5. THERMAL AND OXYGEN STRATIFICATION, PRIMARY PRODUCTIVITY, DECOMPOSITION RATE AND CHLOROPHYLL CONCENTRATION
(Jan Igor Rybak)

Thermal stratification typical of summer periods is formed in Lake Flosek already at the beginning or in middle of May and is most evident in June and July (Fig. 7). Difference in water temperature between the lake surface and depth at 5–6 m reached about 10°C in summer 1991–1992, and 8.5°C – in 1993. Thermocline occurs already at about 4 m (Fig. 7). In August, the lake is more uniformly mixed: the bottom layers of water (5–6 m) exhibit temperatures about 17°C, while surface waters – 20–25°C (Fig. 7). Alike seasonal pattern of temperatures was also found for the period 1966–1970 (Fig. 1 in Hillbricht-Ilkowska *et al.* 1977): thermocline occurred at 3–4 m of depth, and summer stratification lasted from May to the end of July (*ibid.*). In August, mixing of relatively warm waters took place, followed by gradual and thorough water cooling to a relatively uniform temperature about 5°C in November, and 3°C in the freezing period (Fig. 7). Continuous and permanent ice cover (of thickness exceeding even 15–20 cm) is present from the second half of December to the end of March or middle of April.

The above thermal regime of Lake Flosek occurred in nearly all study years and exhibited features unusual for shallow, polymictic lakes where summer mixing frequently occurs down to the bottom. Sharp stratification expressed by the temperature difference up to 10°C between a few successive isobaths may persist here over two and half months (mid-May – the end of July). Ice cover may also be present for more than three months. This results from the fact that the lake is sheltered by a high-growing forest (see: Photo 1) providing sufficient water stability during the periods of maximal and minimal air temperatures.

Oxygen depth profile in Lake Flosek resembles that occurring in shallow lakes (Fig. 8). Usually, layers from the surface to 3–4 m (i.e. to thermocline) are saturated with oxygen uniformly throughout a year, whereas deeper ones (to the bottom, i.e. to 5–6 m) – only at spring and autumn overturns. During the periods of summer stratification (mid-May – the end of July) and winter freezing, oxygen concentration falls near the bottom (at 5 m) reaching about one to a few mg l^{-1} (Fig. 8). Neither have been oxygen depleted nor hydrogen sulphide appeared near the bottom. This has also been confirmed in the previous studies (cf.: Fig. 2 in Hillbricht-Ilkowska *et al.* 1977). A characteristic feature of the lake comprised rapid and considerable shifts in oxygen concentration at a depth of about 4 m in summer of three consecutive years, namely 1991–1993 (Fig. 8), as well as in the former years. Oxygen concentrations were clearly higher there than above or below. Rapid, irregular shifts were also found for concentrations of other chemi-

