at the base of the seasonal thermocline where the chlorophyll-a profiles displayed a subsurface maximum (SCM).

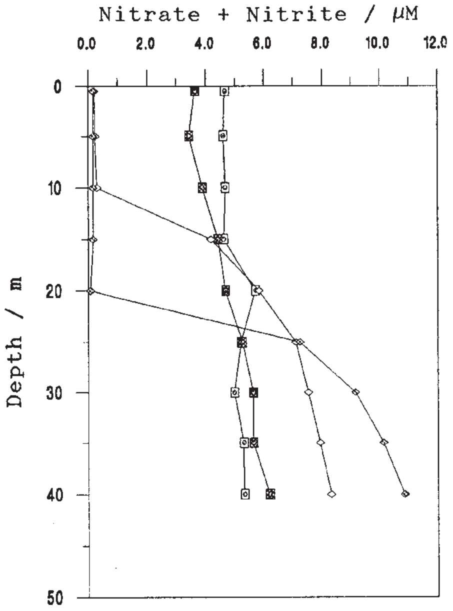

Figure 5a. Nitrate + nitrite profiles (averages of stations A and B).

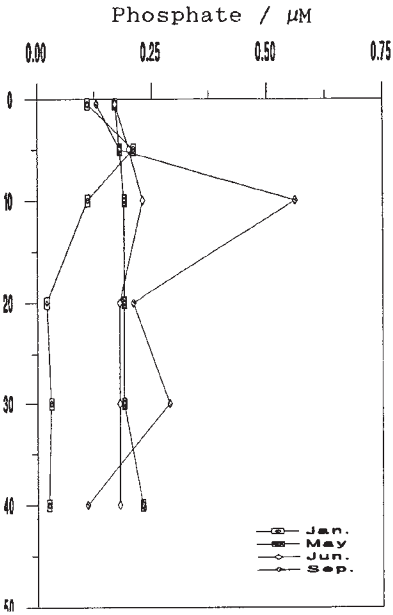

Figure 5c. Total phosphate profiles (averages of stations A and B).

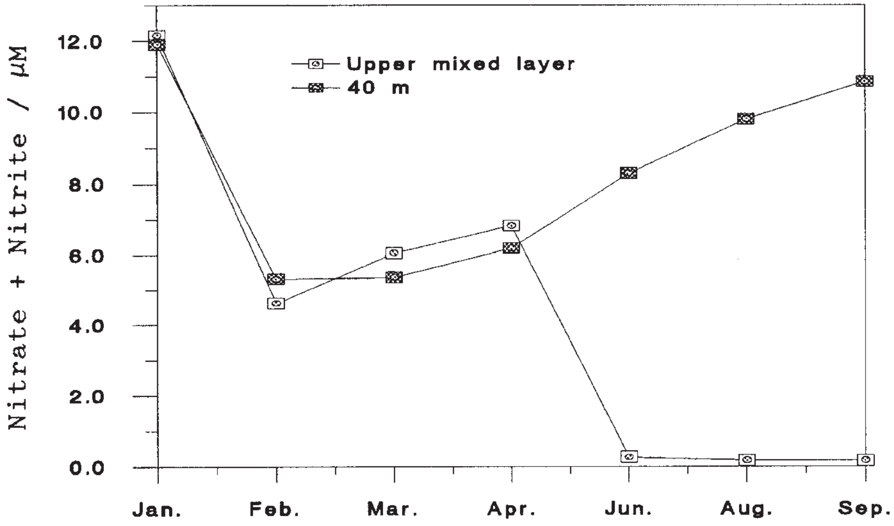

Figure 5b. Seasonal variation of (nitrate + nitrite) concentrations at station A in the surface mixed layer and at the 40 m depth.

