

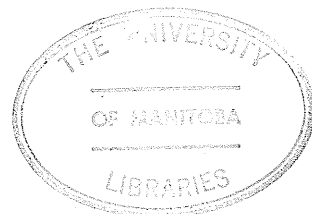
DESCRIPTIVE LIMNOLOGY OF LAKE 120, A MEROMICTIC LAKE
ON THE PRECAMBRIAN SHIELD IN NORTHWESTERN ONTARIO

by

PAUL CAMPBELL

A thesis
submitted to the Faculty of Graduate Studies
in partial fulfilment of the requirements for the
degree of Master of Science

Department of Zoology
University of Manitoba
Winnipeg, Manitoba
Canada



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RATIONALE

Detailed studies have been carried out on the effects of logging stream watersheds, for example, Likens *et al.* (1970), Bormann *et al.* (1974) or Aubertin and Patric (1974). However, little work of this nature has been directed towards lakes. The Experimental Lakes Area (ELA) in Northwestern Ontario (see Volume 28, No. 2, J. Fish. Res. Bd. Canada) provided an ideal location for such a lake study since excellent field facilities were available in an area which was actively being logged by the Minnesota and Ontario Pulp and Paper Company (MANDO).

Lake 120 (Figure 1) located southeast of Kenora, Ontario, ($93^{\circ}50'W$, $49^{\circ}39'N$) was chosen in 1968 for this study for a number of reasons. It was estimated by MANDO that its watershed would be logged in 1970-71 which allowed 2-3 years to describe the lake prior to any disturbance. From a practical point of view, Lake 120 was of the type that would most typically be deemed important economically or aesthetically; that is, the water is relatively clear and of high quality and the lake is of such a depth and morphology that thermal stratification occurs during the summer. Hydrologically, the system appeared to be a relatively simple one. The lake is a headwater lake (see map insert Volume 28, No. 2, J. Fish. Res. Bd. Canada) in an apparently sealed granite basin and the narrow (approximately 20 meters) outflow channel with bedrock sides allowed the measurement of discharge (Figure 2). There is little littoral vegetation in the lake and the soils and terrestrial vegetation are rather uncomplicated.



FIGURE 1. Aerial view of Lake 120. October, 1970.

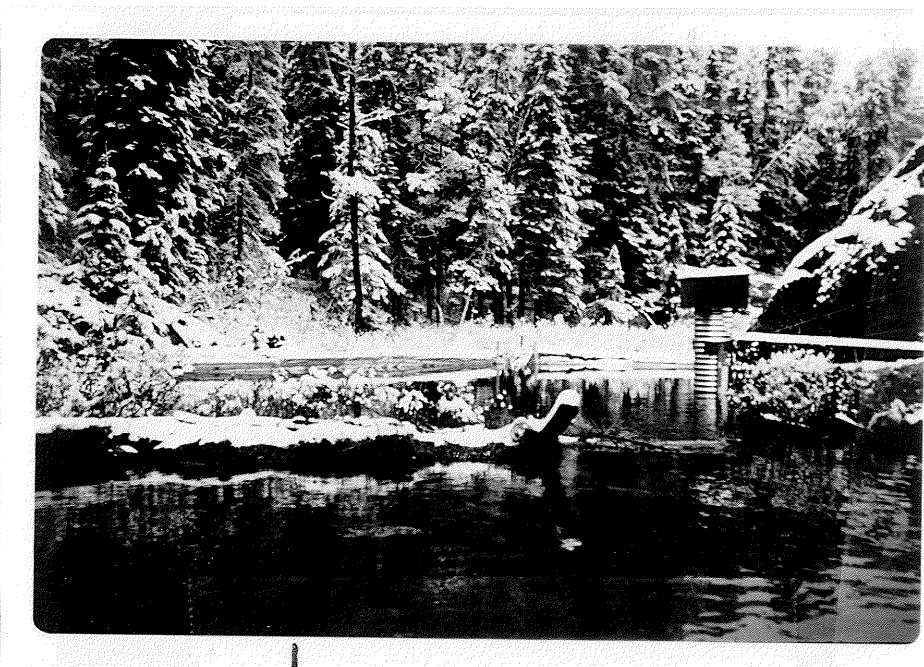


FIGURE 2. Weir and recording well at the outlet of Lake 120. November, 1970. The weir was built at the second of a series of three aged beaver dams. Note first beaver dam in foreground.

This manuscript is a limnological description of the watershed and lake ecosystem before logging.

DESCRIPTION OF THE STUDY AREA

The surface of Lake 120 is approximately 410 meters above sea level. A stream which flows intermittently enters the lake at its south end (Figure 3). The lower half of this stream flows through a black spruce bog with mosses and Labrador tea (*Ledum groenlandicum* Oeder.). Runoff in most other parts of the watershed is direct to the lake, not *via* streamflow. Bottomley (1974) describes in detail runoff processes and mechanisms in ELA. Water leaving the lake through the outflow progresses through a series of small lakes to Dryberry Lake, from Dryberry Lake to Lake of the Woods which drains into the Winnipeg River to Lake Winnipeg. Lake Winnipeg flows to Hudson Bay and the Arctic Ocean *via* the Nelson River (see Figure 1, Brunskill & Schindler 1971).

With exception of the above-mentioned black spruce, the predominant tree species on the rather steep, well-drained slopes of the watershed is jack pine (*Pinus banksiana* Lamb.). Balsam fir (*Abies balsamea* (L.) Mill.) is usually the predominant species in the understory of jack pine or black spruce (*Picea mariana* (Mill.) BSP.). There are two stands of trembling aspen (*Populus tremuloides* Michx.) in the watershed and there are red maples (*Acer rubrum* L.) interspersed among black spruce in and just upslope from the bog. A description of the vegetation in ELA, including a species list of aquatic macrophytes is given by Brunskill and Schindler (1971). There is little littoral vegetation about Lake 120.

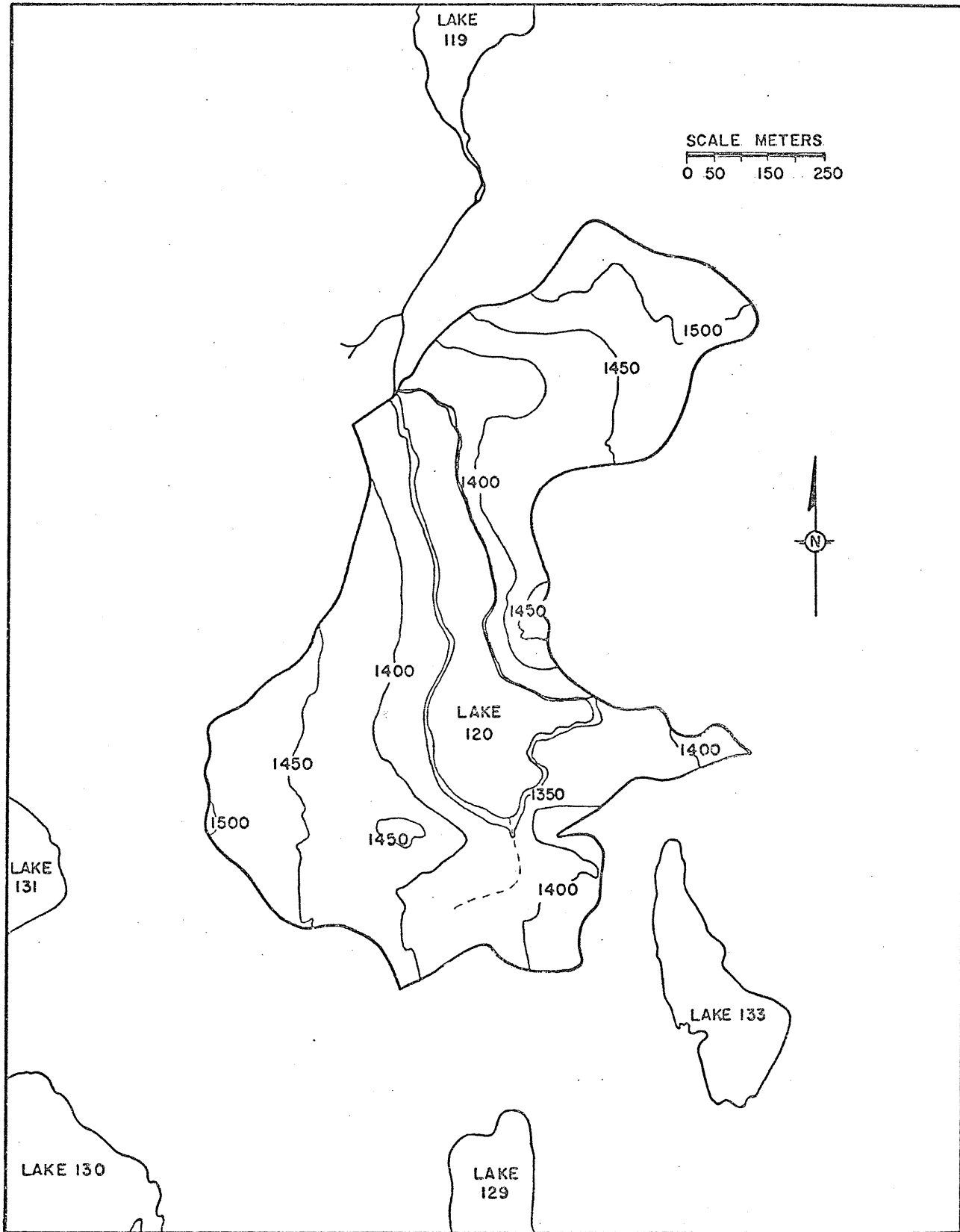


FIGURE 3. Outline and contour map of the Lake 120 watershed. Contour intervals are 50 feet.

Geologically, the drainage basin is as described by Brunskill and Schindler (1971). Detailed discussions of the chemistry and weathering of the granodiorite bedrock and the glacial till in the region are found in Brunskill *et al.*, (1971) and Schindler *et al.*, (1976). An account of the glacial history of the area may also be found in Brunskill and Schindler (1971).

Most of the Lake 120 drainage basin is exposed bedrock covered only with an organic layer. However, in the depression where bog is located, the bedrock is overlain by a sandy till deposit. In the slightly sloping, well drained areas of this depression, soils are typically degraded dystric brunisols (after the The System of Soil Classification For Canada, Canada Department of Agriculture, 1970). The L-H horizon is an organic black mat about 5 cm thick. The leached, grey Ae_j horizon varies from 2-5 cm in thickness. A Bm₁ horizon of about 7 or 8 cm overlies coarse, rusty brown sand (Bm₂ horizon) up to 30-40 cm deep. All sand grains and pebbles comprising the Bm₂ horizon are rounded suggesting that the till overlying the bedrock has been water worked. Towards the center of the depression, the surface levels off and the organic mat thickens to about 10 cm. Drainage is poor here and gleyed dystric brunisols have developed. In the center of the depression, surface deposits are saturated with water and are overlain by peat and moss. There is no profile development and these soils would therefore be classified as regogleysols.

Based on meteorological records from stations in the vicinity of ELA, Brunskill and Schindler (1971) reported annual mean temperatures between 0.5 and 2.2°C. January mean temperatures ranged from -19.4 to

-16.1°C and July mean temperatures from 18.3 to 20°C. Schindler *et al.*, (1976) recorded at the ELA camp site, during the years 1970-73, annual precipitation ranging from 700 mm to 970 mm. Evapotranspiration averaged about 65% of annual precipitation during those four years. Runoff on the Lake 239 watershed was between 220 and 350 mm per year. Maximum runoff occurs during and immediately after ice melt. Lake 120 becomes free of ice between April 15 and May 15. The lake is usually ice-covered by the third week in November.

A brief history of the human population and land use of the area may be found in Brunskill and Schindler (1971).

METHODS

Physical Measurements

Figure 3 is from a portion of a formline map provided by L.A. Smithers, director of the Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario. Contours on this map were used to delineate the boundary of the Lake 120 watershed. Drainage area (A_d) was determined by planimetry.

On July 20, 1969, a lake level datum mark was cut into a rock ledge on the east shore (Station 20, Figure 4). The surface of the lake was 0.91 meters below datum. Sonar transects (a Raytheon Model DE 119D 200 kc Fathometer was used) and construction of the bathymetric chart were performed as described by Brunskill and Schindler (1971). Length of shoreline (L), and maximum length and width of the lake were determined by chartometer. A planimeter was used to calculate lake surface area (A_0) and areas at 2 meter contour intervals. Volumes at 2 meter intervals, total lake volume, mean depth (\bar{z}), shore development (D_L) and volume development (D_V) were calculated after Welch (1948).

Between September, 1969 and August, 1972, fifty vertical profiles were taken at the point of maximum depth (see Figure 4, for exact location of the sampling station). In the initial stages of the investigation, samples were also taken approximately half way up the north arm of the lake (depth about 8-9 meters). However, no difference was found between the quality of the water in the north arm and that of the 0 to 9 meters stratum at the south station. So, in November 1969,

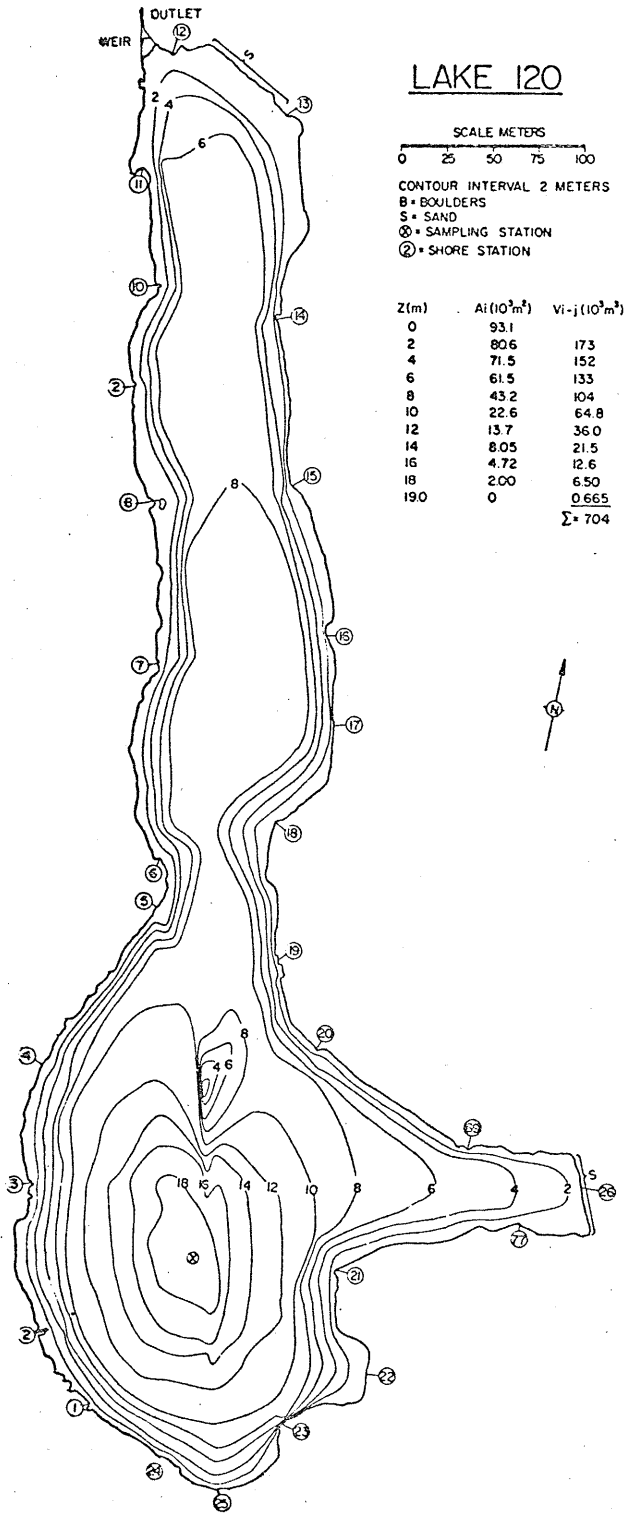


FIGURE 4. Bathymetric chart of Lake 120.

sampling at the north station was discontinued and profiles from the south station taken to be representative of the entire lake. During the open-water season, outflow samples were also collected.

Estimates of light penetration were made in two ways. Routinely, Secchi visibility was measured with a 25 cm diameter Secchi disc. In 1971-72, a Whitney model LMT-8A submersible photometer (cadmium sulphide cell) was also used to measure light transmittance at depth intervals of 1 meter or less. 100% transmittance was taken to be at 0.1 meter. Total solar radiation was recorded by means of an Eppley pyrhelimeter mounted on a tower near the middle of Lake 239. Elaboration on subsurface light measurement including how to calculate photosynthetically useful light reaching a given depth may be found in Vollenweider (1961, 1969) and Schindler (1971). Schindler (1971) also gives an equation probably only applicable to ELA which relates Secchi disc visibility to light transmission. In this study, visual colour of the disc was also recorded at half Secchi depth.

Temperatures were measured *in situ* at 1 meter intervals with either a Yellow Springs model 43 TD tele-thermometer (readable to about 0.2°C) or a Whitney thermistor TC-SA (readable to about 0.02°C). These instruments were calibrated against a U.S. National Bureau of Standards mercury thermometer.

Conductivity was also measured *in situ* at depth intervals of 1 meter or less. A Beckman RB3 Solu Bridge Conductance Meter calibrated against 0.001 and 0.0001 N KCl standard solutions (American Public Health Association, 1965) was used.

Chemical Measurements

Water samples were routinely collected from the lake at a minimum of seven depths, namely 1, 5, 8, 11, 14, 16 and 18 meters. A 3-litre, clear, plexiglass van Dorn sampler was used. From each depth, a 1-litre polyethylene bottle was rinsed and filled for chemical analysis, a 300 ml glass BOD bottle for oxygen measurement and a 150 ml capped bottle for phytoplankton counts. Phytoplankton samples were immediately preserved with Lugol's solution (Kling and Holmgren, 1972).

Dissolved oxygen was determined by the azide modification of the Winkler method (American Public Health Association, 1965) within hours of collection.

At each depth, three samples of suspended particulate material were collected by filtration through pre-ignited (16 hours at 550°C) 4.25 cm diameter Whatman GF/C filters. The Mandel Scientific Company Ltd. claims these glass fiber filters retain particles as small as 1.2 μm . Filters for particulate phosphorus (PP) analysis were stored in screw-cap vials and shipped to the Freshwater Institute (FWI) in Winnipeg for analysis. Phosphorus was extracted from the filter and converted to orthophosphate by heating with dilute HCl (Stainton *et al.*, 1974), and orthophosphate was then determined by the molybdate method of Murphy and Riley (1962). Filters for particulate carbon (PC) and particulate nitrogen (PN) analysis were desiccated in the dark and stored in individual plastic petri dishes. PC and PN were determined simultaneously at the FWI on a modified Carlo Erba Model 1102 Elemental Analyzer (Hauser, 1973 and Stainton *et al.*, 1974). Filters for chlorophyll analysis were frozen

and stored in the dark when it was not possible to analyze the same day as collection. The filters were ground in a 90% acetone medium and the extract fluorescence was measured on a Turner Model III Fluorometer (Strickland and Parsons, 1968). The instrument responds primarily to chlorophyll a. However, equivalent concentrations of phaeopigments elicited a fluorescence of 50% of the chlorophyll a standard. In natural water systems it is unlikely that phaeopigments are absent. As a result, the chlorophyll measurements reported in this study represent unknown proportions of chlorophyll a and phaeopigments, and are probably an overestimation of chlorophyll a.

The filtrate from above was divided into two aliquots. After preservation with 1 ml of 1N HCl, 100 ml was set aside for major cation analysis in Winnipeg. Total dissolved calcium, (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe) and manganese (Mn) were determined using a Perkin Elmer Model 403 atomic absorption spectrophotometer (Stainton *et al.*, 1974).

The remaining filtrate was used for analyses performed in the field laboratory. Dissolved organic carbon (DOC) was measured by gas chromatography (a Fisher Hamilton Model 29 gas partitioner was used) after oxidation to CO₂ (Menzel and Vaccaro, 1964; Stainton, 1973). Nitrate was reduced to nitrite in a cadmium copper reduction column (Wood *et al.*, 1967). The sum of nitrate plus nitrite-nitrogen in the water sample was determined as nitrite either manually or by an automated method using a Technicon Autoanalyzer (Stainton *et al.*, 1974). Phosphate-phosphorus (PO₄-P) was determined by the molybdate method of Murphy and

Riley (1962) either manually or by Technicon Autoanalyzer (Stainton *et al.*, 1974). It should be noted that the method is apparently capable of hydrolyzing labile organic phosphorus compounds, resulting in an overestimate of $\text{PO}_4\text{-P}$ and hence biologically available phosphorus (Stainton *et al.*, 1974). Henceforth, the phosphorus determined by this method will be referred to as soluble reactive phosphorus (SRP). Total dissolved nitrogen (TDN) and dissolved phosphorus (TDP) were determined after ultraviolet photochemical combustion (Armstrong and Tibbitts, 1968). Acidification, addition of H_2O_2 and U.V. photo-oxidation for 4 hours as described by Stainton *et al.* (1974) converted organic phosphorus compounds to phosphate which was determined as outlined above. Similarly, at pH 9 with addition of H_2O_2 and U.V. irradiation for 16 hours, organic nitrogen compounds and ammonia were essentially all decomposed and oxidized to nitrite with a small residual of nitrate which was determined as above (Stainton *et al.*, 1974). However, for some water samples rich in nitrogen and organic carbon, determinations of TDN gave values less than corresponding independent measurements of ammonia-nitrogen ($\text{NH}_3\text{-N}$). It has since been discovered by Stainton (personal communication) that for TDN levels greater than $35 \mu\text{moles litre}^{-1}$ a significant fraction of ammonia usually persisted after photo-oxidation. Since such waters are very high in organic matter it is likely that, during irradiation, oxygen was depleted before all ammonia was converted to nitrite or nitrate. This problem may be overcome by determining $\text{NH}_3\text{-N}$ as well as $\text{NO}_3\text{+NO}_2\text{-N}$. Stainton *et al.* (1976) have also developed a new method for TDN whereby organic nitrogen compounds, nitrate and nitrite are converted

to and measured as ammonia. At any rate, due to the unreliable nature of the method used in this study, TDN concentrations greater than 35 $\mu\text{moles litre}^{-1}$ have not been reported.

