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LIMNOLOGY AND PHYTOPLANKTON PRODUCTION OF A ALTITUDE HIGH LAKE

P. B. RAO, A. P. SHARMA[1] AND J. S. SINGH

Department of Botany and Department of Zoology, Kumaun University, Naini Tal 263 002, India

ABSTRACT

Phytoplankton abundance and production in Lake Naini Tal are described in relation to certain limnological features. The physico-chemical parameters examined in the present study suggest the eutrophic nature of the water body. Phytoplankton abundance was higher during the warm part of the year and blue-green algae constituted a considerable part of phytoplankton wet biomass. The daily rates of gross primary production (450-1125 mg m^{-3} d^{-1}) were high and community respiration comprised about 51% of the total primary production of phytoplankton.

INTRODUCTION

Himalaya offers a wide range of lentic ecosystems which differ from each other in altitude, climate, morphometry and impact of human population. Although limnology of Kashmir lakes is well documented (Kant and Kachroo 1974, 1977, Khan and Zutshi 1980a, b, Zutshi *et al.* 1972), that of Kumaun lakes has remained largely unknown except for some recent studies (Pande and Singh 1978, Pant *et al.* 1980, Purohit and Singh 1981, Sharma and Pant 1979). The present paper on Naini Tal lake of Kumaun augments the existing information on high altitude limnology. Further, on account of unprecedented human population growth during recent decades and the resultant multifarious cultural activities in the catchment, this lake has undergone a considerable limnological evolution ; heavy loads of coliform bacteria and metallic contents have recently been reported by Pant *et al.* (1981).

THE LAKE

Lake Naini Tal is a cup shaped water body, surrounded by steep mountain slopes. A significant part of the catchment has been taken up by the township. Depth contours and bathymetric features of the lake are shown in Figure 1, and the geometeorological features of the lake are given in Table 1. There are several drains in the catchment of lake, which add the natural and man-made run-off material into the lake. Out of these only two are perennial.

The elevational gradient has a significant impact on the climate of the area, wish occasional snow fall and hail-storms occurring during winter. The mean minimum temperature in 1979 varied from 3.7°C in February to 17.2°C in June and the mean maximum from 12.2°C in February to 28.2°C in May (Fig. 2). The monthly rainfall varied from 24 mm (April) to 809 mm (August), with the annual at 2420 mm. On the basis of the weather elements, the year is broadly divisible into three

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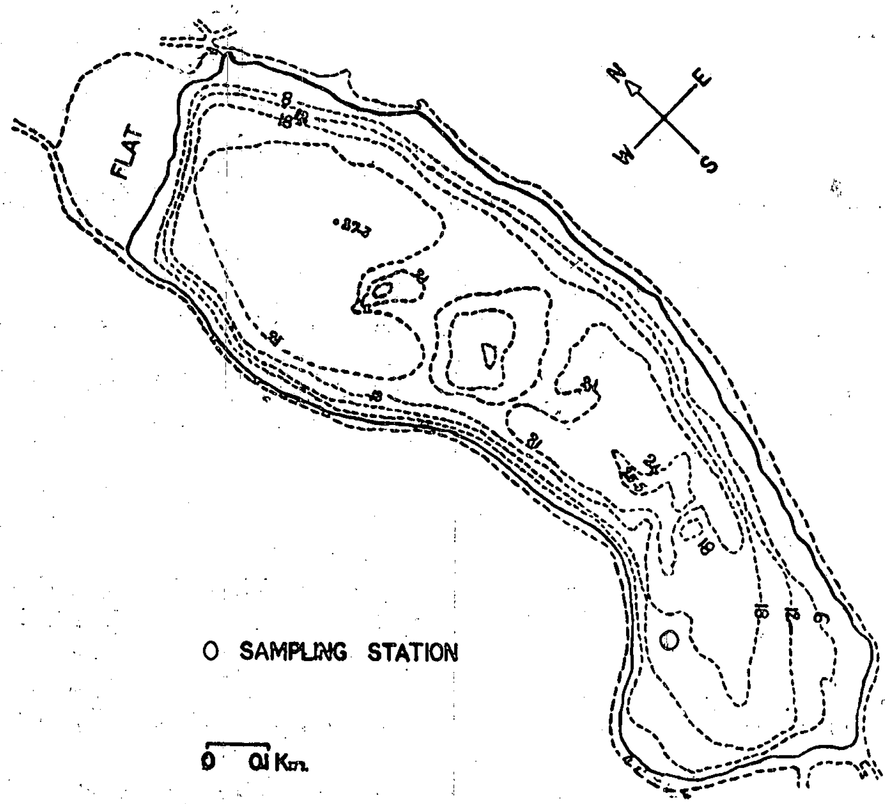

FIG. 1. Bathymetric map of the Lake Naini Tal showing sampling station. Depth contours are in meters.

TABLE 1. *Geometeorological features of Naini Tal Lake*

Latitude	29°24′ N
Longitude	79°28′ E
Altitude	1937 m
Catchment area	3.96 km²
Maximum length	1.372 km
Maximum width	0.457 km
Maximum depth	27.3 m
Surface area	0.48 km²
Length of the shoreline	3.492 km
Minimum-Maximum air temperature	5°C and 30°C
Annual precipitation	2420 mm
Approximate population of the township	40 000

seasons, viz., summer (April to June), monsoon (July to September), and winter (November to February). The months of March and October are transition months between winter and summer and between rainy and winter seasons, respectively.