Throughout the water column, reactive phosphate concentrations were always low (< 0.05–0.1 µM). In contrast, total phosphorus (t-P) concentrations generally ranged between 0.2 and 0.4 µM, with the exception of 0.6 µM peak values at the depths of the SCM (Figure 5c). In fact, when the apparent variation of NO_x^- in the deep waters of the lake is taken into account, one would expect to see a concomitant seasonality in the reactive phosphate content of the hypolimnion. In deep waters, as the DO drops from 350 µM in March to 20–40 µM in autumn, the NO_x^- concentration increases from 5.0 µM to 10.5 µM. This indicates that the NO_x^- increase stems from an oxidative origin, rather than from external input. Though there are no data on the elemental composition of phytoplankton in Sapanca Lake, an N : P ratio of 25 for the sinking organic matter of photosynthetic origin may be assumed from the N : P ratios of particulate matter determined in the phosphate-limited small lake.[14] Thus, based on the seasonal increase of nearly 5.7 µM in the NO_x^- content of deep water and assuming an N : P ratio of 25 for the sinking organic matter, one would expect an increase of about 0.31 µM in the concentration of reactive phosphate in the Sapanaca hypolimnion water from spring till late autumn. However, the seasonality in the measured phosphate (< 0.1 µM) is much less than this calculated value due to the removal of regenerated phosphorus by adsorption onto lithogenic particles of metal (Mn, Fe, Al) hydroxides or oxides deposited on the lake bottom, as first suggested by Longhurst[15] and more recently by Bakan.[16]

Large nitrate concentrations and trace quantities of nitrite and hydrogen sulphide observed in the interstitial water of surface sediments[17] indicate that the reducing conditions are not strong enough to release particulate phosphorus from the metal oxides in lake sediments. In other words, under the present conditions, lake sediments act as a sink for phosphorus. Accordingly, anomalous molar ratios of nitrate to phosphate appear in the lake bottom water, reaching values of 80–120. The ratios of NO_x^- to t-P are still as high as 21–40 even if all the total-phosphorus is considered to be of biogenic origin and attached to the sinking lithogenic particles.

Vertical profiles in Figure 6a show that the total CHLA concentrations (including pheophytin) are relatively high and change slightly with depth in winter and in spring. After the spring stratification limits the nutrient input from the bottom layer, concentrations decrease markedly in the surface mixed-layer and the upper thermocline. In terms of CHLA, phytoplankton biomass in this layer ranges between 0.7 and 2.9 μg/l in summer and in autumn (see Figure 6b). Below this, a sub-surface chlorophyll maximum (SCM) forms at the base of the seasonal thermocline; similar vertical features were reported previously by Yigit and Muftugil.[4] In 1989–1992, concentrations at the SCM depth ranged between 2.0 and 22 μg/l, the highest values being recorded in September. In August–September, the depth of the SCM deepened to 22–25 m where the intensity of solar light was consistently less than 1% of the surface value. Comparable concentrations of

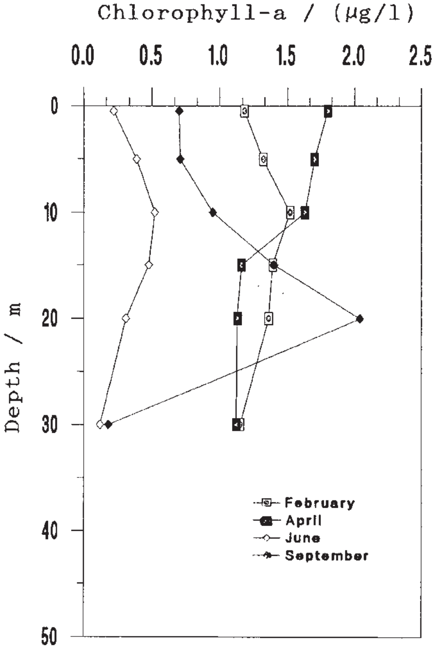

Figure 6a. Chlorophyll-a profiles at station A.