Hydrogen ion concentration (pH), specific conductance, $\text{NH}_3\text{-N}$, dissolved inorganic carbon (DIC), methane-carbon ($\text{CH}_4\text{-C}$) and soluble reactive silicon (Si) were determined on unfiltered water in the field laboratory. $\text{NH}_3\text{-N}$ was done by the phenol-hypochlorite method of Solorzano (1969). Both manual and automated adaptations of the method are described by Stainton *et al.* (1974). Measurement of total carbon dioxide concentrations (CO_2 or DIC) was done by helium stripping into a Fisher Hamilton Model 29 gas partitioner (Stainton 1973). Concentrations of H_2CO_3 , $\text{CO}_3^{=}$ and HCO_3^- were calculated from total carbon dioxide measurements, temperature and pH (Garrels and Christ, 1965). Methane was determined by the method of Rudd *et al.* (1974) or Rudd *in* Stainton *et al.* (1976). Methane was stripped from solution with helium into a Pye 104 gas chromatograph equipped with a flame ionization detector and a phenyl isocyanate/Porasil C column. Soluble reactive silicon was determined after the molybdenum blue method of Armstrong and Butler (1962). Both the manual and automated procedures as outlined by Stainton *et al.*, (1974) were used.

A Spectronic 100 spectrophotometer was used for all colorimetric analyses described above which were performed manually. Precisions to be expected when the above methods are used on waters collected in the Experimental Lakes Area are given by Stainton *et al.*, (1974 or 1976).

Hydrology

In order to compute water and elemental budgets, it was necessary to monitor the outflow of the lake. A V-notch weir was constructed and a recording well installed (Figure 2). Water Survey of Canada first obtained a full year's hydrologic data in 1973. Water budgets during the years 1970-72 were computed by extrapolation from the Lake 239 watershed (Schindler *et al.*, 1976).

Sediment Traps

On 8 April, 1970, traps for the collection of sediment (Brunskill, 1969b) falling to the lake bottom were installed at a depth of 17 meters, approximately 25 meters south of the sampling station shown in Figure 4. The traps were removed from the lake on 20 September, 1973. The tubes were kept in the dark and refrigerated at 5°C prior to analysis in Winnipeg.

Water content of the sediment was determined by freeze-drying at about -30°C. Ashed weight of the sediment was measured after ignition at 550°C for 4 hours. Freeze drying was done in a VirTis Mechanically Refrigerated Freeze Mobile Cabinet Model 10-146MR-BA. Procedures were outlined by the supplier's manual. Determinations of chlorophyll, total phosphorus, nitrogen and carbon were performed on the sediment trap samples as described above for suspended sediments. Carbonate (inorganic) carbon ($\text{CO}_3\text{-C}$) was liberated from the sediment into low carbon water as CO_2 (Stainton, 1973). The liberated CO_2 was determined as for DIC described above. Calcium, potassium, iron, manganese, silicon,

aluminum (Al), and titanium (Ti) were determined simultaneously by X-ray fluorescence spectrometry on an A.R.L. multichannel vacuum X-ray quantometer (Wilson *et al.*, 1965). Precisions are reported by Wilson *et al.* (1969).

Phytoplankton and Primary Productivity

Approximately once a month during the open-water seasons of 1971 and 1972, ^{14}C primary productivity experiments were carried out *in situ* at depths of 1, 3, 5, 7, 10 and 13 meters. Procedures in the field were as described by Schindler and Holmgren (1971). Two light bottles and one dark bottle were suspended at each depth, usually between 10:00 and 14:00 hours. Prior to incubation, each 125 ml sample was inoculated with 1 microcurie of ^{14}C (0.05 ml of $2\ \mu\text{C ml}^{-1}$ solution). Uptake of total carbon (particulate plus extracellular products) was determined as described by Schindler *et al.*, (1972). Formulas used in computing incubation production (mg C litre^{-1}) and full-day photosynthesis ($\text{mg C litre}^{-1}\ \text{day}^{-1}$) are given by Schindler *et al.*, (1972) and Schindler and Holmgren (1971), respectively.

Phytoplankton counts were done on 1 to 10 ml of preserved sample (see above for sample collection and preservation) after sedimentation in a settling chamber using the Utermöhl technique described by Margalef in Vollenweider (1969). Identifications and counts were done using a Wild Model mn 40 inverted microscope with phase contrast illumination (Kling and Holmgren, 1972). Taxonomic keys used are listed by Schindler and Holmgren (1971). Live biomass was computed by assuming a density of

1 gram ml⁻¹ and estimating cell volumes from geometric shapes (Findenegg *in* Vollenweider, 1969).

RESULTS

Physical Limnology

The terrestrial drainage area of Lake 120 (Figure 3) and lake surface area were determined to be 60.4 and 9.31 hectares, respectively. Maximum relief in the watershed is approximately 55 meters. Maximum length and width of the lake are 788 and 304 meters, respectively, and length of the shoreline is 2,130 meters. Areas and volumes at 2 meter contour intervals are reported in Figure 4. The maximum depth (Z_m) of Lake 120 was found to be 19.0 meters and mean depth was calculated to be 7.55 meters. Shore development (D_L) = 1.97 was higher than any reported by Brunskill and Schindler (1971) for 14 other ELA lakes. A high D_L as well as a low slope of the hypsographic curve (Figure 5, constructed after Welch, 1948) between 6 and 10 meters are reflections of the two relatively shallow arms which radiate to the north and east from a rather circular, deep basin (Figure 4). About 42% of the lake bottom lies at a depth of between 6 and 10 meters. Volume development (V_L) = 1.19 indicates that, overall, the lake basin walls are concave towards the waters.

Depth distribution of temperature with time is given in Figure 6 and Table 1 of the appendix. Ice melted from the lake during the last week of April or first week of May. Warming of the surface waters took place very quickly with the establishment of a thermocline at about 3 meters depth by the end of May. During the summer, the thermocline rested at 4-5 meters. Temperatures to 24°C were recorded at the surface

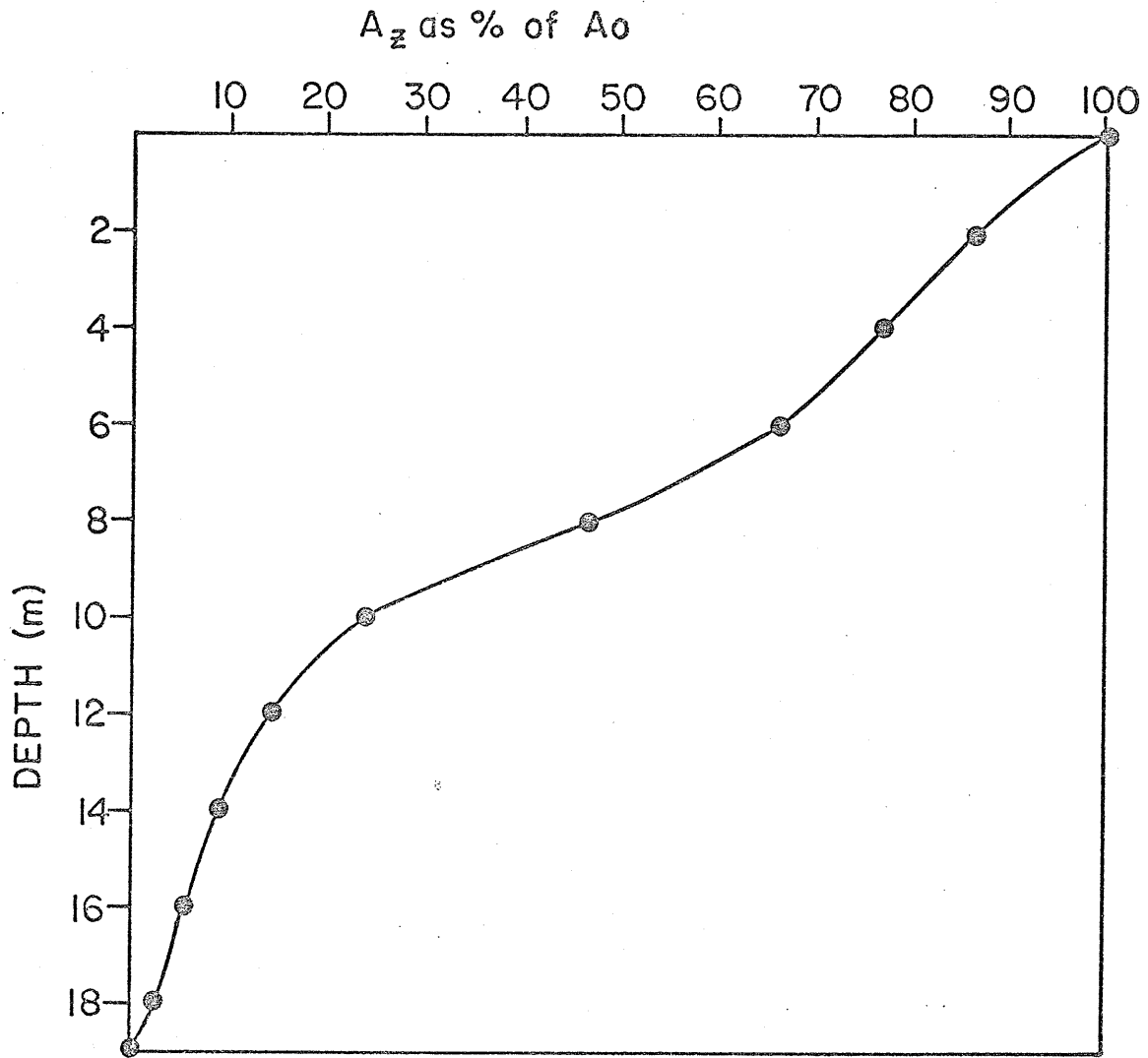


FIGURE 5. Percentage hypsographic curve for Lake 120.

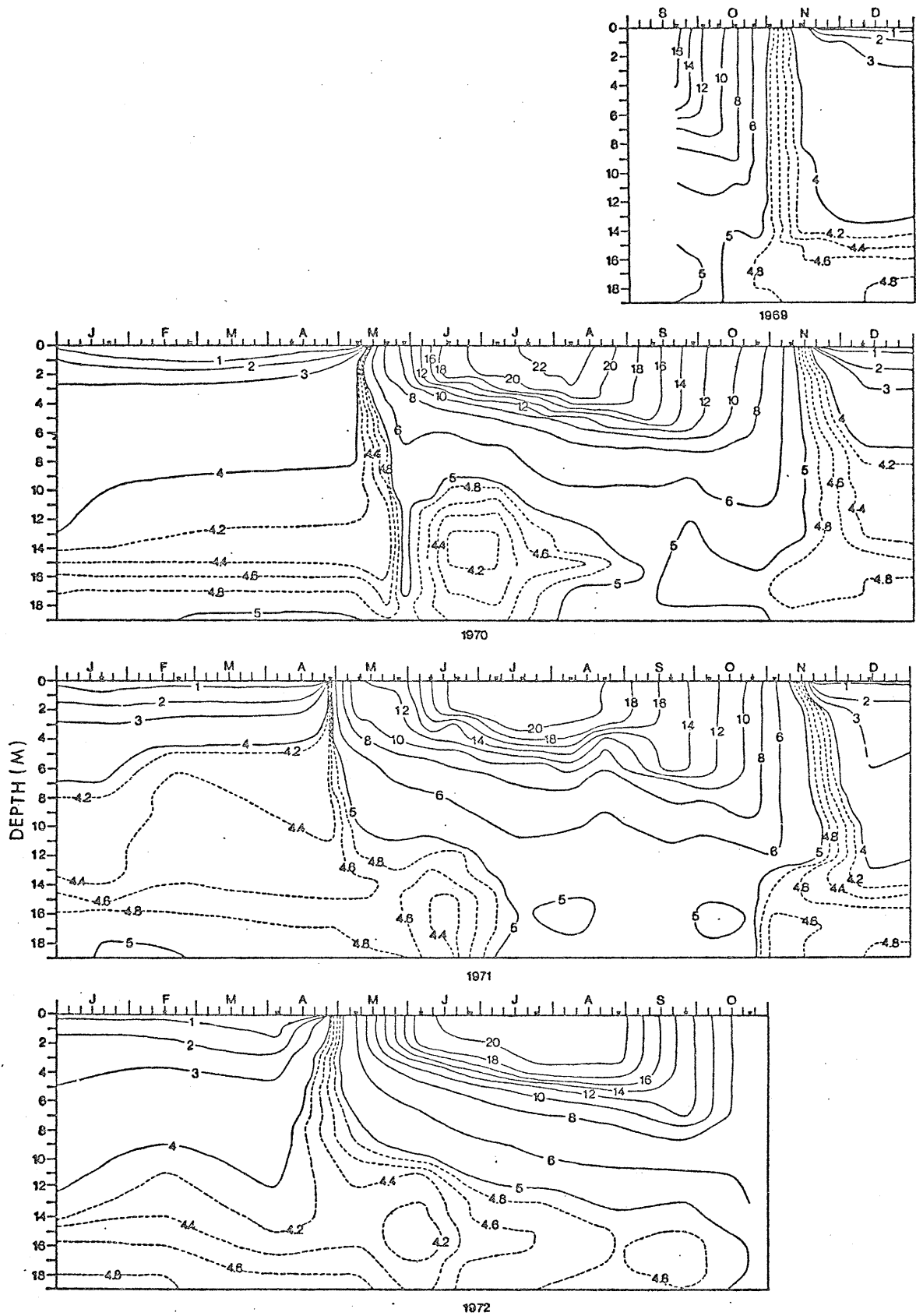


FIGURE 6. Depth-time distribution of temperature for Lake 120, 1969-1972. Isotherms are in degrees centigrade ($^{\circ}\text{C}$).

during July and August. Coincidental with the warming of the upper strata, cooling of the waters at depths greater than 10 meters took place. In this lower stratum, minimum temperatures for the year were recorded during June. A cooling center was observed between 14 and 16 meters. With the onset of autumnal cooling and circulation in September, the thermocline was depressed to 6 or 7 meters. By late October or early November, waters above 14-16 meters had reached homothermy. However, homothermy was never observed from surface to bottom. At all times of the year, a rise in temperature of 0.1 to 0.3°C occurred between 16 meters and the bottom. Ice cover was usually established by mid November.

Summer, winter and total annual heat budgets (H_{bs} , H_{bw} and H_{ba}) were calculated after Hutchinson (1957). The formula

$$H_z = V_z (\theta_z - 4^\circ)$$

was used to calculate at 1 meter depth intervals the heat energy (H_z) required to raise or lower the recorded temperature to 4°C

where V_z = volume of 1 meter thick stratum at depth z
 θ_z = temperature (°C) at depth z .

Since the bottom waters were cooling while overlying waters were gaining heat (see above), separate heat budgets were computed for the 0-14 and 14-19 meter strata. Since water temperatures below 14 meters never

dropped lower than 4°C, for this region only, an annual heat budget was calculated based on the difference between maximum and minimum heat content. Heat budgets for the entire lake (0-19 meters) were also derived. The latent heat of melting of the ice cover was included in winter heat budgets. Maximum ice thickness was usually recorded in February and ranged from 30-42 cm. A summary of the heat budgets for Lake 120 during the years 1969-72 is reported in Table 1. For the 0-14 meter stratum, the average annual heat budget was $12,890 \text{ cal cm}^{-2} \text{ A}_0$. Thirty percent of this budget ($3,930 \text{ cal cm}^{-2} \text{ A}_0$) was attributable to raising the water from the winter minimum to a state of homothermy at temperature of maximum density (4°C). Almost 70% of the H_{bw} ($2,710 \text{ cal cm}^{-2} \text{ A}_0$) was accounted for by the heat energy required to melt the ice cover. Consumption of heat energy was maximal during May and June at a rate of about $115 \text{ cal cm}^{-2} \text{ A}_0 \text{ day}^{-1}$. In terms of total calories consumed (or released), the average annual heat budget for 14-19 meters was extremely small (27.6×10^9 calories) compared to that of 0-14 meters (12.0×10^{12} calories). Figure 7 is a plot against time of the total heat energy (calories) that would be consumed or liberated in achieving a state of homothermy at 4°C. It shows clearly that, during the open-water season, thermal trends in the 14-19 meter stratum are the inverse of those in the 0-14 meter stratum. While the waters from 0-14 meters were warming during June and July, the 14-19 meter stratum reached a state of minimum heat content. Similarly, during the fall when the surface waters were cooling, the waters from 14-19 meters were usually warmer than at any other time of year.

TABLE 1. Heat budgets for Lake 120, 1969-1972. Computations were done after Hutchinson (1957).

YEAR	STRATUM (meters)	SUMMER	WINTER	ANNUAL	
		H_{bs} (calories cm^{-2}A_o)	H_{bw} (calories cm^{-2}A_o)	H_{ba} (calories cm^{-2}A_o)	(calories $\text{cm}^{-2}\text{A}_{14}$)
1969	0-19	9586	4295	13881	
	0-14	9551	4300	13851	
	14-19			30.95	357.9
1970	0-19	8915	3294	12209	
	0-14	8897	3304	12201	
	14-19			46.36	536.1
1971	0-19	8566	3520	12086	
	0-14	8538	3534	12072	
	14-19			18.09	209.2
1972	0-19	8866	4586	13452	
	0-14	8846	4591	13437	
	14-19			23.09	267.1

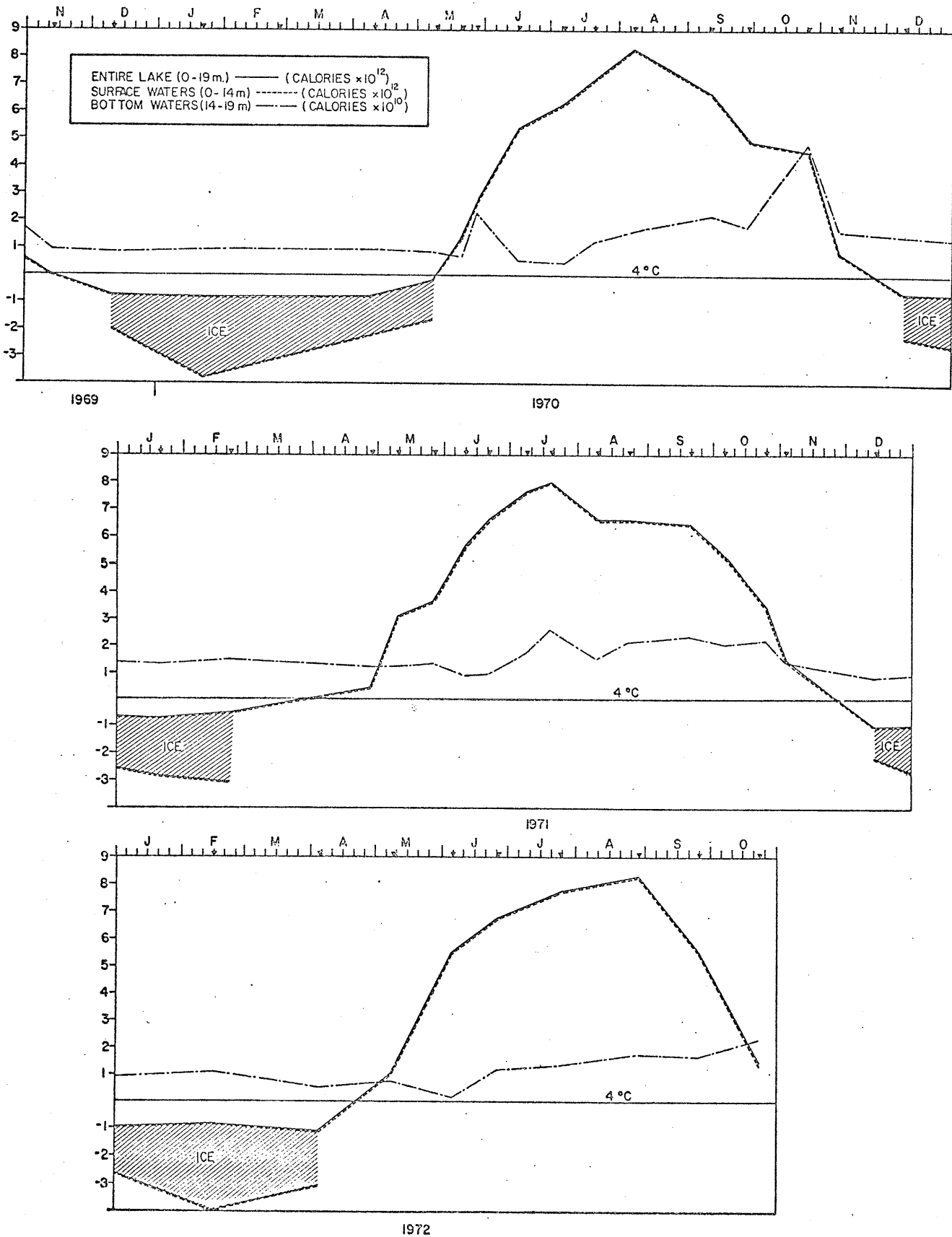


FIGURE 7. Heat budgets for Lake 120, 1969-1972. Total heat energy (calories) that would be consumed or liberated to achieve a state of homothermy at temperature of maximum density (4°C) is plotted against time.