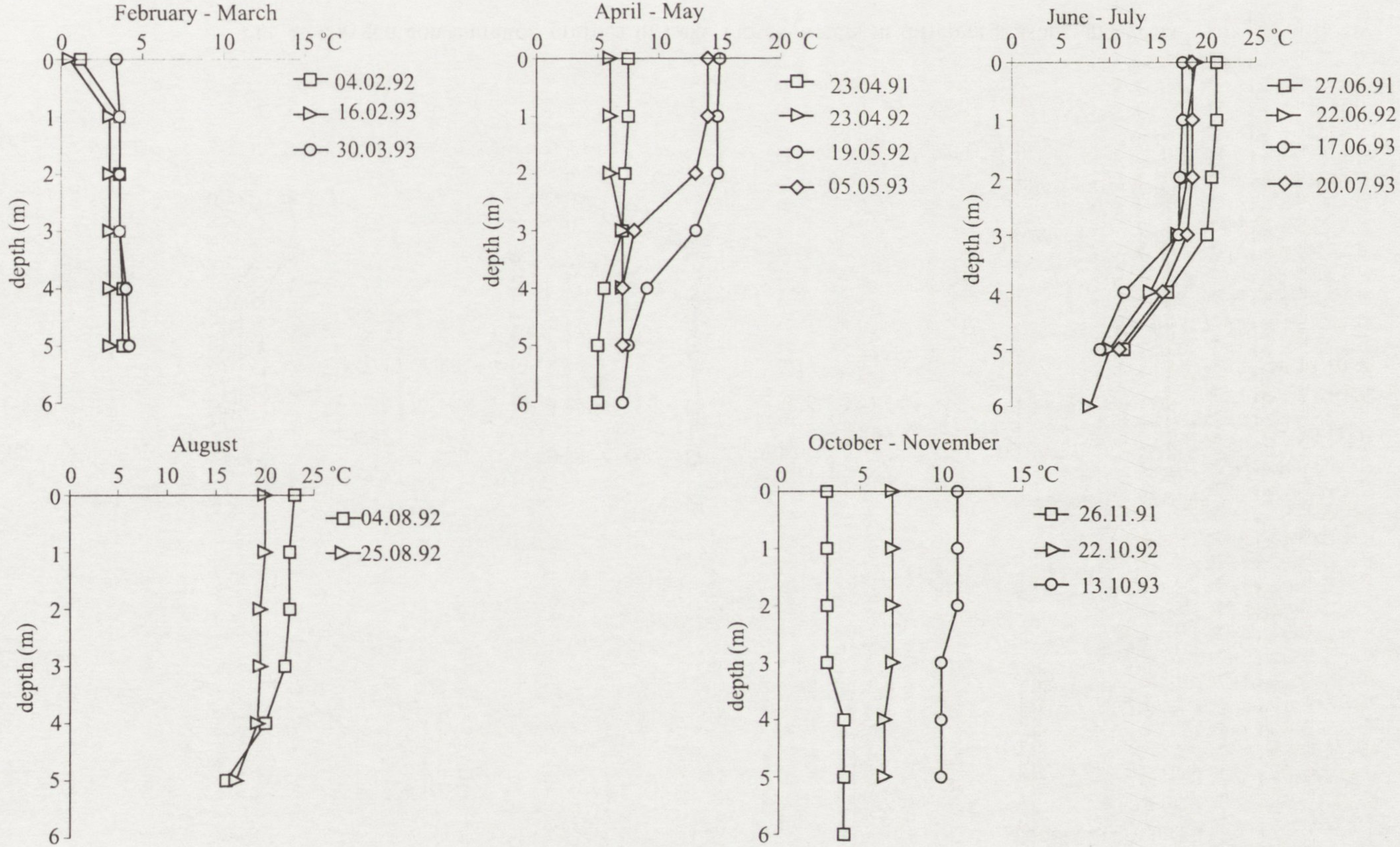

Fig. 7. Thermal stratification of Lake Flosek waters in different seasons and years