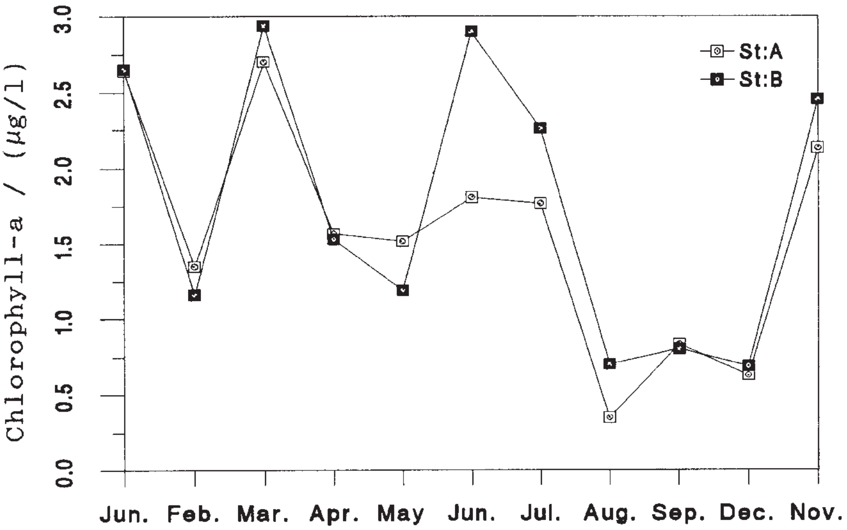

Figure 6b. Monthly variation of chlophyll-a in the upper mixed layer.

pheophytin-a observed at the SCM depths indicate a net accumulation of non-living algae near the base of the thermocline. This may have resulted from the sinking of a fraction of non-living algae from the upper productive zone together with excretion of algae by zooplankton. Detection of larger concentrations of both total-P and TOC at the SCM corroborates this suggestion. As previously emphasized by Banse[18] and Longhurst,[15] in nutrient poor aquatic environments, in addition to accumulation of seston at the SCM, light-shaded algal production may have resulted in substantial decreases in carbon to CHLA ratios in living cells, relative to those in the upper layer. At the SCM, the increase in total-P is less than the increase in total-CHLA (see Figures. 5b and 6a). This agrees nicely with the postulation of anomalous decreases in living-C:CHLA ratios within the lower euphotic zone of nutrient-impoverished environments. In conclusion, the SCM of Sapanca Lake observed below the 1% light intensity depth probably originates from significant increases both in the CHLA content per cell and in the non-living algal cell concentration within the lower thermocline.

Figure 6b shows the depth-averaged concentrations of CHLA (including pheophytin-a) estimated for the layer overlying the prominent SCM. When the CHLA profiles have no prominent SCM in winter and in spring, the figure incorporates averages of CHLA data obtained down to the 30–40 m depth. It appears that the CHLA varies seasonally from about 0.3 in August to 4.4 μg/l in October. The average CHLA concentrations down to the 0.1% light intensity depth (almost corresponding with the base of the thermocline) or down to 30–40 m during winter and spring ranged between 0.8 and

1.5 μg/l (Figure 6b). The highest values were obtained in August when the surface water contained measurable concentrations of nitrate imported from the bottom water during the winter overturn. Depth-integrated CHLA concentrations vary seasonally between 0.8 and 78.0 μg/l m^2, the lowest values occurring in late summer and autumn when the supply of nutrients to the surface waters is limited.

Concentration of total organic carbon (TOC) – mainly DOC – varies seasonally and it is the highest in the productive surface waters of the lake (Figure 7). During the year the epilimnion concentrations range between 158 and 258 μM. A concentration as large as 250–370 μM occurs at the SCM formed within the lower thermocline at the depths where the total P concentrations also peak during stratification. This finding suggests that labile TOC concentrations within the lower thermocline may be as large as 80–200 μM, assuming the monthly deep water concentration of 170 μM to have been in a refractory form. Not unexpectedly, the zone of large TOC gradients coincides with the nitracline at the base of the thermocline. As Figure 7 shows clearly, the upper mixed-layer concentrations ranged from 165 to 200 μM in winter to 250 μM in summer, depending both on the rates of al-