According to Birge (1916),

$$B_z = \frac{V_z \cdot z (\Delta\rho)}{A_o}$$

gives the work performed per $\text{cm}^2 A_o$ in distributing the annual heat income of a layer of water 1 meter thick,

where V_z = volume of the 1 meter thick stratum
 $\Delta\rho$ = the thermal density change corresponding to
 minimum heat content and maximum heat content.

No work was calculated for the latent heat of melting of the ice cover. Depth distributions of work accomplished in the 0-14 meter stratum and the 14-19 meter stratum during 1970, 1971 and 1972 are illustrated in Figure 8. It can readily be seen from this figure that about 90% of the work was done in the first 6 meters, that is most of the work was used in depressing the thermocline. The total amount of work (B) performed in distributing the annual heat incomes of the 0-14 meter stratum and the 14-19 meter stratum was derived by summation. These data are presented in Table 2. Work performed in the 0-14 meter stratum ranged from 228-252 $\text{g cm}^{-2} A_o \text{ year}^{-1}$, whereas that done in the 14-19 meter stratum was from 0.3 to 1.5 $\text{g cm}^{-2} A_o \text{ year}^{-1}$.

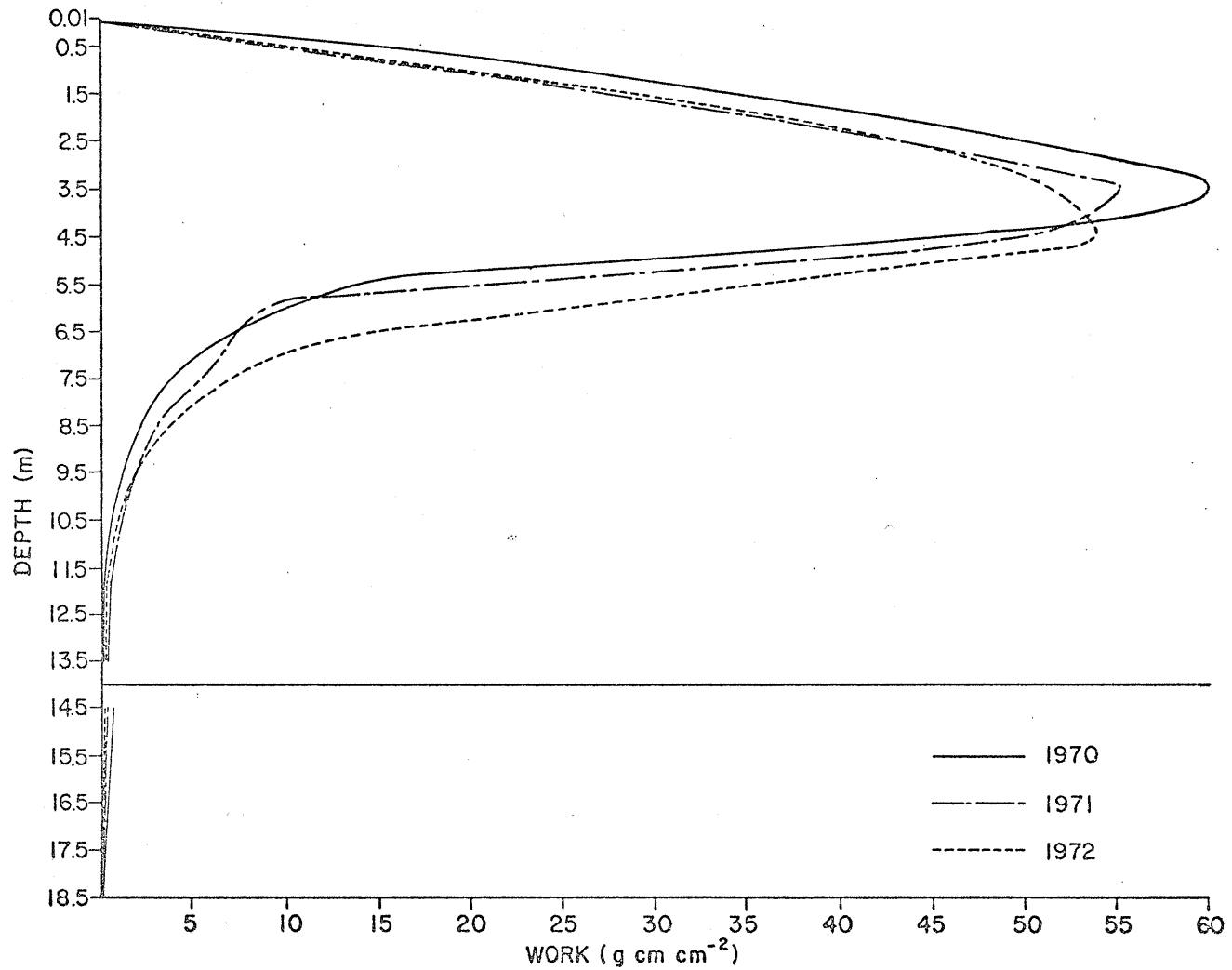


FIGURE 8. Work performed in distributing the annual heat incomes of Lake 120 during the years 1970, 1971 and 1972.

TABLE 2. Work (B) performed in distributing the annual heat incomes of Lake 120 in 1970, 1971 and 1972, and efficiencies (H_{ba^*}/B) of the work. The method used in deriving B was after that of Birge (1916) for computing work of the wind. H_b/B as a measure of efficiency was described by Schindler (1971). Melting of the ice cover is excluded from H_{ba^*} and B.

YEAR	STRATUM (meters)	H_{ba^*} (calories $\text{cm}^{-2}A_o$)	WORK (B) ($\text{g}\cdot\text{cm cm}^{-2}A_o$)	EFFICIENCY (H_{ba^*}/B) (calories per $\text{g}\cdot\text{cm}$)
1970	0-14	9811	232.9	42.1
	14-19	46.36	1.45	32.0
1971	0-14	9363	228.1	41.0
	14-19	18.09	0.384	47.1
1972	0-14	10091	251.7	40.1
	14-19	23.09	0.341	67.7

Hutchinson (1957) concluded that B/H_{bs} is an indicator of the efficiency of wind work in distributing the summer heat income of a lake. Schindler (1971), however, has pointed out that since heat income depends on wind work the ratio H_{bs}/B is a measure of efficiency; the higher the ratio, the greater the efficiency. For Lake 120, H_{ba^*}/B (H_{ba^*} does not include heat used in melting ice cover) is presented in Table 2. For the 0-14 meter stratum, the average H_{ba^*}/B was 41.1 calories per gram cm. The average H_{ba}/B for the 14-19 meter stratum was 50.0 calories per gram cm.

In general, Secchi visibility was relatively constant during spring and summer at depths of 4-5 meters (Table 2, appendix). Also constant was the depth at which light transparency (as measured by photometer) became less than 1% (Table 3, appendix). This depth was usually 8 meters and average vertical extinction coefficients ($\bar{\epsilon}_v^\lambda$) varied little, ranging from 0.59 to 0.72 (Figure 32). Only late in October during the time of maximum circulation was Secchi visibility reduced considerably; for example, 2.6 meters was a minimum on October 23, 1972. On October 23, 1972, maximum $\bar{\epsilon}_v^\lambda$ of 0.92 was also recorded. Colour at half Secchi depth was usually yellow-green during spring and summer but intensified in the late fall to orange or brown.

Chemical Limnology

In situ conductances at depths 0-13 meters were generally less than 50 $\mu\text{mhos cm}^{-1}$ at 25°C (Figure 9, and Table 4 in appendix). However, a marked increase was observed from 14 meters to the bottom. Conductance

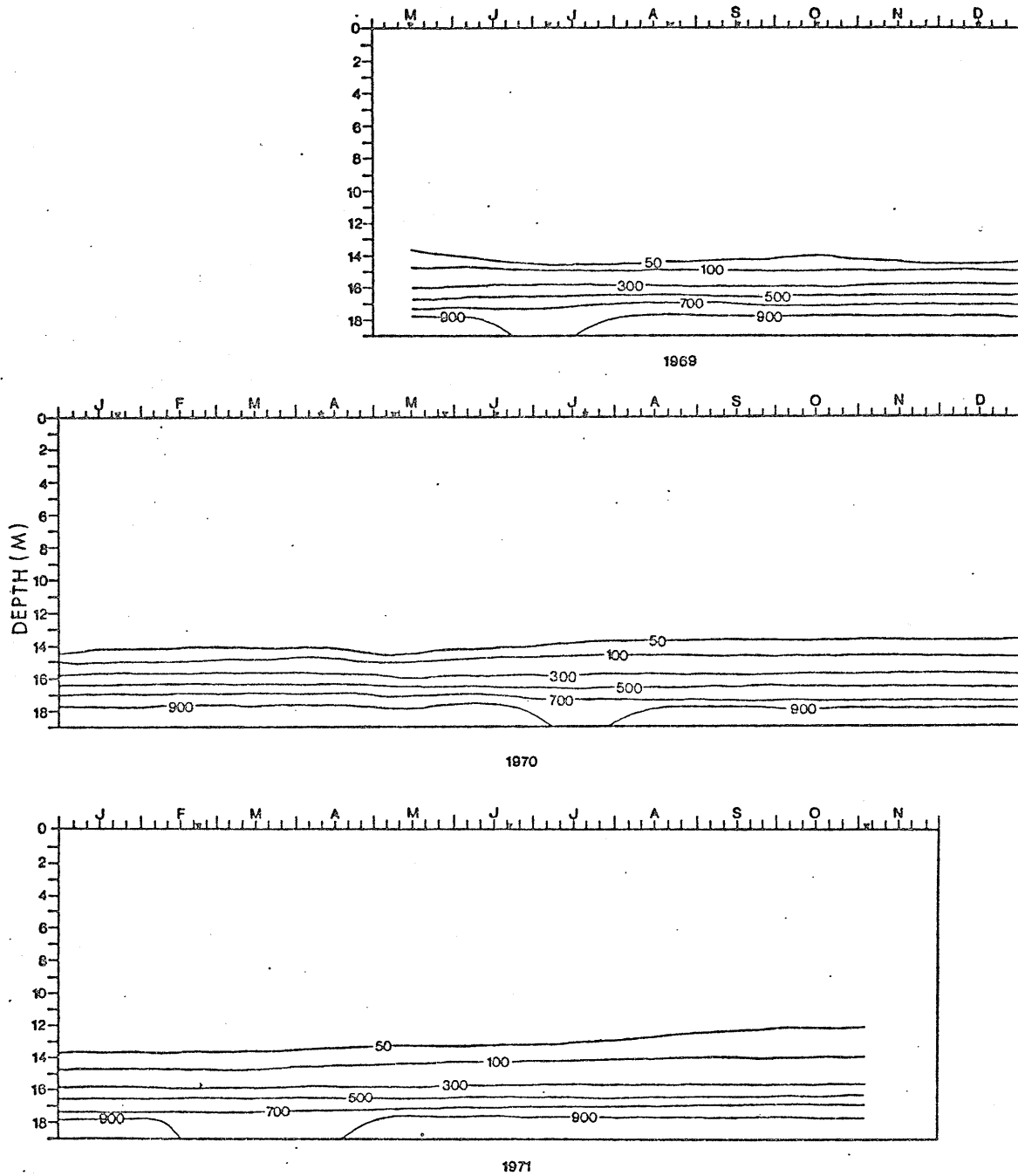


FIGURE 9. Depth-time distribution of conductivity measured *in situ* in Lake 120, 1969-1971. Isoleths are $\mu\text{mho cm}^{-1}$.

of the bottom waters was up to 50 times that of the surface waters. Maximum conductances of 800-1100 $\mu\text{mhos cm}^{-1}$ were always recorded between 18 and 19 meters. Little temporal variation in the conductivity gradient was observed.

Hydrogen ion concentration (as pH) ranged from 5.8 to 7.0 (Table 5, appendix). Profiles of pH were found to be dichotomous with minimum pH between 11 and 14 meters depth. For only very brief times, coinciding with spring and fall circulation, pH at depths 0-14 meters was rather uniform but consistently lower than that of the deeper waters. Only in very deep waters (18 meters) could it be said that pH remained constant (6.6-6.7) from season to season (Figure 10).

During the course of this study, dissolved oxygen was never detected below 16 meters (Table 6, appendix). Oxygen occurred at depths as great as 16 meters only during times of vernal and autumnal circulation. Under winter ice and during summer stratification, further depletion of oxygen was observed in the deep waters. Depletion was more severe during the summer than during the winter (Figure 11). By late summer, concentrations were usually less than 1 mg O_2 liter⁻¹ below 10 or 11 meters whereas at the end of winter concentrations were lower than 1 mg liter⁻¹ at depths greater than about 13 meters. Maximum oxygen concentration was observed during late summer at or just below the thermocline. Maxima during the winter were observed directly below the ice surface.

Depth-time distribution of total dissolved carbon dioxide ($\text{CO}_2 +$

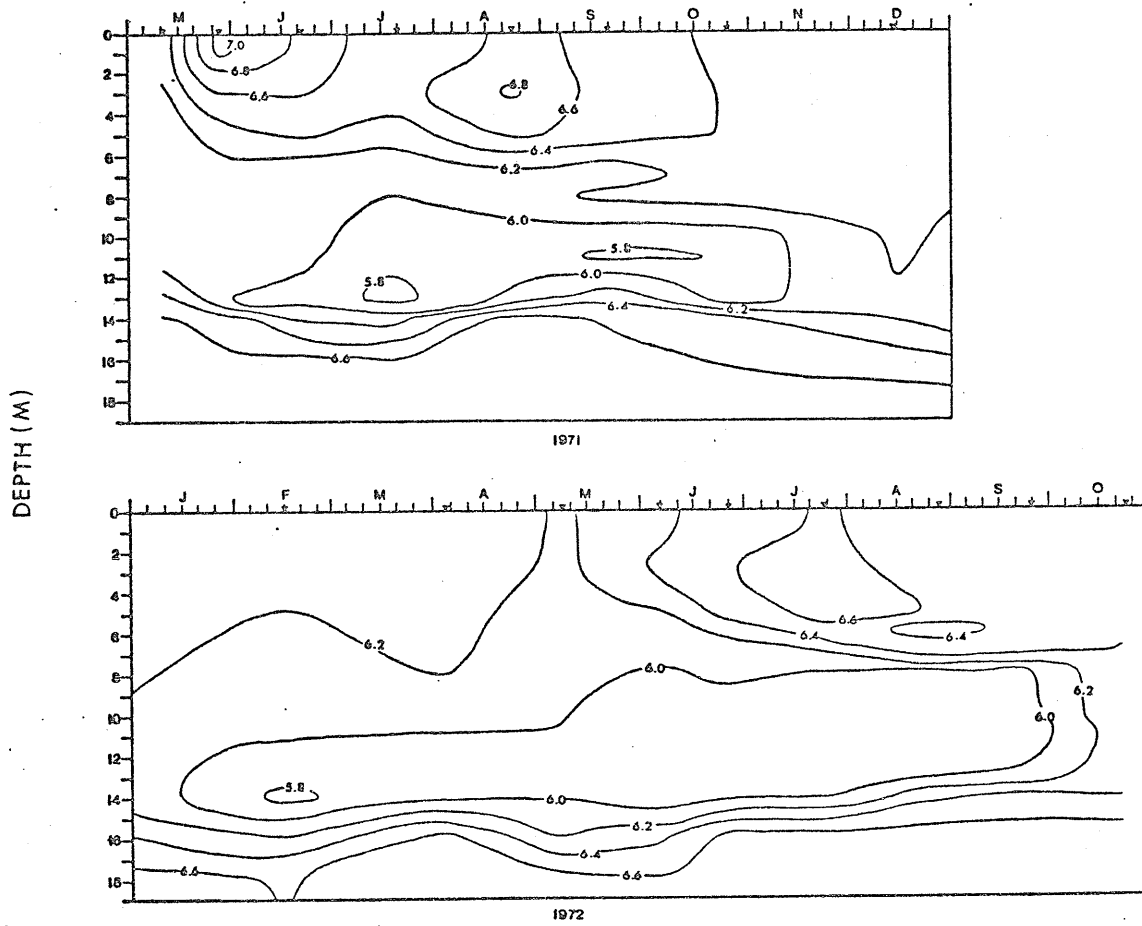


FIGURE 10. Depth-time distribution of $-\log$ hydrogen ion concentration (pH) in Lake 120, 1971-1972. Isopleths are pH units.

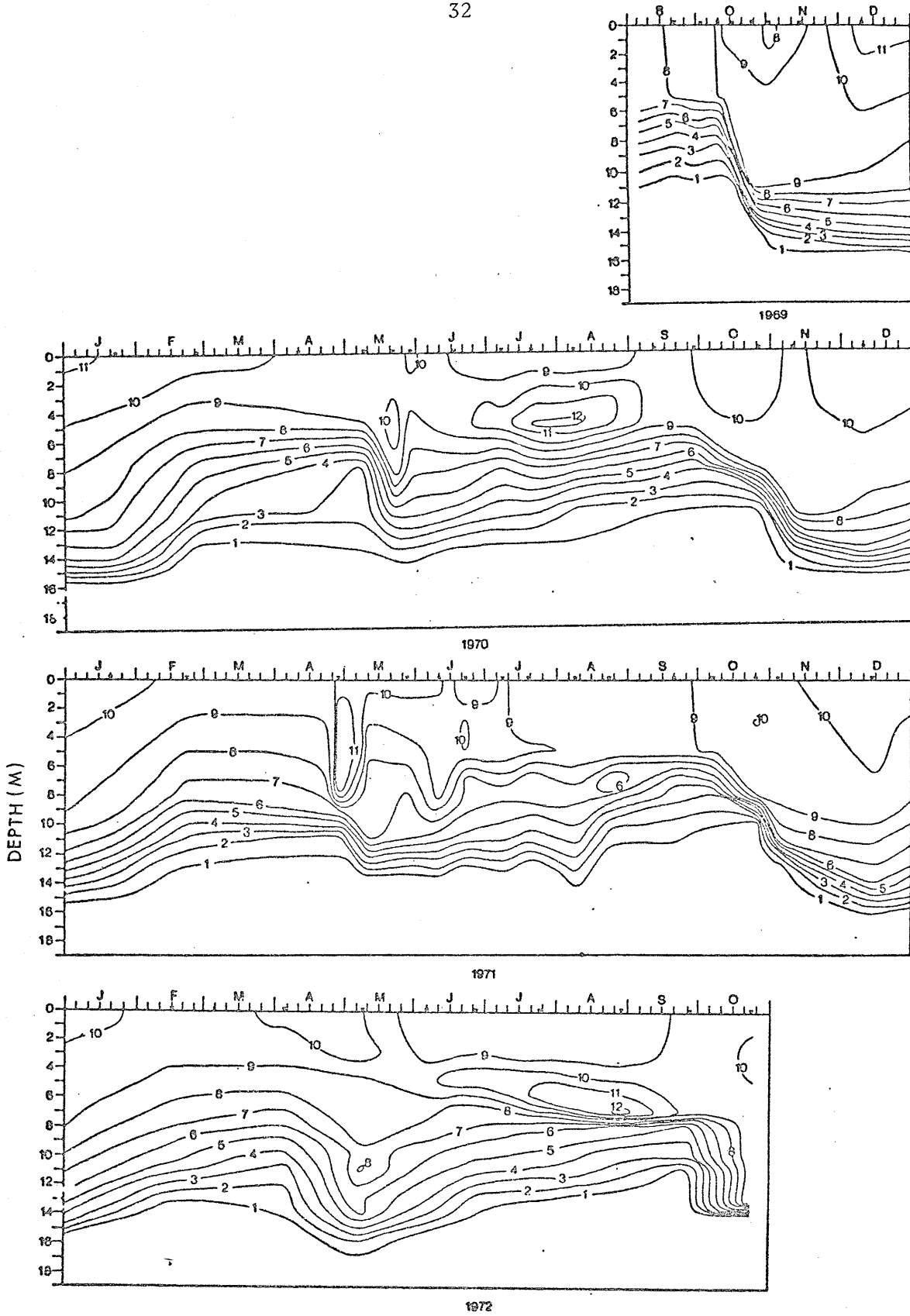


FIGURE 11. Depth-time distribution of dissolved oxygen (O_2) in Lake 120, 1969-1972. Isoleths are $mg\ liter^{-1}$. O_2 was not detectable at the 1-meter depth interval immediately below the 1 $mg\ liter^{-1}$ isopleth.

$\text{H}_2\text{CO}_3 + \text{HCO}_3^- + \text{CO}_3^{=}$) appeared inversely related to trends in dissolved oxygen. The deep anaerobic waters were CO_2 enriched. Up to 12,000 $\mu\text{moles } \Sigma\text{CO}_2 \text{ liter}^{-1}$ were measured at 18 meters, whereas at depths less than 14 meters, ΣCO_2 concentrations greater than 300 $\mu\text{moles liter}^{-1}$ were uncommon (Table 7, appendix). ΣCO_2 concentrations greater than 300 $\mu\text{moles liter}^{-1}$ at depths less than 14 meters (Figure 12) coincided with summer and winter oxygen depletion. Similarly, minimum ΣCO_2 concentrations of less than 100 $\mu\text{moles liter}^{-1}$ were observed in the surface waters during the summer which at least in part coincided with oxygen maxima. Although the deep waters (14-18 meters) were always greatly enriched in ΣCO_2 with respect to the overlying waters, it should be noted that in terms of absolute concentrations a marked decrease was observed in the bottom waters during the winter. In this stratum, ΣCO_2 during February to April was approximately one half that observed during mid and late summer. Concentrations of dissolved methane in the bottom waters equalled those for total carbon dioxide (Table 8, appendix). As with ΣCO_2 , Figure 13 shows that amounts of methane in the bottom waters during winter were also about one half the summer maximum of almost 11,000 $\mu\text{moles liter}^{-1}$. In the aerobic stratum, methane was usually not detectable. A marked concentration gradient was also evident for dissolved organic carbon. DOC from 0-14 meters ranged from about 50 to 500 $\mu\text{moles liter}^{-1}$ but at 18 meters ranged from 2,300 $\mu\text{moles liter}^{-1}$ during late winter to over 9,000 $\mu\text{moles liter}^{-1}$ in mid summer (Figure 14 and Table 9, appendix). It should be noted that, on an average, from 0-14 meters almost 70% of the total dissolved carbon was organic whereas from 14-19 meters less than 30% was organic (Table 3).