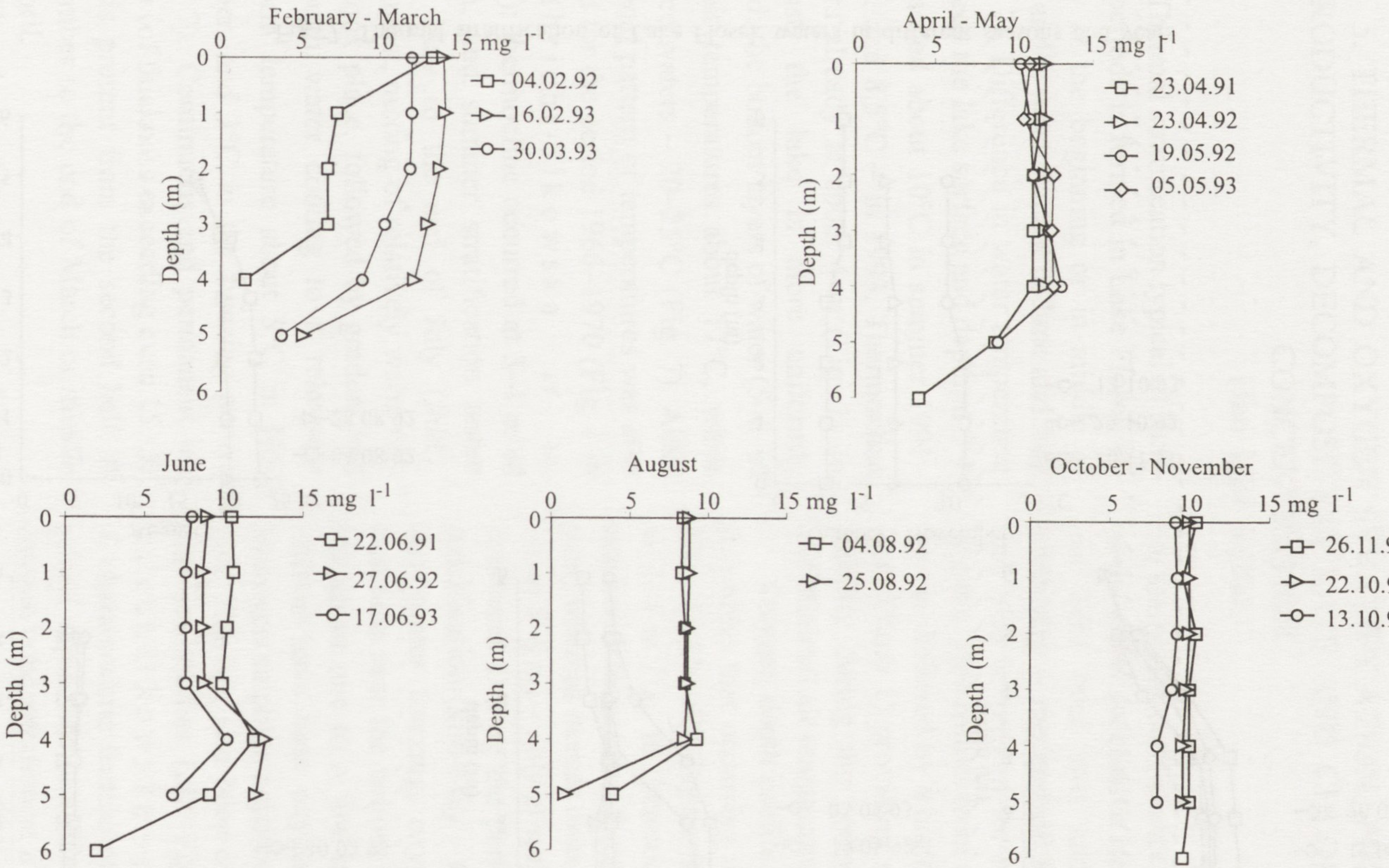

Fig. 8. Oxygen concentration profiles in Lake Flosek waters in different seasons and years

cal compounds (cf.: Chapter 4), as well as for chlorophyll (see below).

In 60-ties and 70-ties, i.e. at the time of liming and thereafter, observations of Secchi's disc transparency (SD) have not been made routineously. However, the lake has always displayed transparency of at least 2 m. This is suggested by good visibility of bottom sediments at that depth. Systematic measurements made in 1992–1993 revealed transparency up to 3.5–4 m in spring–summer period, and lower (1.8–2.5 m) in autumn and winter (Fig. 9). The regularity is opposite to that common to non-humic, meso- and eutrophic lakes. The changes in water transparency observed in two consecutive years: 1992 and 1993 correlated well with corresponding shifts in chlorophyll *a* content in the 0–3 m water layer (Fig. 9). SD values reaching 4 m in summer may only be found in deep mesotrophic lakes (Hillbricht-Ilkowska 1989, Zdanowski 1992), as well as in lakes of I purity class (Kudelska *et al.* 1983). High quality and transparency of the Lake Flosek water is accompanied by efficient transmission of solar radiation – about 10% of light penetrates to a depth of 3.0–3.5 m (Rybak, unpublished data).

A tentative comparison was made of monthly and yearly mean values of gross primary phytoplankton production between 1966–1974 (interpolated from Fig. 6 and Table II in Hillbricht-Ilkowska *et al.* 1977) and 1990–1992 (Table 3). Measurements made occassionally in the latter period (particularly in 1990 and 1991) did not exhibit any clear long term trends. Production estimates for summer of 1990–1992 were about 42–46 kJ m^{-2} day^{-1}, and thus approximated the values found in 1974 (i.e. four years after liming) and 1966 (the control year preceding lake liming) (Table 3). Such high values were not found for summer of the liming year (1970) nor the three subsequent years (1971–1973) (Table 3). It has been suggested (Hillbricht–Ilkowska *et al.* 1977) that the decrease in primary production of phytoplankton immediately after the lime application may be attributed to "inorganic carbon starvation" brought about by temporary immobilisation of the carbon by calcium ions. In 1974, phytoplankton production increased, especially in summer (Table 3). Presumably, production level from 1974, i.e. summer mean of 42–46 kJ m^{-2} day^{-1}, and annual mean value of about 29–33 kJ m^{-2} day^{-1}, could be maintained until 90-ties. It should be emphasised that these values are very low and indicate low production of phytoplankton in the lake. By comparison, annual mean production (excluding winter time) of deep, highly eutrophic Lake Mikołajskie amounted to 251–553 kJ m^{-2} day^{-1} (per m^2 of water