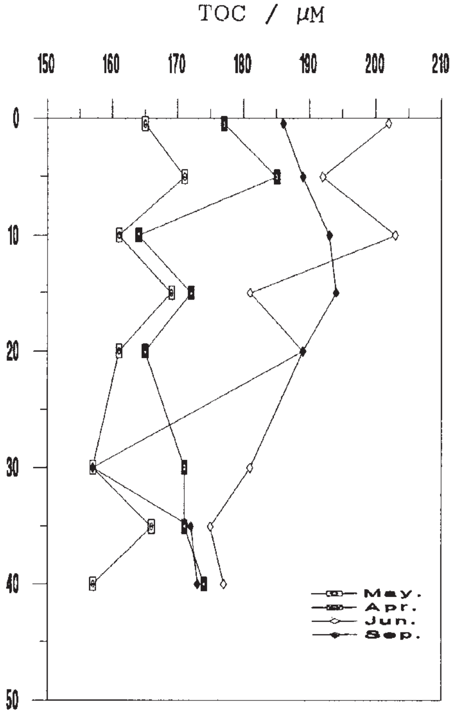

Figure 7. Total organic carbon profiles at station A.

gal production and the extent of dilution by deep water during the winter overturn. In 1989–1992, the deep water concentrations varied slightly between 140 and 200 μM.

The daily primary production per unit volume of the lake water demonstrates that throughout the year, photosynthesis occurred principally in the upper 10–15 meters. Primary production (PP) decreased sharply below 15 m where the light intensity was consistently less than 10% of its surface value. In other words, the rate of PP was low within the nutrient-poor thermocline waters of the lake. The depth-integrated daily production in the euphotic zone (Table IV) was observed to change seasonally from 35 mg C/ m^2 in January, to 81–93 mg C/m^2 in February–March, to 75–85 mg C/ m^2 in August and to 43–51 mg C/m^2 in November, 1992. The annual rate of PP for Sapanca Lake, derived from the limited data for 1990–1991, is of the order of 67 mg C/m^2.

The result of bioassay experiments carried out under laboratory conditions confirmed algal production to be phosphorus limited only in experiments where the phosphorus was added to samples containing sufficient concentrations of iron ions together with a chelating agent of EDTA (Table III). Similar increases in ^{14}C uptake were recorded in samples spiked with nitrate + molybdenum. These findings suggest strongly that reactive phosphate and nitrate are potentially the limiting nutrients for algal production in the lake provided that the lake water contains adequate concentrations of biologically essential metal ions and organic chelates.

Trace concentrations of nutrients measured in the upper mixed layer and in the thermocline, accompanied by the low primary production and the penetration of solar light below the summer thermocline to 20–22 m, indicate the oligotrophic state of Lake Sapanca. In order to define the current state of the water quality we use the trophic state index (TSI) developed by Carlson,[19] who used the relationship between algal biomass and CHLA, to-

TABLE IV

Daily primary productivity in Sapanca Lake/mg C m^{-2} day^{-1}

Month	Station A	Station B
August 1989	264	259
September 1989	294	321
November 1990	51.1	43.47
January 1991	34.89	35.66
February 1991	95.0	90.6
March 1991	88.4	73.8
August 1991	85.5	78.26

tal phosphorus (t-P) or Secchi Disc (SD) transparency. The assumptions inherent in the equations given below have been discussed by Carlson.[19]

$$\mathrm{TSI\ (SD)} = 60 - 14.427 * \ln \mathrm{(SD)} \quad (1)$$

$$\mathrm{TSI\ (CHLA)} = 30.6 + 9.81 * \ln \mathrm{(CHLA)} \quad (2)$$

$$\mathrm{TSI\ (t\text{-}P)} = 4.15 + 14.427 * \ln \mathrm{(t\text{–}P)} \quad (3)$$

The TSI values for Sapanaca Lake have been calculated using these equations, from the measurements of SD depth (in meters), t-P (μg/L), and CHLA (μg/L, corrected for pheophytin-a) in the productive upper layer. The estimated TSIs, together with the measured values of each parameter, are given in Table V. The numbers generated are an index of the trophic status of the lake, though it is as yet unclear which parameter is the most appropriate for Sapanca Lake. The TSI estimated for Sapanca Lake ranged from 16 to 36 for the July–September period.