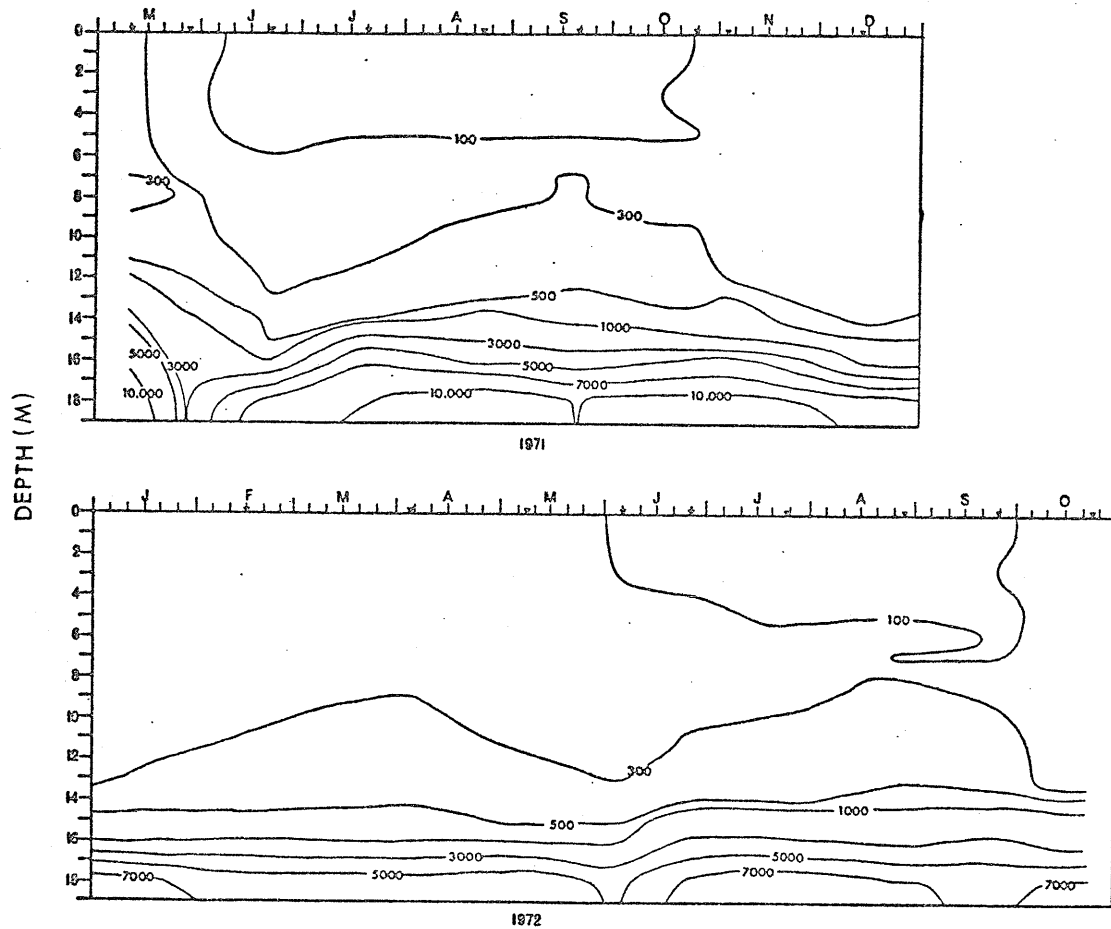
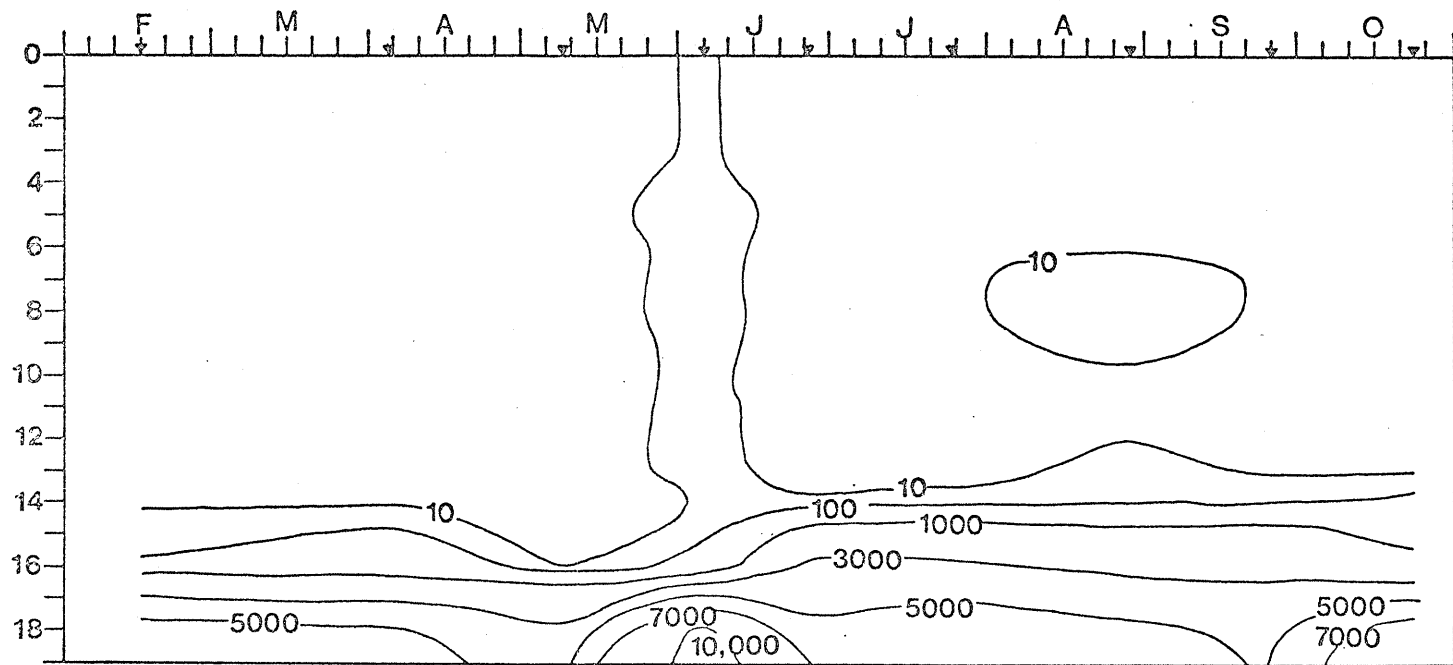


FIGURE 12. Depth-time distribution of total dissolved carbon dioxide ($\text{CO}_2 + \text{H}_2\text{CO}_3 + \text{HCO}_3^- + \text{CO}_3^{2-}$) in Lake 120, 1971-1972. Isopleths are $\mu\text{moles liter}^{-1}$.



1972

FIGURE 13. Depth-time distribution of dissolved methane (CH_4) in Lake 120 during 1972. Isoleths are $\mu\text{moles liter}^{-1}$.

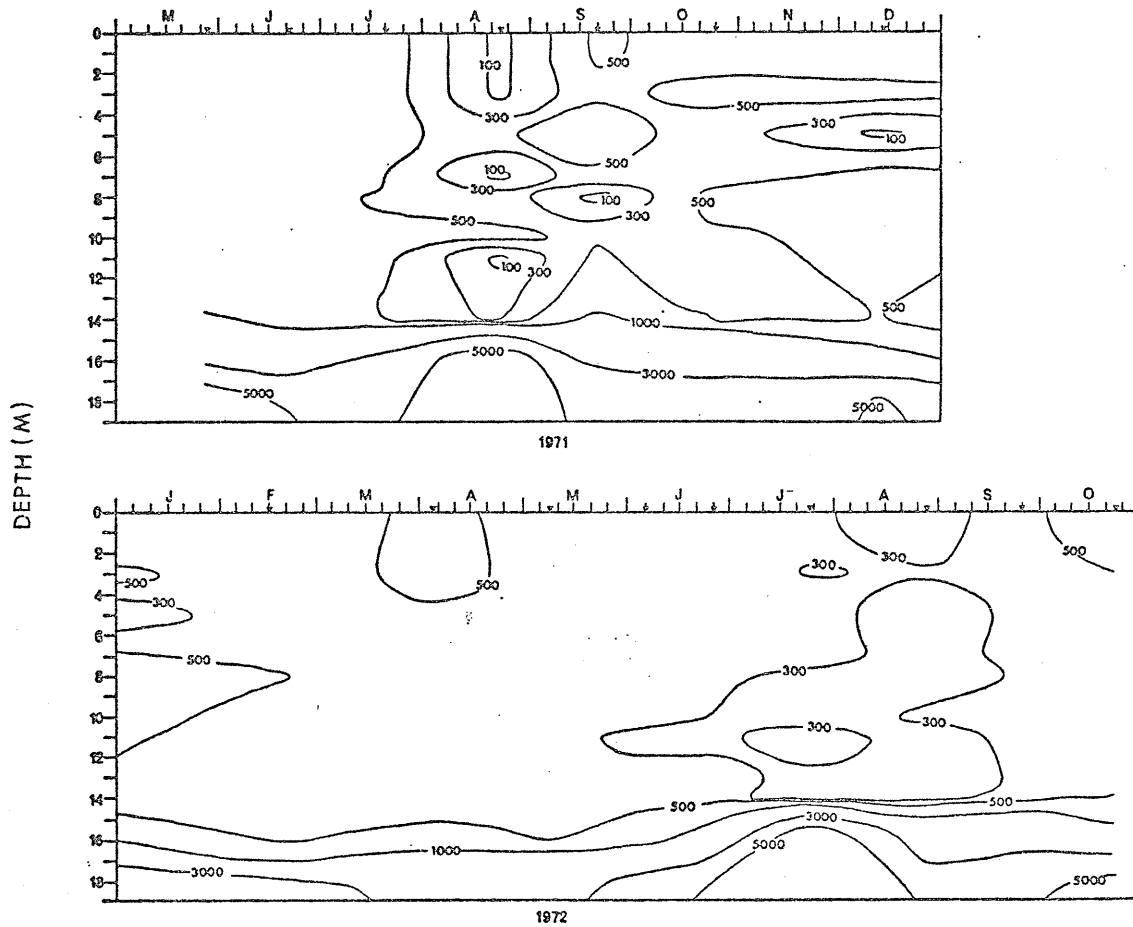


FIGURE 14. Depth-time distribution of dissolved organic carbon (DOC) in Lake 120, 1971-1972. Isopleths are $\mu\text{moles liter}^{-1}$.

TABLE 3. Average concentrations of dissolved inorganic, dissolved organic, and suspended fractions of carbon, nitrogen and phosphorus measured in Lake 120 during 1971 and the percentage contribution of each fraction to the total.

	MEAN CONCENTRATION ($\mu\text{moles liter}^{-1}$)		$\frac{\text{CONC}'\text{N } z=14-19}{\text{CONC}'\text{N } z= 0-14}$	% OF TOTAL	
	z=0-14	z=14-19		z=0-14	z=14-19
C					
Dissolved inorganic ($\Sigma\text{CO}_2+\text{CH}_4$)	235	7353	31	29	69
Dissolved organic (DOC)	498	2939	6	62	28
Suspended (PC)	73.6	352	5	9	3
N					
Dissolved inorganic ($\text{NH}_3+\text{NO}_2+\text{NO}_3$)	3.03	822	271	15	89
Dissolved organic ($\text{TDN}-[\text{NH}_3+\text{NO}_2+\text{NO}_3]$)	12.71	74*	6	61	8
Suspended (PN)	4.93	26.78	5	24	3
P ^x					
Dissolved inorganic (SRP) [†]	0.06	0.33	6	13	15
Dissolved organic (TDP-SRP)	0.23	0.82	4	48	38
Suspended (PP)	0.19	1.00	5	40	47

* From determinations carried out in 1974. In 1974 $\text{NH}_3+\text{NO}_2+\text{NO}_3$ nitrogen was 91% of TDN.

x Most individual determinations of P were at or below the limits of detection of the methods employed during this study.

† Probably includes some dissolved organic phosphorus (see Methods Section).

From Table 3 it can also be seen that dissolved nitrogen from 0-14 meters was predominantly organic (80%). However, as for dissolved carbon, the trend was reversed from 14-19 meters. The organic fraction in that part of the lake was only about 8% of the total dissolved nitrogen. (Recall that in the methods section it was stated that during this study determinations for TDN $>35 \mu\text{moles liter}^{-1}$ were found to be unreliable for these kinds of samples. As a result, no TDN data will be reported here for the 14-19 meter stratum. More reliable TDN determinations carried out in 1974 were used to compute the dissolved organic fraction cited above where dissolved organic nitrogen = $\text{TDN} - [\text{NH}_3 + \text{NO}_2 + \text{NO}_3\text{-N}]$). A paucity of dissolved inorganic nitrogen was observed in the oxygenated waters (Tables 10 and 11, appendix). $\text{NO}_3 + \text{NO}_2\text{-N}$ concentrations ranged from undetectable (<0.07) to less than $10 \mu\text{moles liter}^{-1}$; $\text{NH}_3\text{-N}$ was usually less than $1 \mu\text{mole liter}^{-1}$. TDN (Table 12, appendix) was usually between 10 and $20 \mu\text{moles liter}^{-1}$. From the depth-time distribution shown in Figure 15 it can be seen that a buildup of $\text{NO}_3 + \text{NO}_2\text{-N}$, centered usually at about 11 meters, occurred twice each year. These buildups concurred with times of maximum oxygen depletion under winter ice and during summer stratification. Levels of $\text{NH}_3\text{-N}$ (in essence, dissolved inorganic nitrogen) in the 14-19 meter stratum were well over $2,000 \mu\text{moles liter}^{-1}$ by late summer (Figure 16). As for dissolved carbon, in these waters concentrations of $\text{NH}_3\text{-N}$ were reduced by at least one half by late winter. $\text{NO}_3 + \text{NO}_2\text{-N}$ reported at depths below 14 meters should probably be looked upon with suspicion since no correction was made during analysis for absorbance due to the natural colour of the water; also, it is possible that during sample collection and preparation exposure to air oxidized a small

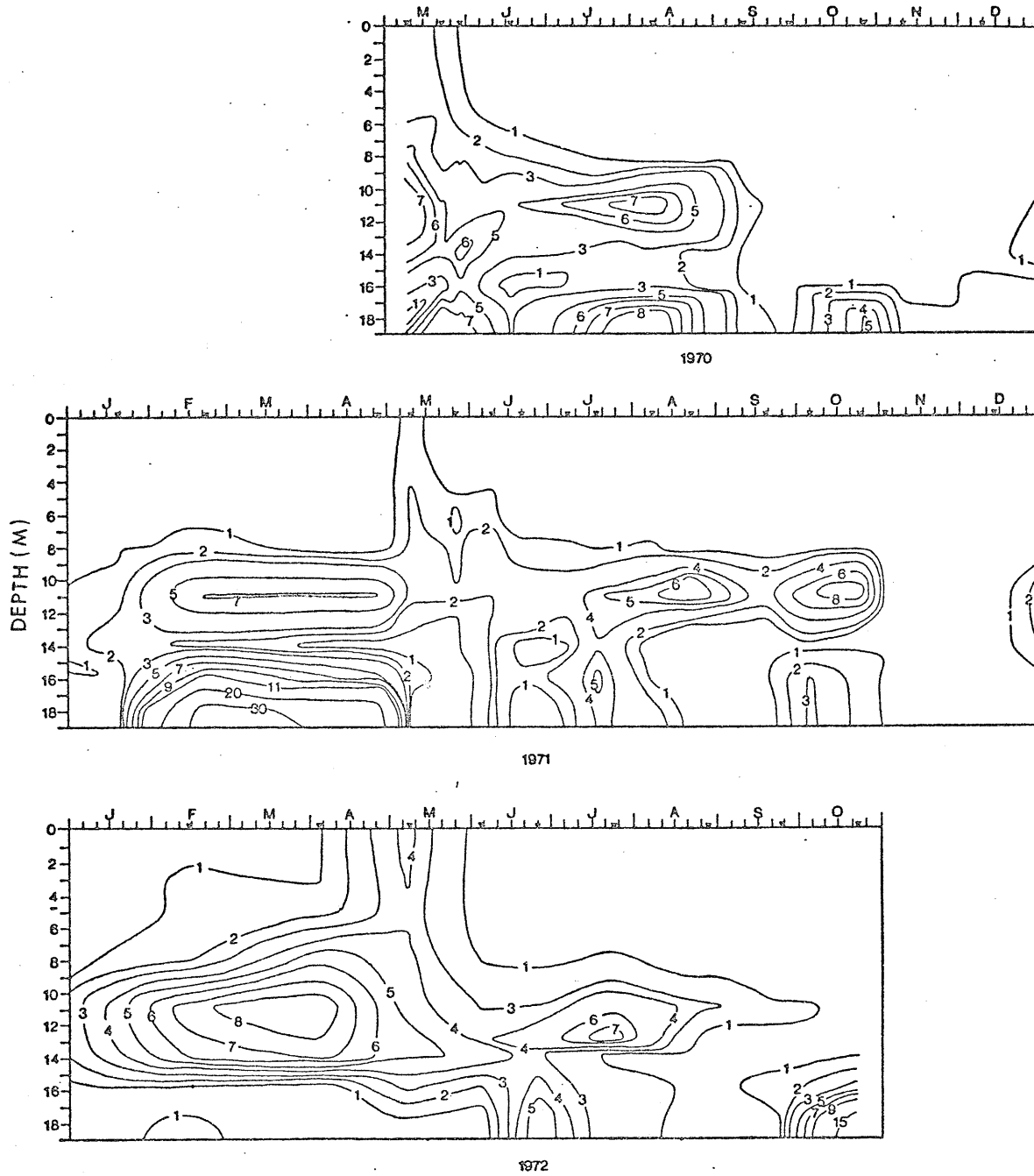


FIGURE 15. Depth-time distribution of nitrate plus nitrite nitrogen ($\text{NO}_3 + \text{NO}_2 - \text{N}$) in Lake 120, 1970-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

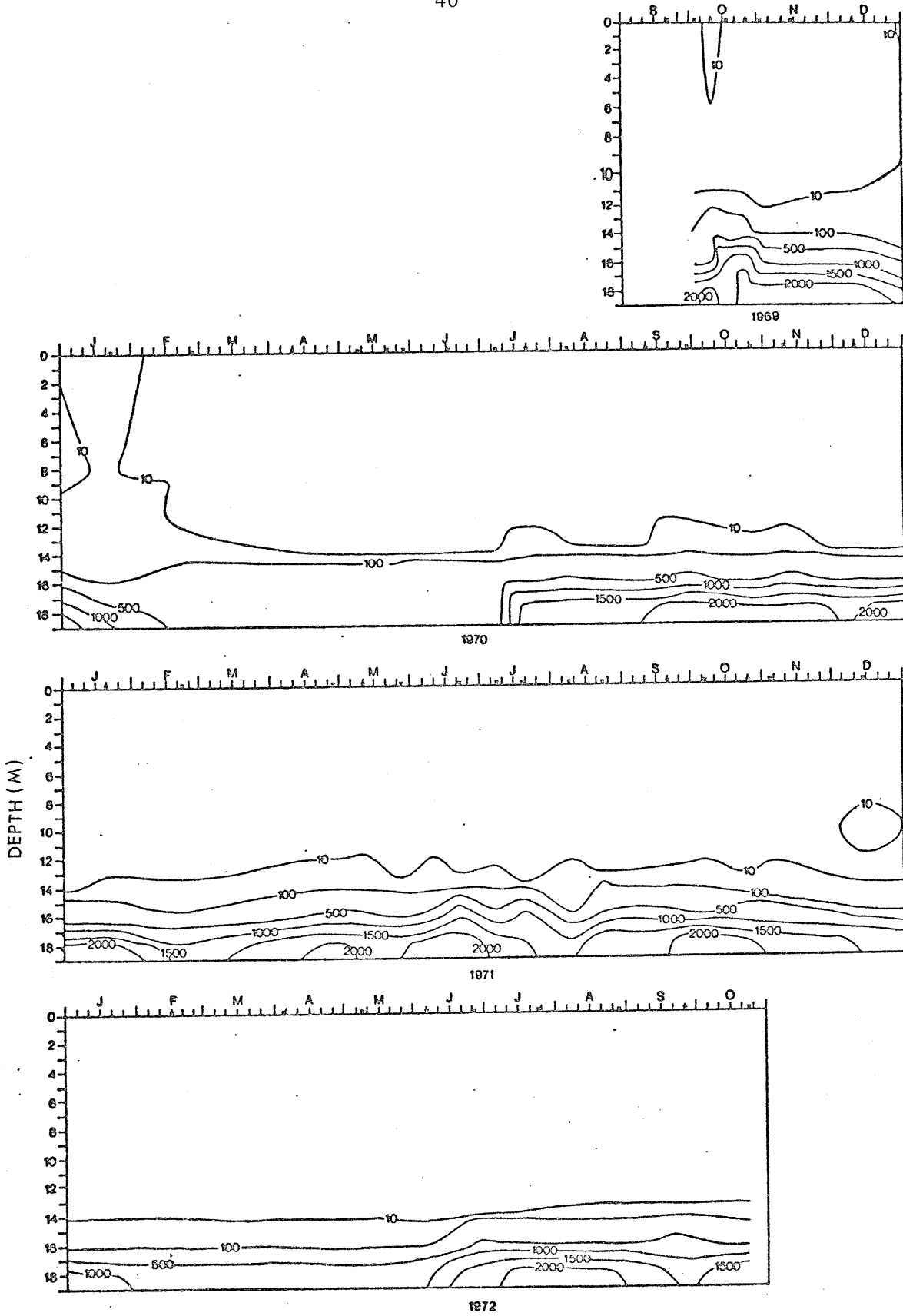


FIGURE 16. Depth-time distribution of ammonia nitrogen ($\text{NH}_3\text{-N}$) in Lake 120, 1969-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

fraction of the $\text{NH}_3\text{-N}$.