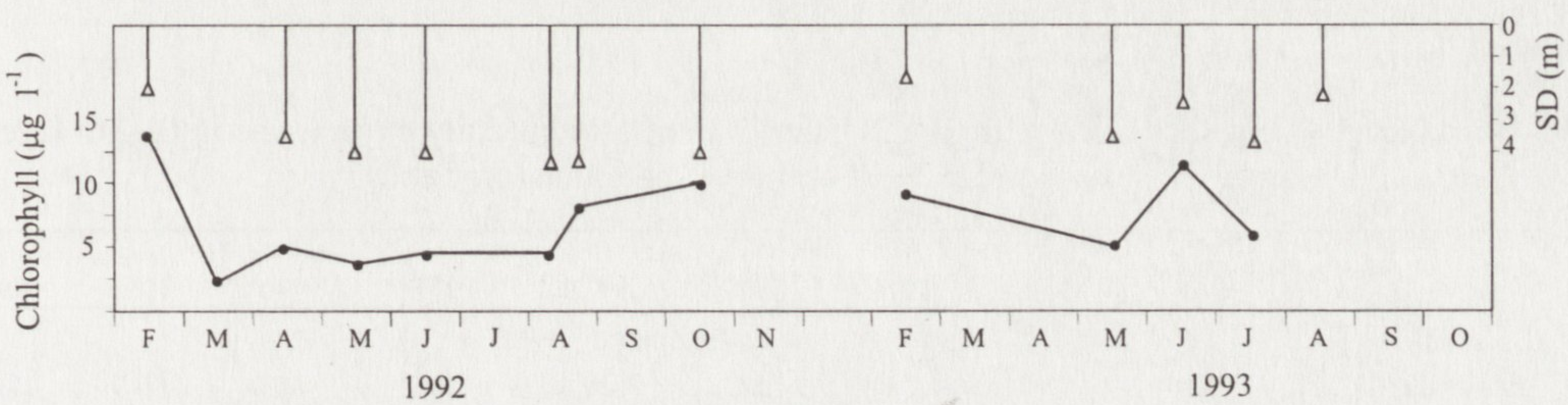

Fig. 9. Seasonal changes in water transparency (SD m) and chlorophyll *a* concentration (mean value for 0–4 m) in Lake Flosek in 1992 and 1993 year

column to 0–6 m) in 1966–1972, and a corresponding value found for a large (~100 km^2), eutrophic and polimictic Lake Śniardwy was about 200 kJ m^{-2} day^{-1} (in 1966) (Hillbricht-Ilkowska 1989). Thus, primary productivity of pelagic zone of Lake Flosek, except a temporary decrease immediately after liming, has been maintained at the level by at least several times lower than that found for eutrophic lakes.

Primary production of plankton of Lake Flosek was high in winter (in February, under ice cover) (Table 3) reaching about 42 kJ m^{-2} day^{-1}, i.e. level similar to that of summer period. Caution is however recommended as ice cover presence in February and measurement procedure (in air-hole) with consequent short-lasting light penetration might have lead to overestimation of the value. Nevertheless, the result indicates high potential for winter photosynthetic productivity of the lake, and the values correlate well with chlorophyll *a* content reaching as much as 15 µg l^{-1} in that period (Fig. 9).

It has been found (Hillbricht-Ilkowska *et al.* 1977) that liming of the lake (1970) favoured organic matter decomposition, i.e. mean daily oxygen uptake in water column 0–4 m (Table 4). The rate of decomposition was over two times higher than the rate of organic matter production. In the years after liming (to 1974), the rate of organic matter decomposition was on average slightly

Table 3. Gross primary production of phytoplankton in kJ m^{-2} day^{-1} (0–4 m) in Lake Flosek in different months and years