According to the TSI table proposed by Carlson,[19] TSI values of less than 45 indicate oligotrophy. Thus, the TSI values given in Table V strongly suggest that the Sapanca is in an oligotrophic state.

TABLE V

Monthly variations in trophic state indices calculated form the Secchi disk, transparency, chlorophyll-a and total phosphate for the Sapanca Lake

Month	Trophic State Index		
	SDD/m	CHLA/μg l^{-1}	t-P/μg l^{-1}
July '89	32	31.8	33.6
August '89	30.9	30.98	34.8
October '89	43.7	40.8	35
December '89	43	34.2	35
April '90	40.4	32.5	38.5
July '90	34.7	34.6	36.7
November '90	32.9	39.2	35.5
April '91	36.5	32.9	29.9
June '91	42.9	37.9	30.9
August '91	32.99	23.4	31.6
September '91	32.7	26.2	29.9
January '92	38.1	40.3	18.6
March '92	43.9	40.7	20.5

CONCLUSIONS

Sapanca lake with its winter overturn is a typical warm-monomictic lake. The lake is oligotrophic. Total concentrations of major cations and anions are of the order of 3700–4400 μM, permitting the surrounding residents to use the lake for drinking water. The lake water is mixed thoroughly from top to bottom in February–March, providing enrichment of the surface layer with nutrients from deep waters as well as ventilation of bottom waters. In the hypolimnion water, the DO drops in autumn from saturated levels (375 μM) to 20–40 μM; the NO_x^- concentrations of oxidative origin increase concurrently due to the decay of biogenic particles sinking from the productive upper layer. A steep nitracline is formed at the base of the seasonal thermocline. Interestingly, the concentration of reactive phosphate in the lake is very low, (< 0.05 μM) throughout the year, indicating net phosphorus export from the water column to the sediment layer. A prominent SCM is established below the depth of 1% light intensity, due to shade-adapted algal production, sinking of living cells and the consequent grazing by zooplankton. Primary production, with an annual value of 0.5 g C/m^2, occurs principally in the top 10–15 m, below which light intensity is less than 10% of its surface value. Algal production in the lake is probably limited by more than one nutrient parameter, an important consideration when modelling and developing rational plans for preserving the lake's ecosystem.

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SAŽETAK

Trofičke značajke jezera Sapanca (Turska)

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Sustavna mjerenja optičkih svojstava, koncentracije glavnih i sporednih kemijskih tvari te primarne proizvodnje tijekom 1989–1992 omogućile su identifikaciju oligotrofnog stanja jezera Sapanca kraj Mramornog mora, Turska. Voda jezera ima niske koncentracije glavnih aniona i kationa (ukupno 49 μM) te se miješa vertikalno u veljači i ožujku, ventilirajući pridnene vode i obogaćujući površinske vode hranjivim tvarima s dna. Voda s površine hladi se do 6,5 °C pri kraju zime, a zatim se grije do 26 °C pri kraju ljeta. Tijekom godine temperatura u donjem sloju varira izmedju 6,5 i 10 °C. Kada nastaje sezonska termoklina, na njezinu gornjem rubu pojavljuje se maksimum otopljenog kisika, dok se u hipolimniju koncentracija mijenja od 11,5 – 12,0 ppm (350–375 μM) u ožujku do 0,5–1,7 ppm (16–56 μM) u kasnu jesen. Koncentracije nitrata na površini mijenjaju se sezonski, i to od < 0.15 μM ljeti do 5.7 μM u ožujku, dok se koncentracija u pridnenim vodama mijenja od 13,5–14 μM kasno ljeti do 5,7 μM nakon vertikalnog miješanja. Koncentracije fosfata uvijek su manje od 0,1 μM duž vertikalnog profila. U kasno ljeto podpovršinski se maksimum klorofila-a spušta na dubinu od 20–25 m gdje je intenzitet svjetla manji od 1% vrijednosti na površini. Ispod 10–15 m primarna produkcija je malena. Integrirana vrijednost mijenja se od 35 do 93 mg C/m^2 dan^{-1}, što je slično vrijednostima ostalih oligotrofnih jezera.