Since SRP determinations (Table 13, appendix) were usually at the limit of detection of the method, and since detection of some organically bound P as well as dissolved inorganic P ($\text{PO}_4\text{-P}$) was likely, the data must be interpreted with caution. At any rate, SRP from 0-14 meters ranged from undetectable (<0.03) to $0.2 \mu\text{moles liter}^{-1}$. In the bottom waters, concentrations increased to maxima of $2.0 \mu\text{moles liter}^{-1}$ during summer but during mid and late winter decreased to about $0.2 \mu\text{moles liter}^{-1}$ (Figure 17). Concentrations of TDP (Table 14, appendix) were also considerably higher in the bottom waters than in the surface waters. Up to $1.0 \mu\text{mole liter}^{-1}$ of TDP was recorded at depths 0-14 meters. Greater than $5 \mu\text{moles liter}^{-1}$ were observed at 18 meters in late summer but during winter concentrations were usually less than $2 \mu\text{moles liter}^{-1}$ (Figure 18). A concentration of TDP greater than $12 \mu\text{moles liter}^{-1}$ was recorded in the surface waters on one occasion (August 7, 1970). It is possible that such high levels recorded on that day resulted from contamination during analysis. Unlike carbon and nitrogen, no marked shift to a predominance of dissolved inorganic P over dissolved organic P was observed in the bottom waters. Dissolved inorganic P in the 0-14 meter stratum was less than 20% TDP; in the 14-19 meter stratum dissolved inorganic P was still less than 30% TDP (Table 3).

Individual determinations of suspended carbon, nitrogen and phosphorus are reported respectively in Tables 15, 16 and 17 of the appendix. Average concentrations of PC, PN and PP in the 0-14 meter stratum during 1971 were 75, 5 and $0.2 \mu\text{moles liter}^{-1}$ respectively.



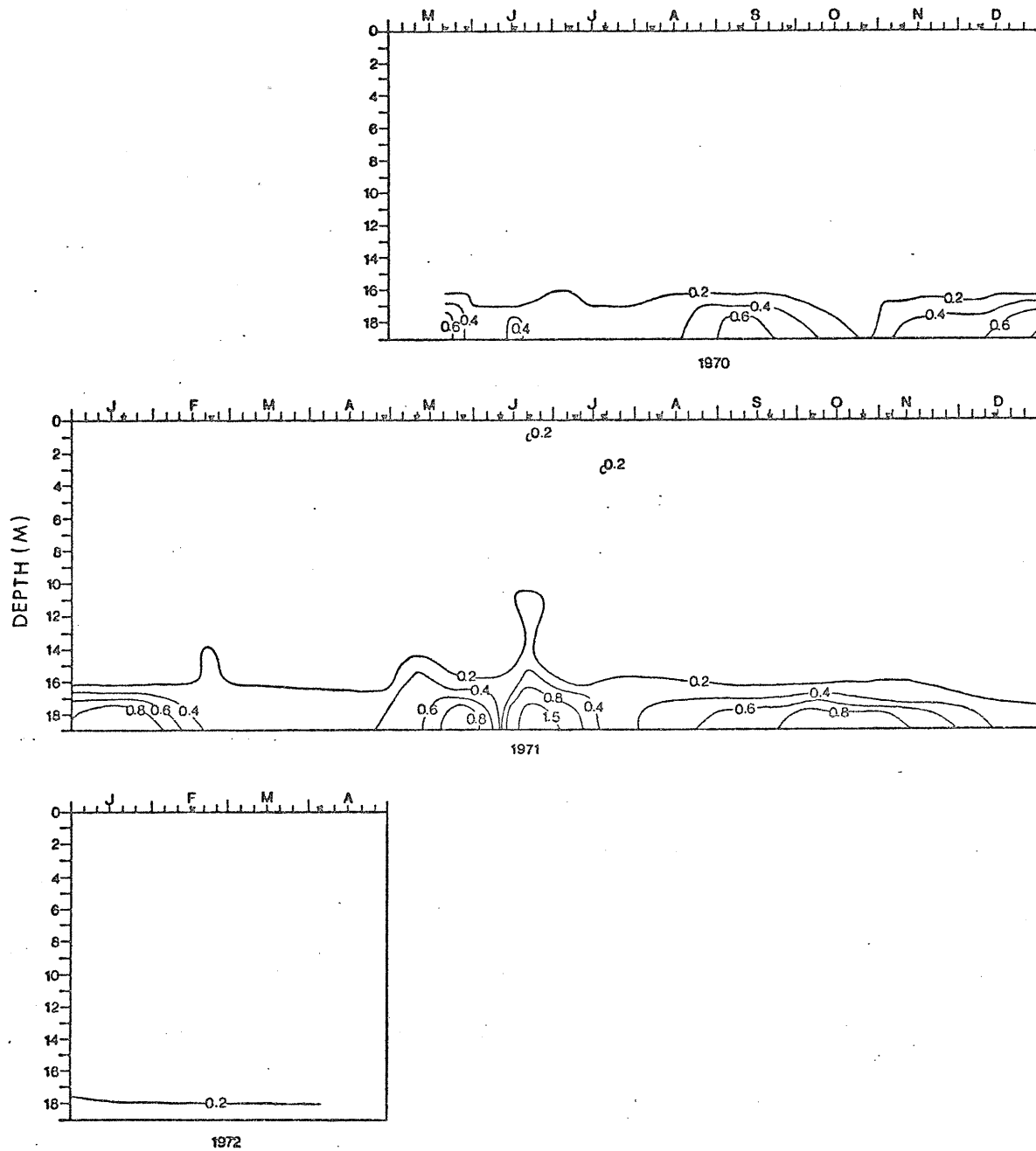


FIGURE 17. Depth-time distribution of soluble reactive phosphorus (SRP) in Lake 120, 1970-1972. SRP is not only a measure of dissolved inorganic phosphorus ($\text{PO}_4\text{-P}$) but also to some extent a measure of organically bound phosphorus in solution. Isopleths are $\mu\text{moles liter}^{-1}$.

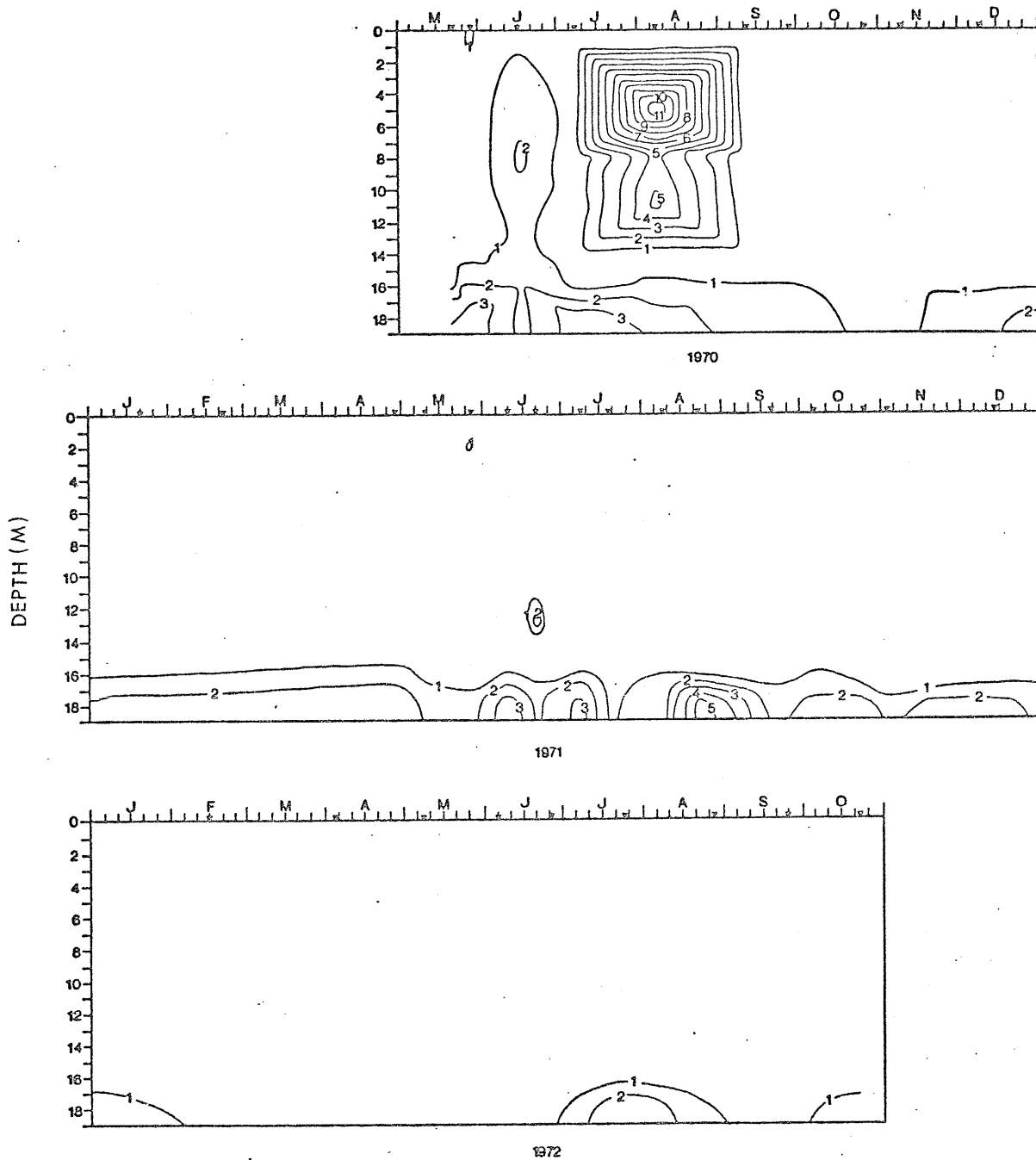


FIGURE 18. Depth-time distribution of total dissolved phosphorus (TDP) in Lake 120, 1970-1972. High levels determined at 5, 8 and 11 meters on August 7, 1970 may have been a result of contamination during analysis. Isopleths are $\mu\text{moles liter}^{-1}$.

Sharp rises in concentration were observed from 14-19 meters. In this stratum, average concentrations of PC, PN and PP were 5 times higher than in overlying waters (Table 3). Depth-time distribution of PC, PN and PP are shown in Figures 19, 20 and 21, respectively. Nutrients in the suspended phase in both the surface and bottom waters were at a minimum during the winter. At 18 meters depth, PC concentrations rose from winter minimums of about $150 \mu\text{moles liter}^{-1}$ to greater than $1,000 \mu\text{moles liter}^{-1}$ during summer. Similarly, concentrations of PN at this depth were observed to increase from less than 20 to greater than 75 $\mu\text{moles liter}^{-1}$ and PP increased from less than 1 to greater than 3 $\mu\text{moles liter}^{-1}$. During summer stratification, the highest levels of particulate nutrients in the 0-14 meter stratum were recorded at depths corresponding to the lower reaches of the thermocline.

Concentrations of soluble reactive silicon (Si) at depths 0-14 meters ranged from about $40-70 \mu\text{moles liter}^{-1}$ (Table 18, appendix). Si was depleted to levels less than $50 \mu\text{moles liter}^{-1}$ at depths 0 to about 8 meters during summer stratification. Values less than $50 \mu\text{moles liter}^{-1}$ were also observed under winter ice during January and February of 1971 (Figure 22). Concentrations of Si greater than $400 \mu\text{moles liter}^{-1}$ were observed at 18 meters during the summer. By the end of winter, concentrations in the deep waters had usually halved. Average concentrations of Si observed during 1971 in the 0-14 meter and 14-19 meter strata are reported in Table 4. On an average, levels of Si in the 14-19 meter stratum were four times those of the 0-14 meter stratum.

Average concentrations of dissolved Ca, Mg, Na, K, Fe, and Mn in

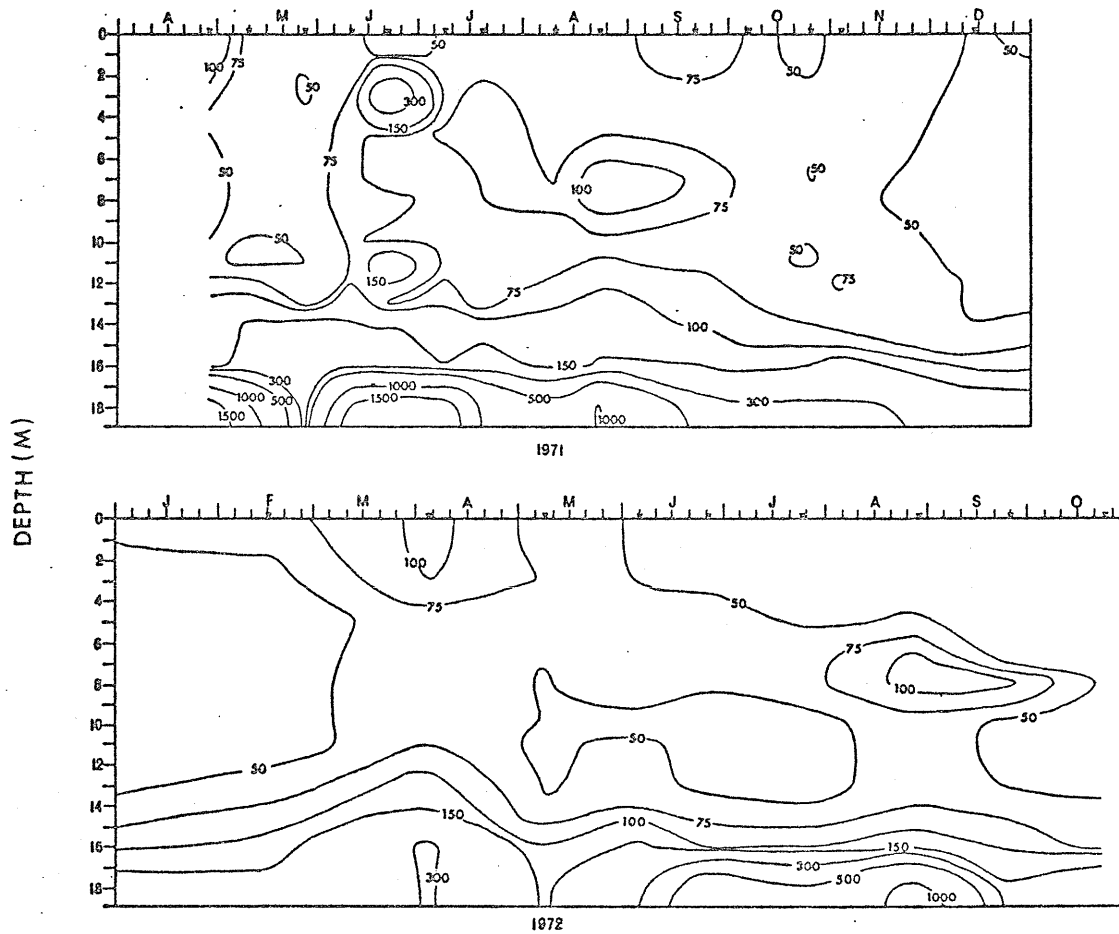


FIGURE 19. Depth-time distribution of suspended particulate carbon (PC) in Lake 120, 1971-1972. Isopleths are $\mu\text{moles liter}^{-1}$.

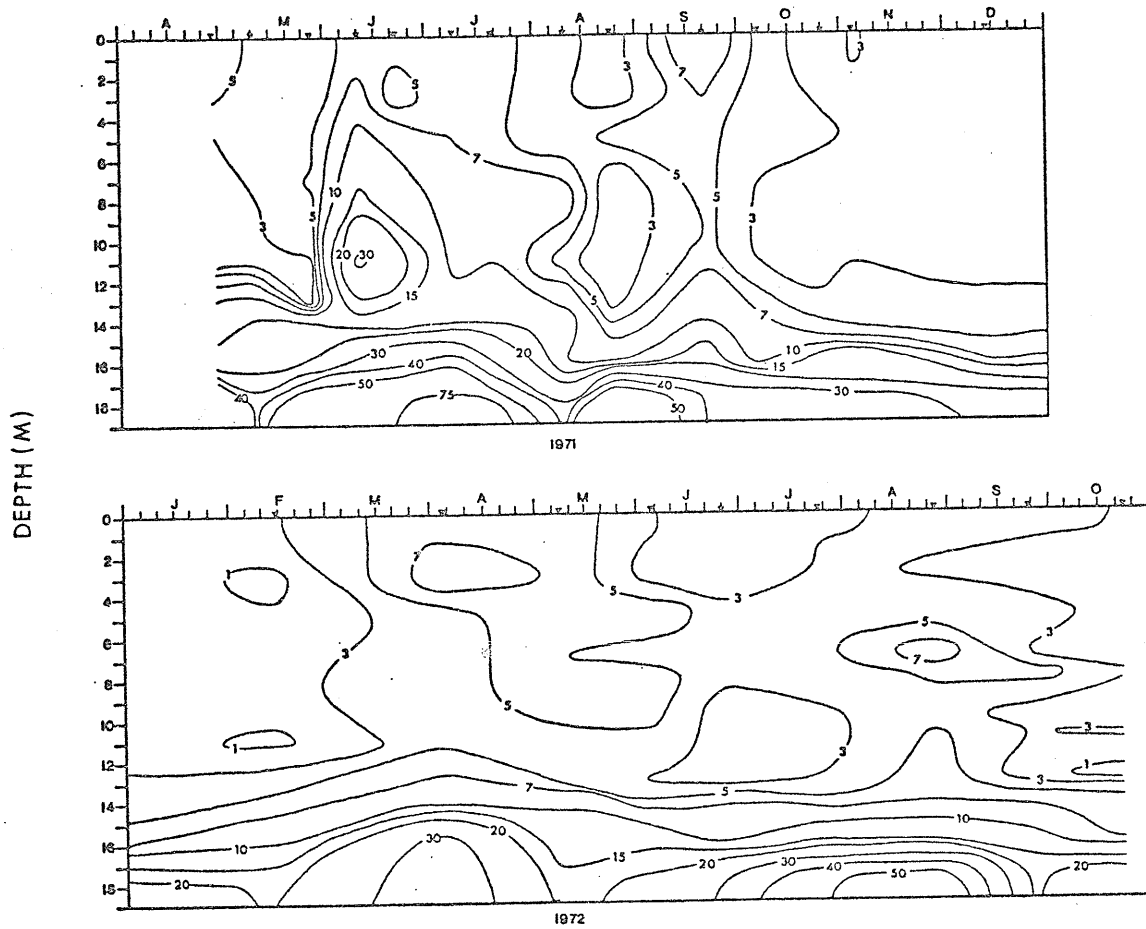


FIGURE 20. Depth-time distribution of suspended particulate nitrogen (PN) in Lake 120, 1971-1972. Isopleths are $\mu\text{moles liter}^{-1}$.

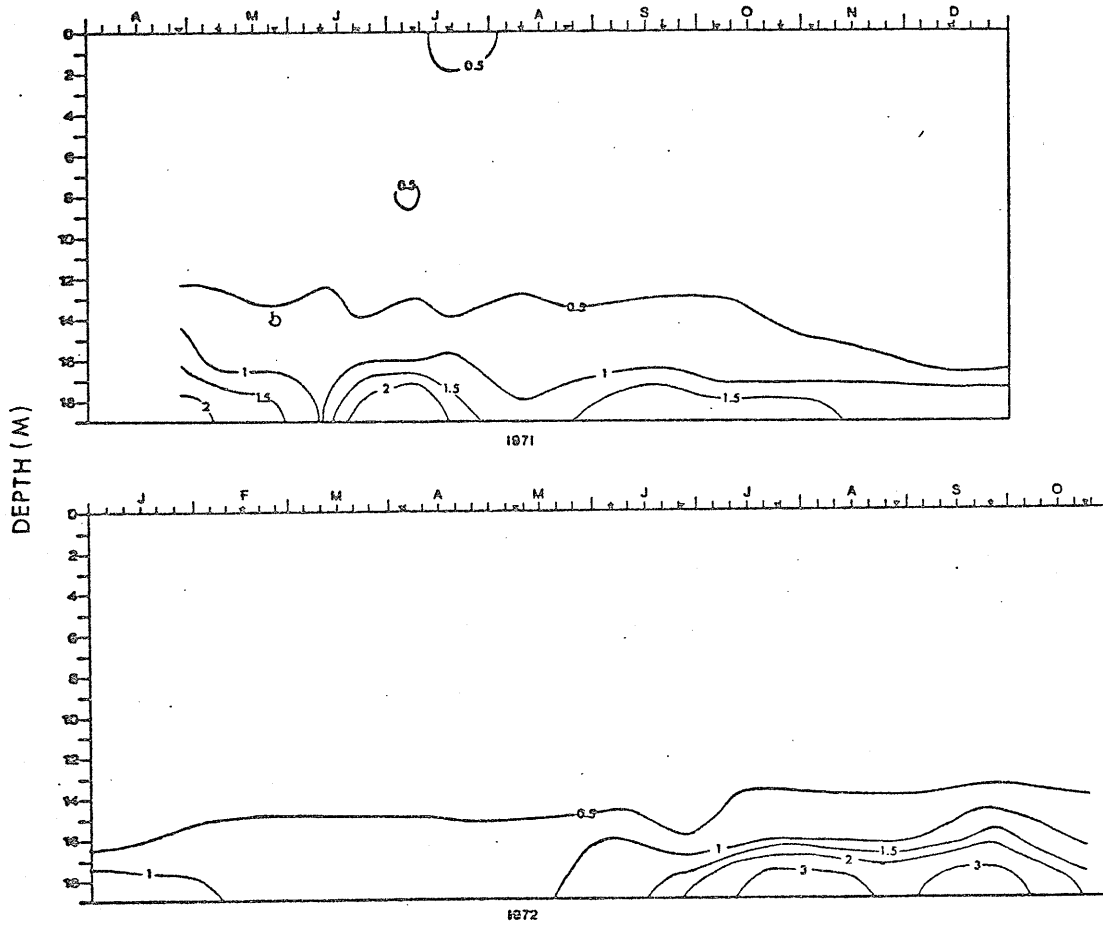


FIGURE 21. Depth-time distribution of suspended particulate phosphorus (PP) in Lake 120, 1971-1972. Isopleths are $\mu\text{moles liter}^{-1}$.