Month	1966[1)]	1970[1)] liming	1971[1)]	1972[1)]	1973[1)]	1974[1)]	1990	1991	1992
Febr.	–	–	–	–	–	–	–	–	43.9
April	–	–	8.4	20.9	–	18.8	–	29.3	14.7
May	75.4	–	10.5	33.5	18.8	20.9	–	–	23.4
June	29.3	6.3	16.7	20.9	33.5	35.6	23.4	33.9	22.2
July	20.9	12.6	16.7	18.8	27.2	67.0	–	46.9	–
Aug.	41.9	10.5	16.7	16.7	20.9	50.2	45.6	–	38.1
Sept.	46.0	12.6	12.6	14.7	12.6	27.2	–	–	–
Oct.	29.3	–	12.6	12.6	8.4	16.7	19.3	–	–
Nov.	–	–	12.6	8.4	6.3	–	–	5.9	–
Average	33.9	11.3	13.4	17.6	18.4	36.4	29.3	29.3	24.7[2)]

[1)] cf. Fig. 6 and Table II in Hillbricht-Ilkowska *et al.* 1977
[2)] without data for February

Table 4. Average (May–Oct.) rate of organic matter decomposition (daily oxygen use in 0–4 m layer) in kJ m^{-2} day^{-1} and in % of primary production (cf. Table 3)

	1966[1)]	1970[1)]	1971[1)]	1972[1)]	1973[1)]	1974[1)]	1990[2)]	1991	1992
kJ m^{-2} day^{-1}	21.8	28.9	23.4	24.7	20.5	38.9	18.0	56.9	41.9
%	64	258	174	140	113	106	62	194	170

[1)] cf. Table II in Hillbricht-Ilkowska *et al.* 1977
[2)] 3 measurements in the period June–October

higher (by 6–40%) than photosynthetic production (Table 4). Unlike, in the control year (1966) the decomposition rate was merely higher than half of organic matter production in the plankton (Table 4). A hypothesis has been drawn (Hillbricht-Ilkowska *et al.* 1977) that acidity neutralisation following liming enhanced decomposition of organic matter accumulated in the lake, and thereby of heterotrophic use of organic matter became greater than *in situ* production. Such a situation seems to have been maintained over subsequent years, which is supported by the decomposition rate estimates nearly twice as high as those of production in the period 1991–1992 (excluding incomplete data from 1990) (Table 4). The enhanced decomposition of organic matter measured by e.g. the rate of oxygen uptake by sediments and suspended matter, abundance of heterotrophic bacteria or by other methods is, according to Olem's review (1991), a common phenomenon in limed lakes, although duration and scale of the effect may vary depending on e.g. pH alterations. Majority examples quoted by Olem (1991) related to pH shifts of about 2–3 units. This is supported by Tranvik *et al.* (1994), who have not found any significant changes in heterotrophic decomposition over pH range of 5.5–6.9.

Chlorophyll *a* content of the Lake Flosek water did not exceed 15 μg l^{-1} (a mean for 0–4 m layer) (Fig 9). Such high values were found for e.g. winter (February) 1992 and for summer period of 1993 (Fig. 10). Similar values were noted in 1973, 1974, i.e. 3–4 years after liming, when chlorophyll *a* measurements has begun (Hillbricht-Ilkowska *et al.* 1977). It should be noticed that chlorophyll *a* content was as a rule lower at the surface (0–1 m) than above the bottom where it reached the values 15–25 μg l^{-1} (Fig. 10). According to trophic classifications of lakes (Hillbricht-Ilkowska 1989), the average value found in Lake Flosek (~ 5 μgl^{-1}) is a very low, it locates Lake Flosek among mesotrophic lakes or lakes of I purity class (Kudelska *et al.* 1983). Chlorophyll *a* concentrations measured at a depth of 4–5 m were sometimes much higher than those at the surface (Fig. 10). This reflects abrupt vertical shifts in other compounds in deeper layers of the lake (see: Chapter 4).

Both the short and long term alterations in primary production of phytoplankton in Lake Flosek generally resemble those frequently noticed after lake liming (Olem 1991). There are reports of temporary decreases in production due to lowered concentration of inorganic carbon as captured by calcium ions, due to environmental shock (Jarvinen *et al.* 1995) killing algal cells, as well as rapid increases in production usually attributed to reduced Al-toxicity, increased phosphorus availability and overall enhanced organic matter decomposition and nutrient regeneration (Olem 1991). Although manifold and often controversial, the modifications are the stronger, the more distinct the pH shifts are (Bukaveckas 1988, Henricksen 1989). Sometimes the transformations are, however, temporary and short-lasting. Generally, functional properties of planktonic producer communities (measured by the rate of production or chlorophyll *a* content), and even biomass, seem to be less variable than their structural features under conditions of moderate pH changes (Morling and Willen 1990, Schindler *et al.* 1991, Havens 1992a, b).