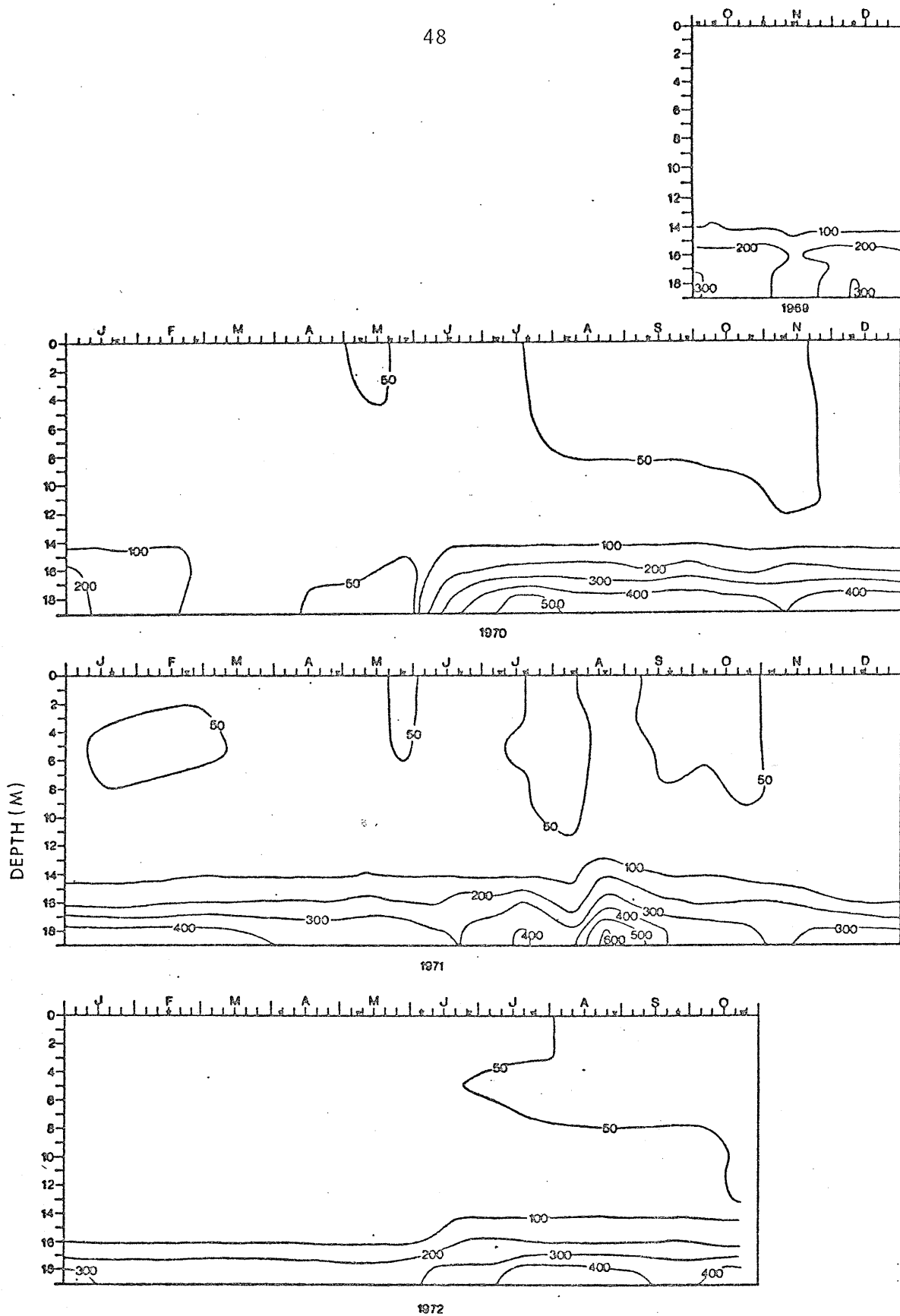


FIGURE 22. Depth-time distribution of soluble reactive silicon (Si) in Lake 120, 1969-1972. Isopleths are $\mu\text{moles liter}^{-1}$.

TABLE 4. Average concentrations of soluble reactive silicon (Si), dissolved calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe) and manganese (Mn) in Lake 120 during 1971.

	AVERAGE CONCENTRATION ($\mu\text{moles liter}^{-1}$)		$\frac{\text{CONC}'N \text{ } z = 14-19}{\text{CONC}'N \text{ } z = 0-14}$
	z = 0-14	z = 14-19	
Si	56	224	4
Ca	38	330	9
Mg	23	40	2
Na	31	38	1
K	6	19	3
Fe	5	1260	250
Mn	2	48	24

the 0-14 and 14-19 meter strata are also reported in Table 4. For all the above-mentioned cations, enrichment was observed in the 14-19 meter stratum. However, the degree of enrichment varied considerably. The concentration of Fe in the bottom waters was 250 times that of the surface waters whereas that for sodium was only slightly greater than 1 (Table 4). Individual determinations of Ca, Mg, Na, K, Fe, and Mn are reported respectively in Tables 19, 20, 21, 22, 23 and 24 of the appendix. As a rule, concentrations of major cations in the 0-14 meter stratum varied little from season to season (Figures 23, 24, 25, 26, 27 and 28). However, noticeable decreases in Ca, Mg, Na and K levels were observed during January and February of 1971. The relative order of abundance (moles) of these dissolved cations in the surface waters was $Ca > Na > Mg > K > Fe > Mn$. In the 14-19 meter stratum the order was very different where $Fe > Ca > Mn > Mg > Na > K$. In the bottom waters there was a marked seasonal variation in concentration. Without exception, concentrations of the above-mentioned cations were much lower during the winter than during the summer.

Hydrological and Chemical Budgets

Annual water budgets for Lake 120 during 1970, 1971 and 1972 were computed by extrapolation. Precipitation, runoff, and evaporation were measured on the nearby Lake 239 watershed (Schindler *et al.*, 1976). Storage in the lake was assumed to be zero (storage never accounted for more than 4% of the annual input of water to Lake 239). Outflow from the lake was calculated by subtracting lake surface evaporation from the

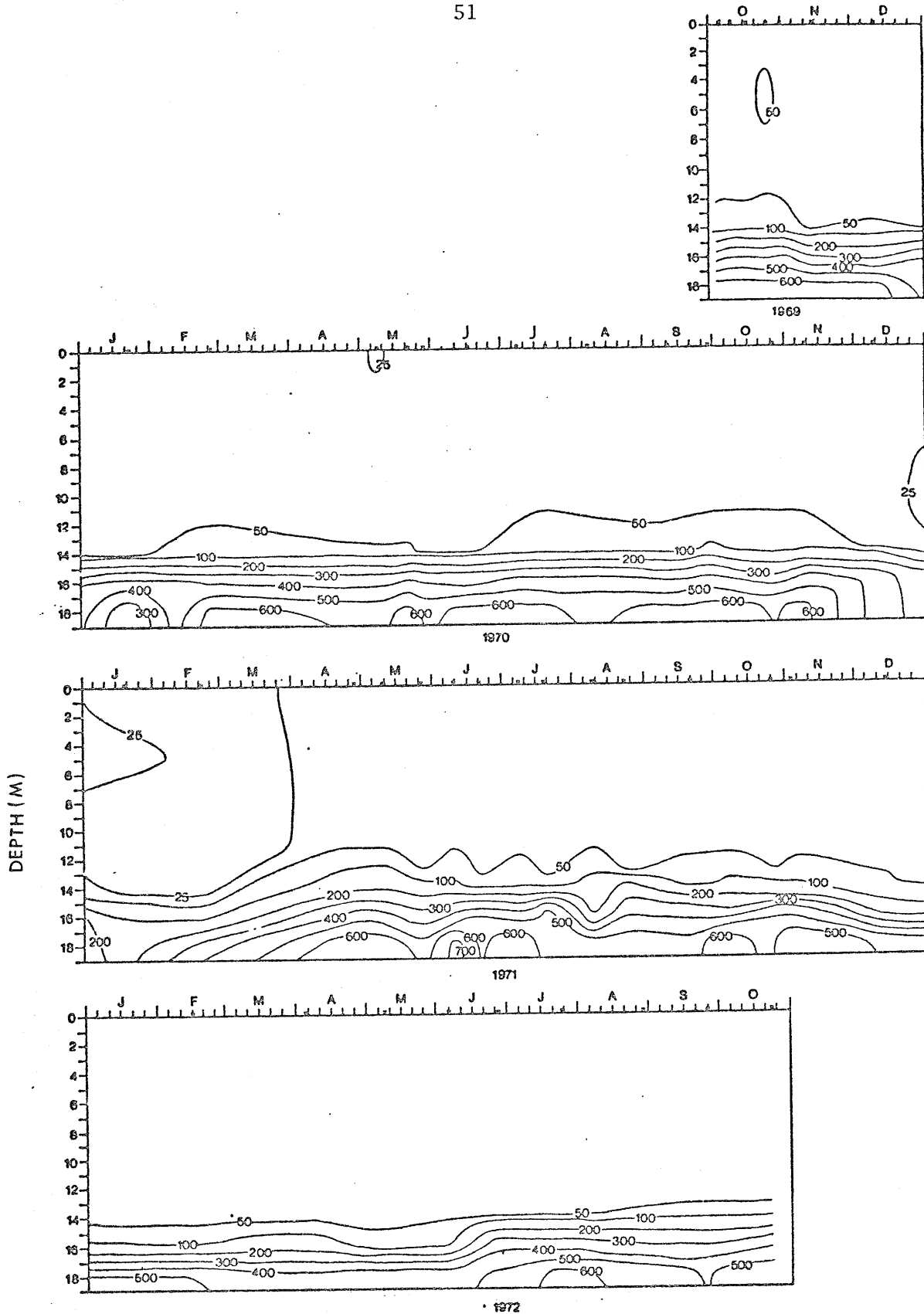


FIGURE 23. Depth-time distribution of dissolved calcium (Ca) in Lake 120, 1969-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

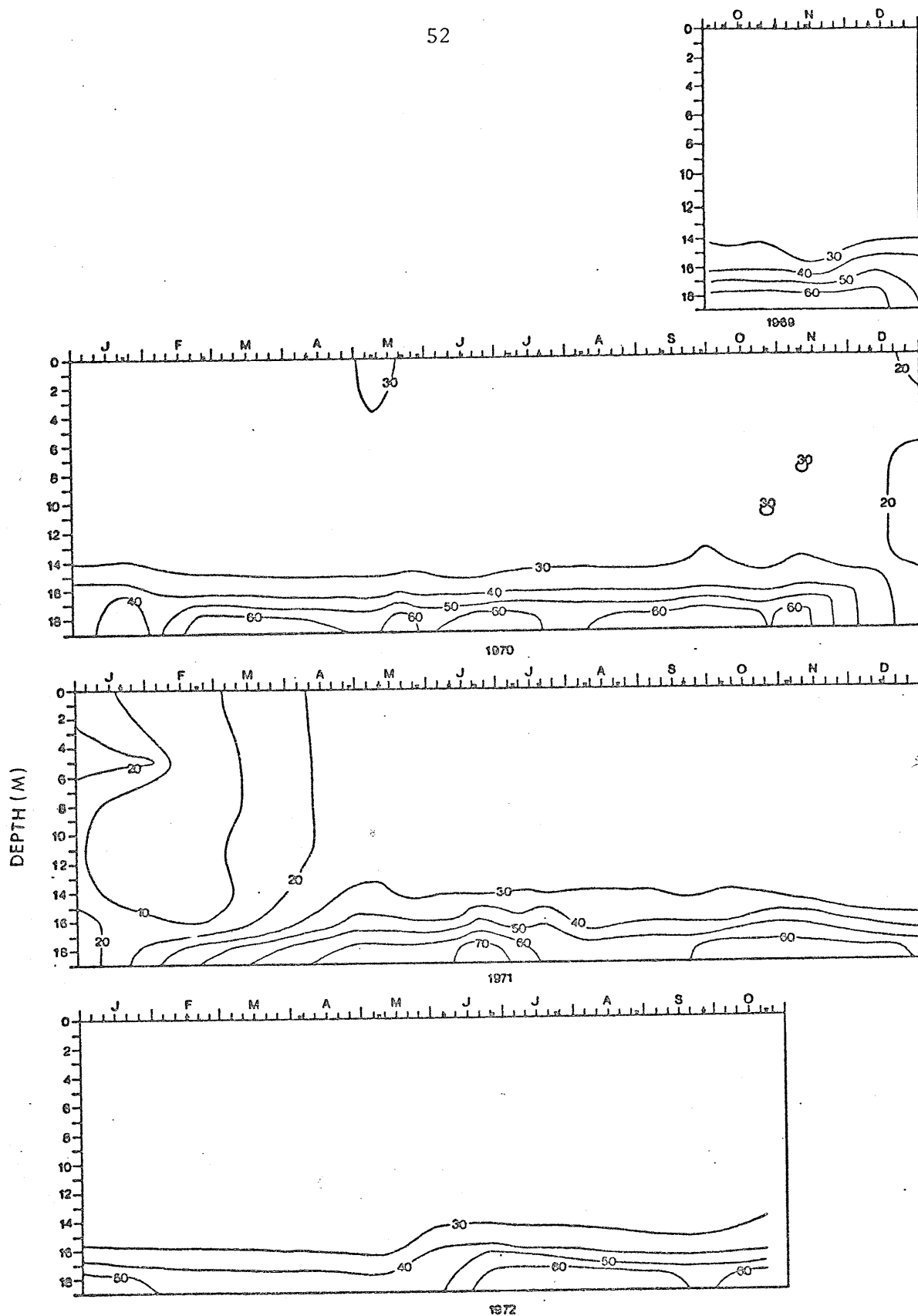


FIGURE 24. Depth-time distribution of dissolved magnesium (Mg) in Lake 120, 1969-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

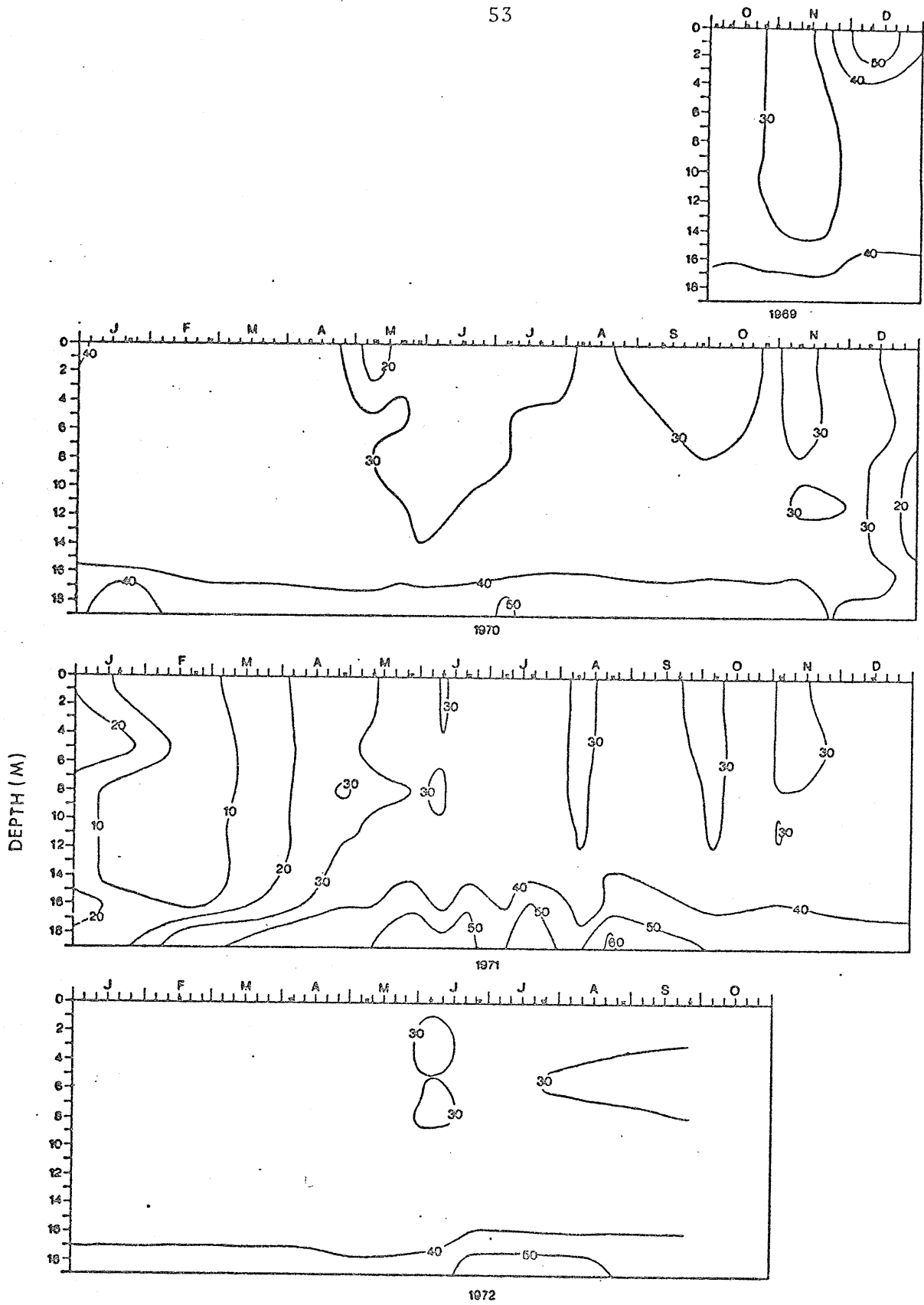


FIGURE 25. Depth-time distribution of dissolved sodium (Na) in Lake 120, 1969-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

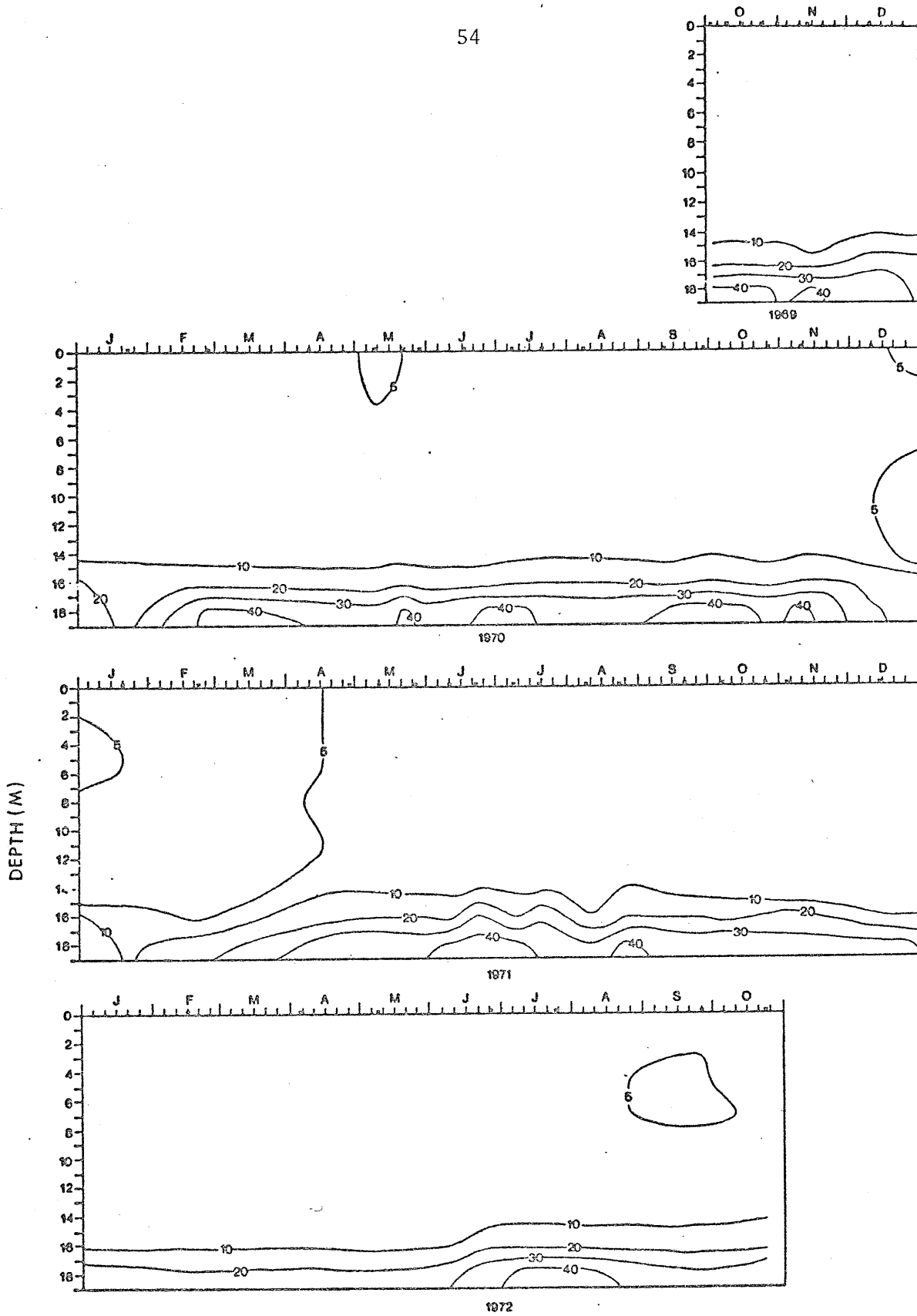


FIGURE 26. Depth-time distribution of dissolved potassium (K) in Lake 120, 1969-1972. Isoleths are $\mu\text{moles liter}^{-1}$.

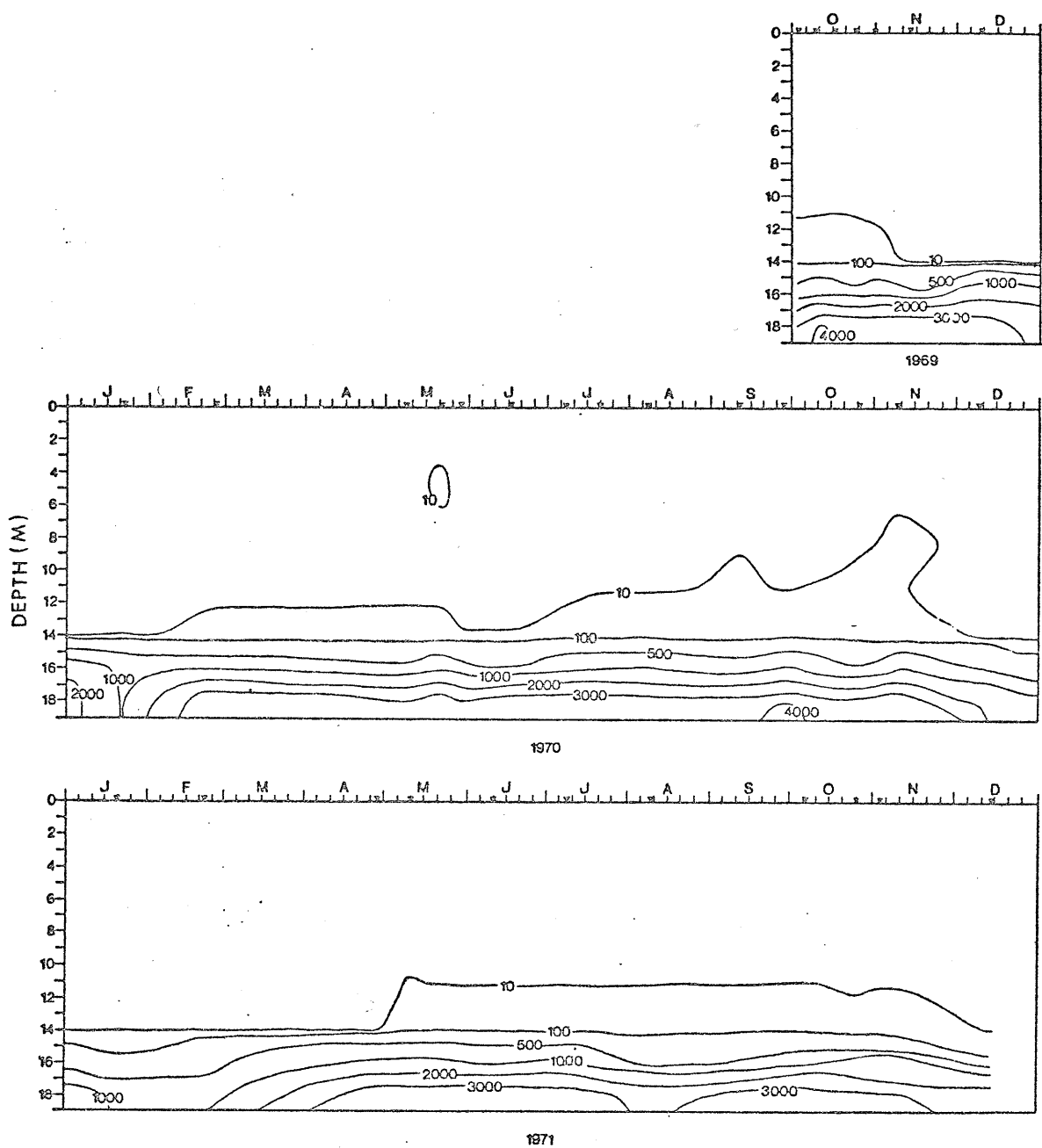


FIGURE 27. Depth-time distribution of dissolved iron (Fe) in Lake 120, 1969-1971. Isoleths are $\mu\text{moles liter}^{-1}$.

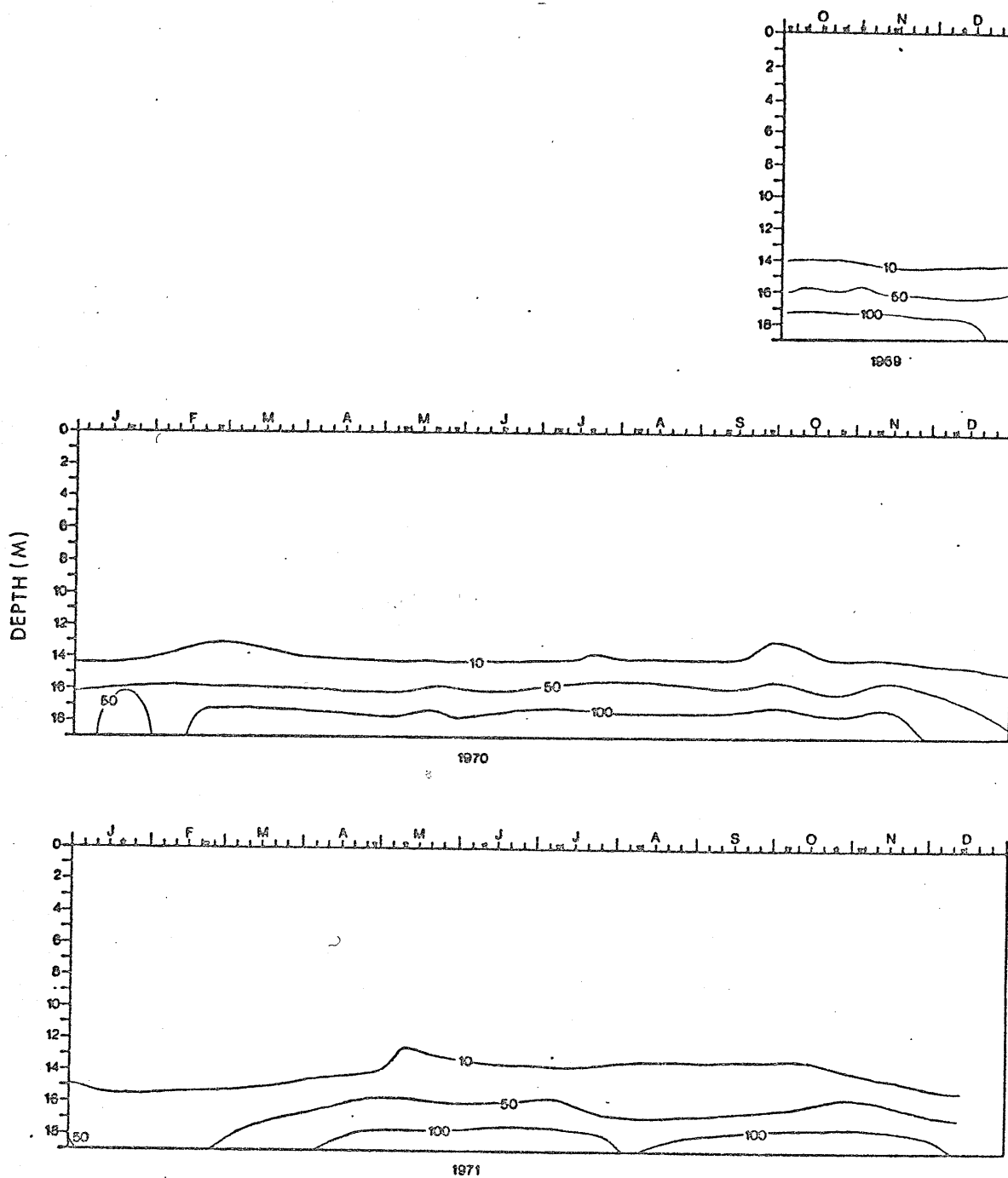


FIGURE 28. Depth-time distribution of dissolved manganese in Lake 120, 1969-1971. Isoleths are $\mu\text{moles liter}^{-1}$.

total input (total input = runoff + precipitation direct to the lake surface). From Table 5 it can be seen that computed outflows (1970-1972) are in reasonable agreement when compared with that measured directly by Water Survey of Canada during 1973. About 70% of the total input of water to the lake was by runoff from the terrestrial watershed. The remaining 30% was by precipitation direct to the lake surface. It is unlikely that in a granite basin such as that of Lake 120 that there exists subsurface inflow from adjacent watersheds. Over 80% of the water that left the lake did so *via* the outlet. Less than 20% of the total water loss was by evaporation. A minimum estimate of water renewal time ($\tau = 3.0$ to 4.8 years) was computed by dividing total annual outflow into lake volume.

Annual chemical budgets were also computed for Lake 120 by extrapolation of data from the Lake 239 watershed (Schindler *et al.*, 1976). Input of an element to Lake 120 *via* precipitation was determined by direct application, on an areal basis, of values for input *via* precipitation to the surface of Lake 239. Input *via* runoff was similarly computed by extrapolation from the Lake 239 Northwest sub-basin which best represented the characteristics of the Lake 120 watershed. Loss of an element in a year from the lake outflow was obtained by multiplying annual outflow (Table 5) by the mean concentration of the element measured in the Lake 120 outflow (annual mean concentrations were derived from the individual determinations reported in the appendix, Tables 7-23 inclusive). Lake "retention" of an element was computed by taking the difference between total input and outflow *via* the outlet.

TABLE 5. Annual water budgets for Lake 120. Precipitation, runoff and evaporation were measured on the Lake 239 watershed (Schindler *et al.*, 1976). Storage in the lake was assumed to be zero. Outflow from the lake *via* the outlet during 1970-72 was calculated by subtracting surface evaporation from total input. Residence time of water in the lake was computed by dividing lake volume by annual flow through the outlet.

		1970		1971		1972		1973		MEAN (1970-72)	
		m ³	m	m ³	m	m ³	m	m ³	m	m ³	m
	Precipitation direct to lake surface	89,900	0.967	74,700	0.803	65,200	0.701			76,600	0.824
IN	Runoff	179,300	1.923	196,800	2.116	134,600	1.447			170,200	1.830
	Total	269,200	2.895	271,500	2.919	199,800	2.148			246,800	2.654
	Evaporation from lake surface	45,700	0.491	37,900	0.407	52,300	0.562			45,300	0.487
OUT	Outflow through outlet	223,500	2.404	233,600	2.512	147,500	1.586	154,200*		201,500	2.167
	Total	269,200	2.895	271,500	2.919	199,800	2.148			246,800	2.654
	Residence time (years)	3.1		3.0		4.8		4.6		3.5	

* Measured directly by Water Survey of Canada

Annual budgets of total (suspended + dissolved) carbon (ΣC), nitrogen (ΣN) and phosphorus (ΣP) and dissolved calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe) and silicon (Si) are reported in Table 6. Usually, over 90% of the total carbon as well as the dissolved Ca, Mg, Na, K, Fe and Si entering the lake were supplied by runoff. In contrast, slightly more than half of total nitrogen and phosphorus was supplied by precipitation direct to the lake surface. "Retention" (input - output) by the lake was 50-60% for total carbon, nitrogen and phosphorus and dissolved silicon (lake "retention", especially of carbon, nitrogen and phosphorus, is elaborated upon in the discussion). The removal of dissolved Ca, Mg, Na, K and Fe *via* the outflow was about equal to their input to the lake *via* precipitation and runoff (also see discussion).

Sedimentation

A comparison of the elemental composition of the sediment collected in sediment traps from 1970-73 with surface (0-20 cm) bottom sediment analyzed by Brunskill *et al.* (1971) is presented in Table 7. It can readily be seen that the elemental compositions were very similar. Approximately 95% of the weight of the fresh unaltered sediment was water. About 50% of the weight of freeze-dried sediment was lost upon ignition which is an estimate of sediment organic matter. Net (over a period of slightly more than 3 years) sedimentation rates (grams meter⁻² year⁻¹) of freeze-dried sediment as well as rates for individual elements (moles meter⁻² year⁻¹) are also presented in Table 7. It was obvious when

TABLE 6. Estimated annual budgets of total (suspended + dissolved) carbon (ΣC), nitrogen (ΣN) and phosphorus (ΣP) and dissolved calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe) and silicon (Si) for Lake 120, 1970, 1971 and 1972.

Element	Year	INPUT TO LAKE (moles x 10 ³)			OUTFLOW VIA OUTLET		COMPUTED RETENTION ((A) - (5))	
		Precip'n ⁽¹⁾	Runoff ⁽³⁾	Total ^(A)	Total ⁽⁵⁾ (moles x 10 ³)	% of Input	Total (moles x 10 ³)	% of Input
ΣC	1971	34.16	387.5	421.7	256.5	61	165.2	39
	1972	20.60	234.1	254.7	82.01	32	172.7	68
	Mean	27.38	310.8	338.2	169.3	50	168.9	50
ΣN	1971	4.86	5.88	10.74	6.38	59	4.36	41
	1972	4.77	3.04	7.81	2.98	38	4.83	62
	Mean	4.82	4.46	9.28	4.68	50	4.60	50
ΣP	1971	0.158	0.140	0.298	0.158	53	0.140	47
	1972	0.073	0.049	0.122	0.047	39	0.075	61
	Mean	0.116	0.095	0.211	0.103	49	0.108	51
Ca	1970	1.21	6.09	7.30	9.77	134	-2.47	-34
	1971	0.768	10.39	11.15	10.58	95	0.57	5
	1972	0.651	4.51	5.16	6.20	120	-1.04	-20
	Mean	0.876	7.00	7.88	8.85	112	-0.97	-12
Mg	1970	0.344	5.34	5.68	5.54	98	0.14	2
	1971	0.387	7.09	7.48	5.79	77	1.69	23
	1972	0.337	3.33	3.67	2.99	81	0.68	19
	Mean	0.356	5.25	5.61	4.77	85	0.84	15
Na	1970	0.847	8.03	8.88	6.66	75	2.22	25
	1971	0.741	10.75	11.49	7.31	64	4.18	36
	1972	0.363	4.48	4.84	4.31	89	0.53	11
	Mean	0.650	7.75	8.40	6.09	73	2.31	27
K	1970	0.383	1.03	1.41	1.40	99	0.01	1
	1971	0.236	1.77	2.01	1.42	71	0.59	29
	1972	0.160	0.787	0.947	0.826	87	0.121	13
	Mean	0.260	1.20	1.46	1.22	84	0.24	16
Fe	1972	-	0.643	0.643	0.590	92	0.053	8
Si	1970	0.062	23.72	23.78	11.53	48	12.25	52
	1971	1.26	34.03	35.29	12.36	35	22.93	65
	1972	0.074	16.71	16.78	7.35	44	9.43	56
	Mean	0.455	24.82	25.29	10.41	41	14.88	59

TABLE 7. Comparison of Lake 120 bottom sediment (from Brunskill *et al.*, 1971) with material collected in sediment traps during 1970-73 and estimates of annual net sedimentation rates in the south basin. All concentrations are per gram of dried sediment. Sedimentation rates are for freeze dried sediment. The sedimentation rate of material collected in the traps and freeze dried was computed to be 13.3 grams per meter² lake surface per year or 91.3 grams per meter² chemocline area per year.

	BOTTOM SEDIMENT (0-20 cm)	SEDIMENT COLLECTED IN TRAPS	SEDIMENTATION RATE PER METER ² PER YEAR	
			Chemocline (A ₁₄)	Surface (A ₀)
Water content (% of fresh unaltered sediment)	94.5	95		
Ashed weight (% of dry weight)	57.9	48.0		
Chlorophyll <u>a</u> plus phaeopigments (µg)	15.6	10.8	986	144
C (mMoles)	16.83	21.04	1920	280
CO ₃ -C (mMoles)	-	0.88	80.3	11.7
N (mMoles)	1.29	1.66	152	22.1
P (mMoles)	0.07	0.07	6.39	0.93
Ca (mMoles)	0.12	0.04	3.65	0.53
Mg (mMoles)	0.07	-	-	-
Na (mMoles)	0.12	-	-	-
K (mMoles)	0.08	0.08	7.30	1.06
Fe (mMoles)	0.51	0.96	87.6	12.8
Mn (mMoles)	0.01	0.03	2.74	0.40
Si (mMoles)	7.47	6.99	638	93.0
Al (mMoles)	1.54	1.58	144	21.0
Ti (mMoles)	0.03	0.02	1.83	0.27

comparing concentrations of suspended C, N and P in the 14-19 meter stratum with concentrations in the 0-14 meter stratum (Table 3) that sediment was, in effect, being concentrated by funneling into the smaller volume of the deep anaerobic waters. As a result, if the amounts of sediment collected in the traps were applied directly to the lake surface area, great overestimates of sedimentation rates would be obtained. If the amount of P collected in the traps was applied directly to A_0 to compute a total annual sedimentation rate of P to the lake bottom this value would be 5.5 times the retention (input-output) computed in Table 6. The assumption was then made that sediment collected in the traps actually estimated the sedimentation rate at depth 14 meters and the lake surface area under which this sediment must have been derived to give a 5.5 times overestimate for P was then computed. The lake surface area so computed was $44,275 \text{ m}^2$ which is reasonably close to the $55,000 \text{ m}^2$ lake surface area of the south basin (if the northern limit of the south basin is taken to be a transect between Shore Stations 6 and 18, Figure 4). So, it seems that essentially all of the autochthonous and allochthonous sediments deposited in the south basin were funneled into the bottom waters and sediments below a depth of 14 meters; sedimentation rates per square meter lake surface area have been computed on that basis. Phosphorus was chosen in computing a lake surface sedimentation correction factor because it was the only element for which budgets were determined in total (suspended plus dissolved) and for which it could positively be

said that no gaseous flux would occur at the surface of the lake (as is not the case for carbon and nitrogen). That is, the agreement between "retention" computed in Table 6 and measured sedimentation should be better for phosphorus than for any of the other elements studied here. The average net annual sedimentation rate of freeze-dried sediment was computed to be $13.3 \text{ grams meter}^2 \text{ A}_0 \text{ year}^{-1}$ or $91.3 \text{ g m}^{-2} \text{ A}_{14} \text{ yr}^{-1}$. The net sedimentation rates of specific elements are given in Table 7.

Phytoplankton and Primary Productivity

Concentrations of chlorophyll ranged from less than 1 to $22 \mu\text{g liter}^{-1}$ (Table 25, appendix). In midwinter, concentrations of chlorophyll in the 0-14 meter stratum were less than $1 \mu\text{g liter}^{-1}$. However, in the 14-19 meter stratum, levels rarely dropped below $3 \mu\text{g liter}^{-1}$. Concentrations of chlorophyll in the bottom waters increased during the summer to $5-10 \mu\text{g liter}^{-1}$. Higher chlorophyll concentrations (up to $20 \mu\text{g liter}^{-1}$) were usually recorded in the region just below the thermocline in July and August (Figure 29).

Individual determinations of the biomass of live phytoplankton (wet weight) are presented in Table 26 of the appendix. Average biomass of phytoplankton in the 0-14 meter water column on any given sampling date is given in Figure 30 and Table 26 of the appendix. Average phytoplankton biomass was at a minimum (250 mg m^{-3}) in mid winter when depth profile maxima were located between 0 and 3 meters (Figure 31). Chrysophyta* accounted for at least 80% of the total biomass (Figure 30). From 0-11 meters depth *Botryococcus braunii* was the major contributor to algal

* In this study, Chrysophyta includes only the Xanthophyceae and Chrysophyceae. The Diatomeae have been treated separately.