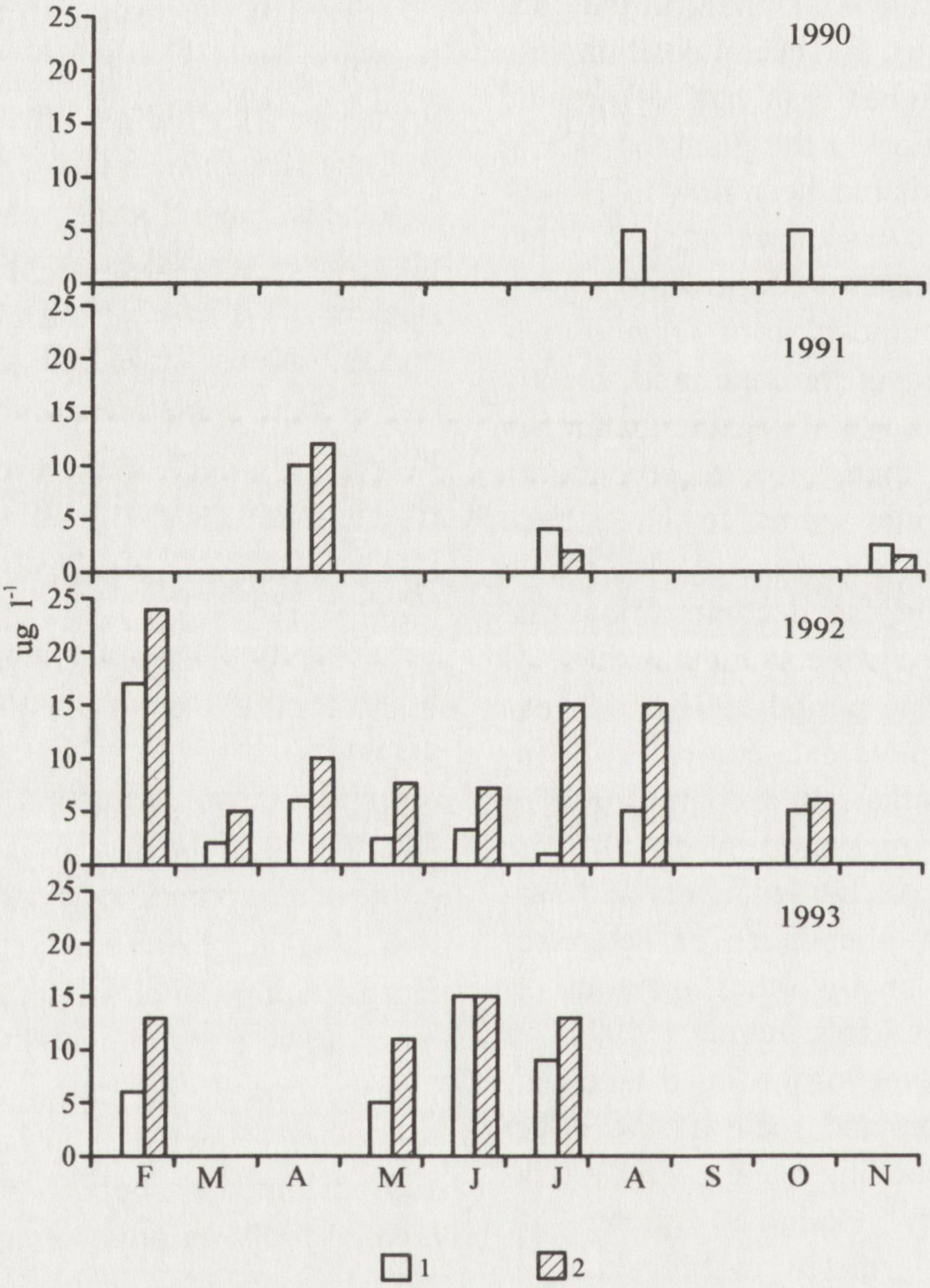

Fig. 10. Chlorophyll *a* concentration in surface (1) and bottom (4 m) (2) water layers in Lake Flosek in different seasons and years