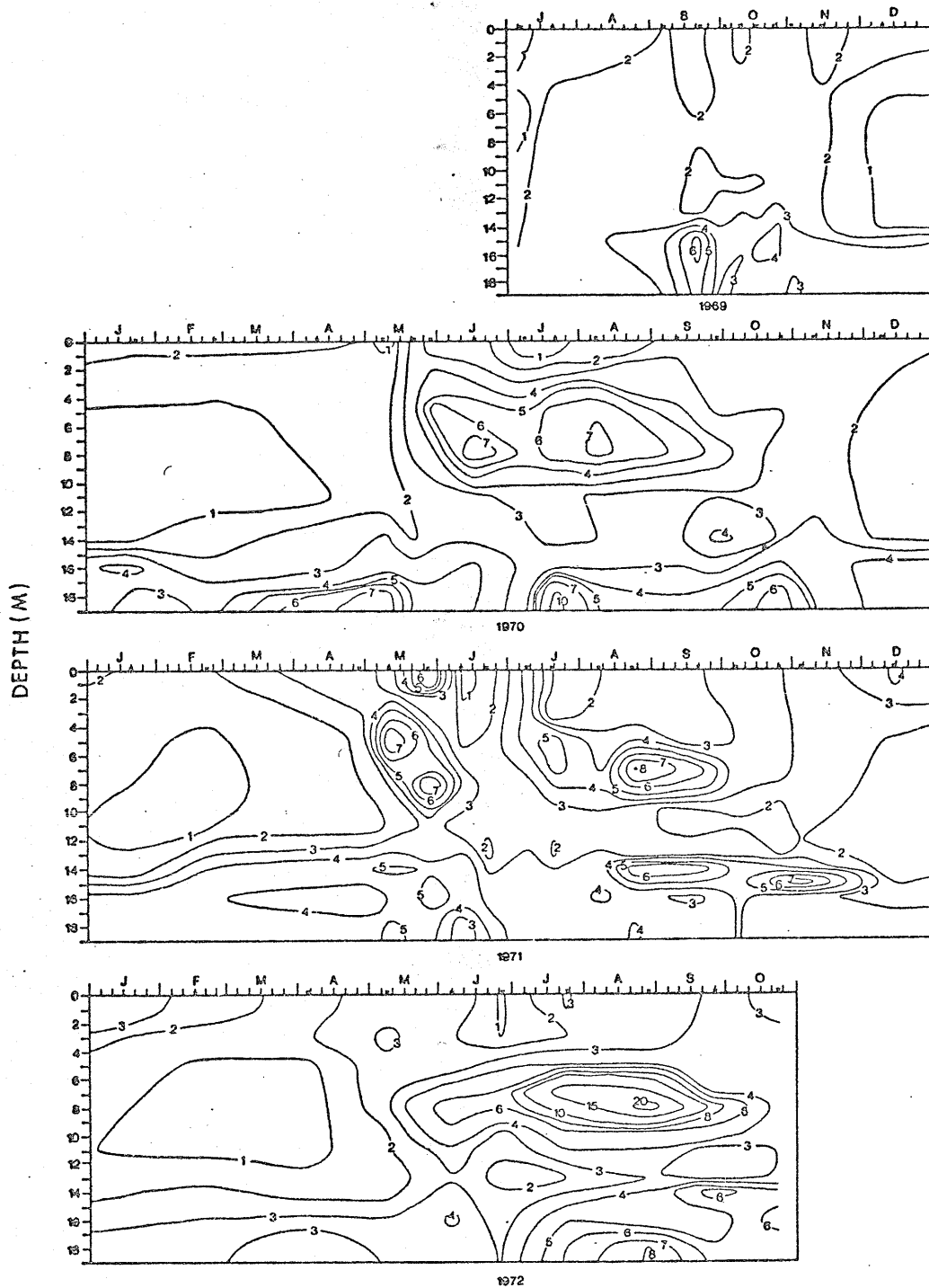


FIGURE 29. Depth-time distribution of chlorophyll *a* plus phaeophytin in Lake 120, 1969-1972. Isopleths are $\mu\text{g liter}^{-1}$.

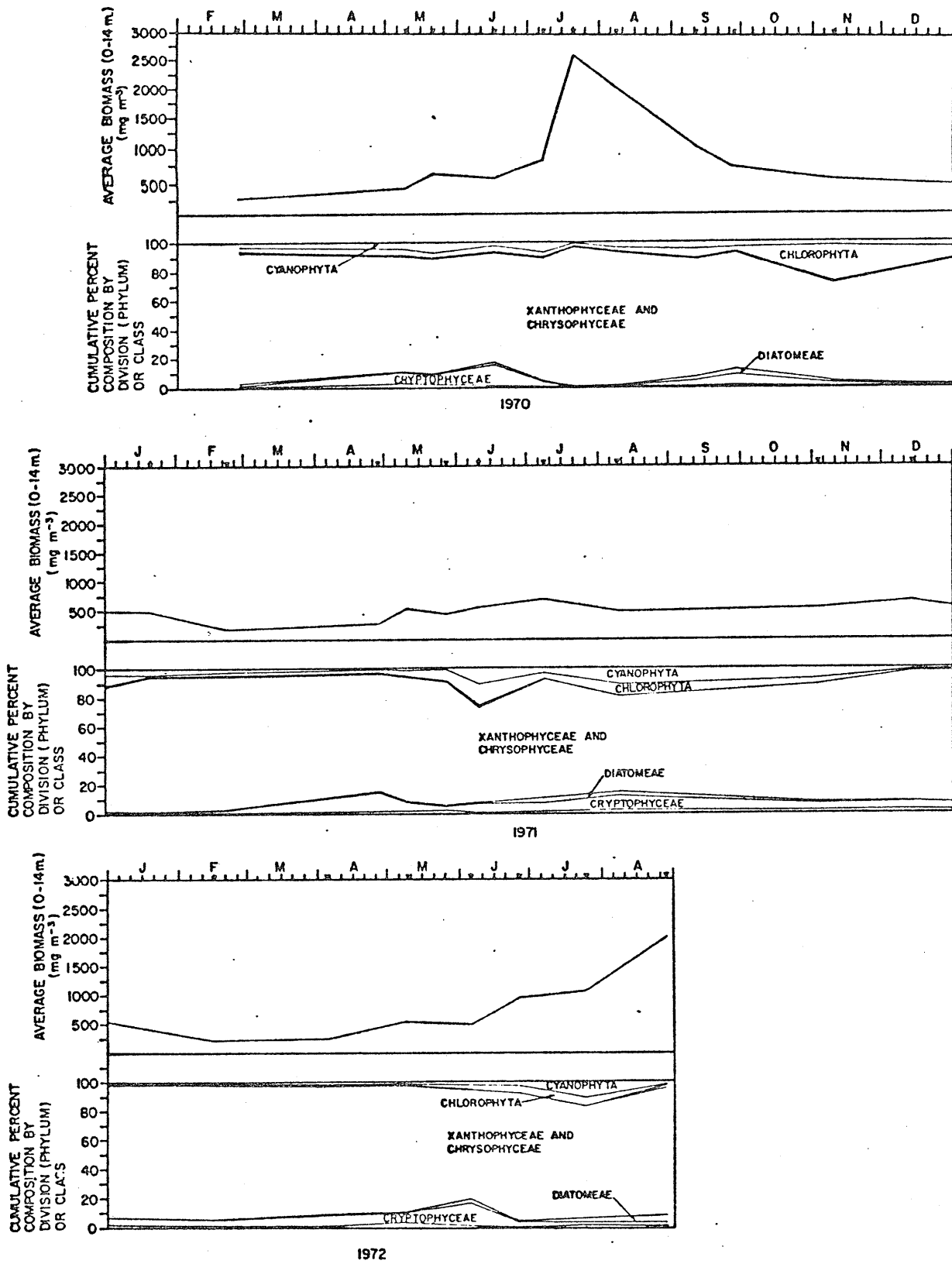


FIGURE 30. Temporal variation of the average biomass (wet weight) and the composition of the phytoplankton in Lake 120, 1970-1972.

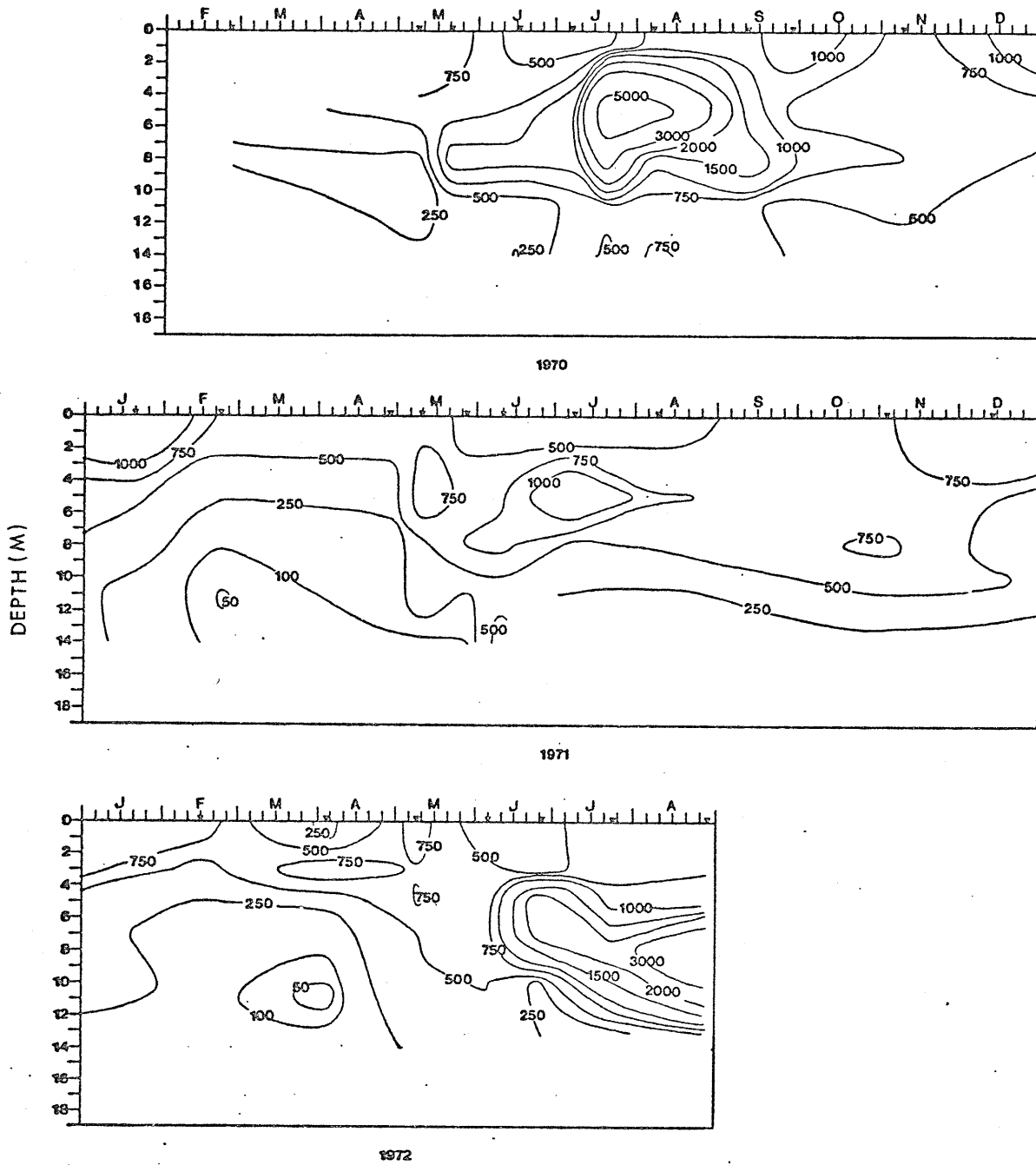


FIGURE 31. Depth-time distribution of live phytoplankton biomass in Lake 120, 1970-1972. Isopleths are mg m^{-3} (wet weight).

biomass. At 14 meters, however, the Chrysophyta were not usually dominant. Rather, small blue-greens or the Cryptophyceae (usually *Cryptomonas playturis* or *Cryptomonas obovata*) were dominant. Immediately after the ice cover melted, average biomass rose to 500-600 mg m⁻³. During this time a short-lived pulse was observed for the Cryptophyceae; that is there was a rise in the total biomass such that they constituted up to about 15% of the total algal population (Figure 30). However, in terms of the depth profile there was no change from winter in the location of dominant groups. The Cryptophyceae (and usually small blue-greens) accounted for a major portion of the biomass at 14 meters only. At depths above 14 meters *Botryococcus braunii* and, irregularly, *Dinobryon* species were the major fraction. During late May and early June the average biomass remained constant or declined slightly. Similarly, little change was observed in the composition of the population. By mid to late June, however, the standing crop began to increase rapidly, attaining a maximum level of greater than 2,000 mg m⁻³ in July or August. During this rise in biomass, a small pulse was observed for both the Cyanophyta and Chlorophyta (each of these divisions constituted up to 5% of the total biomass at this time). These pulses were due to the predominance of *Ankistrodesmus* species at a depth of 1 meter and a predominance of small blue-greens at 14 meters. It should be noted, however, that the biomass at these depths remained relatively constant or even decreased (Figure 31). The rapid increase in biomass was attributable to a buildup of standing crop just below the thermocline at depths of 5-8 meters. *Chrysophaerella* colonies were the main contributors of biomass in this

stratum; secondary contributors were *Botryococcus braunii*, *Dinobryon* species and *Mallomonas* species. It should be noted that during the summer of 1971 the peak biomass attained was just under 700 mg m^{-3} (Figure 31). Unlike the summers of 1970 and 1972, *Chryso-sphaerella* species were not abundant. Rather, only *Botryococcus braunii* was predominant in the 5-8 meter stratum. Following peak biomass in July and August, a gradual decline was observed throughout late summer and early fall. The Cyanophyta and Chlorophyta each usually constituted up to 5% of the total biomass during that time of the year and a second weak pulse in the Cryptophyceae was observed in August or September. This second pulse was due to the presence of *Cryptomonas* species at depths of 11-14 meters, although small blue-greens were also present in large numbers. The exceptional pulse in Chlorophyta (about 25% of total biomass) observed only in November of 1970 was the result of a prevalence of *Oocystis* species from 8-14 meters. As a rule, *Botryococcus braunii* was prominent throughout the water column by the time of fall turnover although small blue-greens were sometimes of secondary importance at 14 meters depth. Average biomass by this time had declined to about 500 or 600 mg m^{-3} (Figure 30). Maximum biomass in the water column was centered at 8 meters depth (Figure 31). It was not until after ice cover had been established that maximum biomass relocated immediately below the surface.

Vertical profiles of primary productivity in Lake 120 were always dichotomous (Figure 32a and 32b). Peak autotrophic net uptake of carbon by phytoplankton was usually observed at 1 or 3 meters and at 10 or 13 meters. Maximum productivity occurred during spring ($354 \text{ mg C m}^{-2} \text{ day}^{-1}$ on June 21, 1971 and $240 \text{ mg C m}^{-2} \text{ day}^{-1}$ on June 5, 1972). Minimum

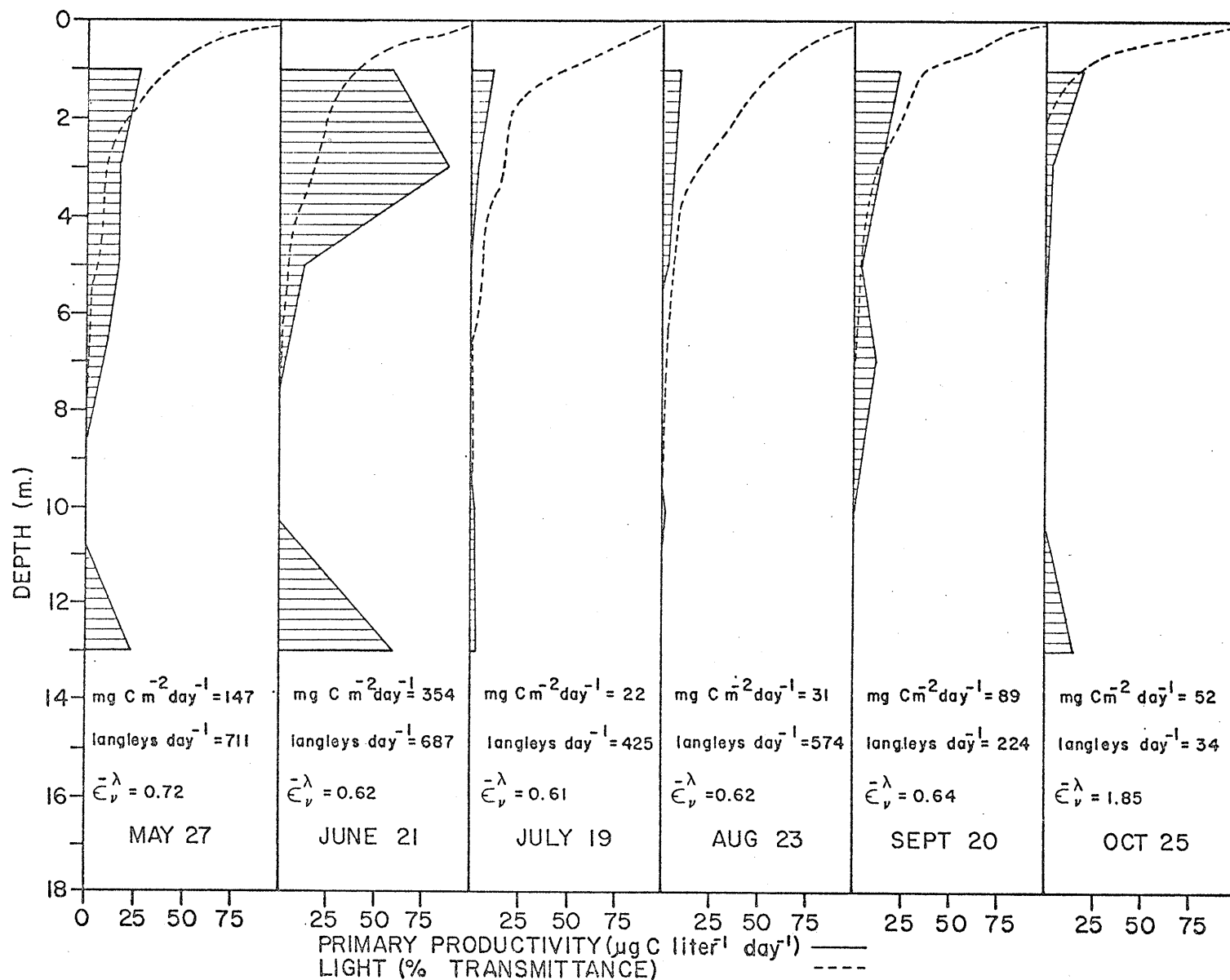


FIGURE 32a. Depth profiles of daily net productivity of phytoplankton and % transmittance of light in Lake 120 during 1971.

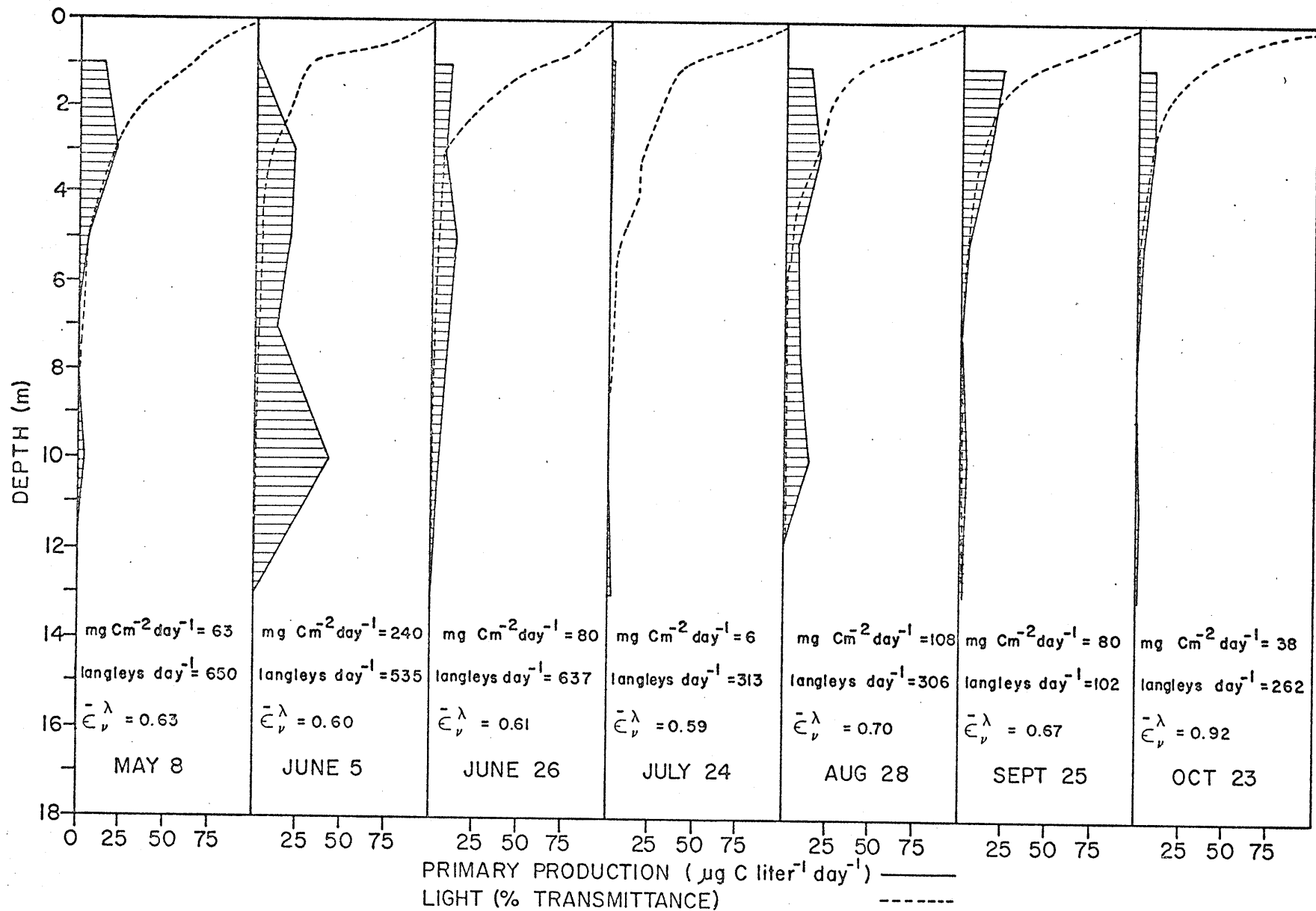


FIGURE 32b. Depth profiles of daily net productivity of phytoplankton and % transmittance of light in Lake 120 during 1972.