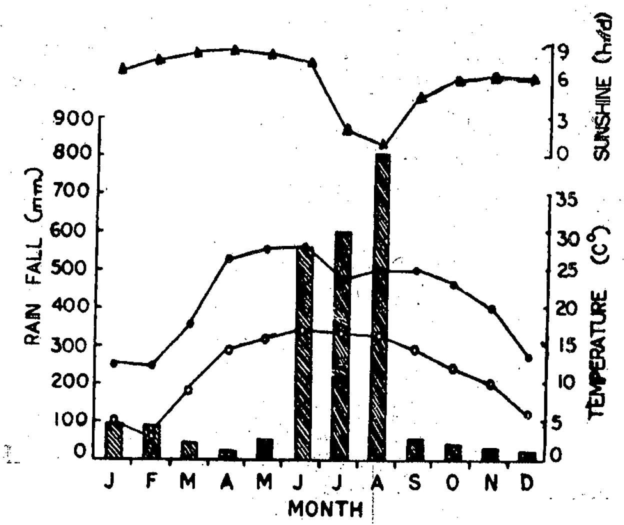

FIG. 2. Climatic conditions of the area for the year 1979. Bars=Rainfall, O—mean minimum temperature, ●—mean maximum temperature, ▲—average sunshine.

METHODS

Samples were collected from surface and 5 m deep waters, during July to December 1979, at a fixed sampling station (Fig. 1). The surface water was directly taken into polyethylene bottles, whereas a Nansen's water sampler was used to get the water from 5 m depth.

Water temperature was measured with the help of a standard mercury thermometer and water transparency by using a standard Secchi-disc. Oxygen was determined by the unmodified Winkler's method and pH with the help of a Phillips pH meter. The alkalinity (indicators phenolphthalein and methyl orange) and free CO_2 were determined following standard methods of APHA (1971).

For estimating the abundance of phytoplankters, 100 litres of lake water from each level (surface and 5 m) were filtered through a bolting silk cloth (0.064 mm aperture) net of 0.28 m diameter. The census of phytoplankton population was done by Lackey and Drop's method as described in Vollenweider (1969).

Cell volume of each species was also computed by measuring average dimensions and simulating to various geometric shapes (Vollenweider 1969). The cell volume was converted to biomass (wet weight) assuming the specific gravity of phytoplankton as 1.0 (Nauwerck 1963).

To determine the dry weight of the plankton, 100 litre aliquots of lake water were filtered through the plankton net. The material was refiltered through a preweighted Whatman no. 44 filter paper ; the filter paper was dried in an oven at 80°C till constant weight and reweighed. The difference between these two weights, represented dry biomass of plankton of lake water.

Primary productivity was estimated by 'light and dark bottle' technique (Garder and Graan 1927).

The determination of chlorophyll pigment was done by filtering known volumes (one l) of water through Whatman no. 14 filter paper ; the extraction done in 90% acetone and optical density of the solution was read at 630, 645 and 663 nm in a spectrophotometer. The amounts of chlorophyll *a*, *b* and *c* were calculated by the UNESCO and SCOR equations (Anonymous 1975).

RESULTS

Physico-chemical Environment

Surface water temperature fluctuated between 8 to 23°C, with highest and lowest values occurring during July and December, respectively. Secchi-transparency varied from 80 to 156 cm ; the highest water transparency was found in winter and the lowest during monsoon.

The dissolved oxygen ranged from 3.2 to 16.8 mg l^{-1} in the surface waters. Strikingly lower values were recorded for 5 m deep waters. The maximum differences were noted in July-August (6.4-8.4 mg l^{-1}) (Table 2).

TABLE 2. *Physico-chemical features of the lake water*

Sampling Date	Temperature surface (°C)	Secchi transparency (cm)	pH		Dissolved Oxygen (mg l^{-1})		Free CO_2 (mg l^{-1})		Alkalinity (mg l^{-1})			
									Phenolphthalein		Methyl Orange	
			Surface	5 m	Surface	5m	Surface	5m	Surface	5m	Surface	5m
15 July 79	22.0	98.5	9.3	9.0	16.8	8.0	0	0.5	16	0	136	180
15 Aug 79	21.0	80.0	8.9	8.2	15.5	8.9	0.2	0.8	13	0	130	128
27 Sept 79	20.0	81.0	8.8	7.8	10.8	12.0	0	5.0	15	12	144	150
14 Oct 79	18.5	101.0	7.2	8.6	9.6	9.2	12.0	26.0	12	0	165	173
28 Oct 79	17.0	108.0	8.6	7.6	9.2	8.4	8.0	31.0	20	16	155	185
14 Nov 79	14.0	104.5	8.8	8.6	11.6	10.4	18.0	22.0	0	0	190	180
28 Nov 79	15.0	141.0	8.6	8.8	10.4	10.0	17.0	18.0	0	0	195	186
14 Dec 79	8.0	151.0	8.6	8.8	5.6	4.4	36.0	95.0	0	0	200	210
28 Dec 79	11.0	154.0	8.6	8.6	3.2	3.0	..	..	0	0	218	227

The pH values also showed seasonal variations; higher values occurred during warm and the lower during winter months. The range of variation was from 7.2 to 9.3 and from 7.6 to 9.0, for surface and 5m deep waters, respectively. The difference in pH between surface and 5m waters in July was slight (0.3); this increased in August (0.7) and attained maximum values in September and the end of October (1.0).

The lake water was characterised by high alkalinity, which ranged from 130 to 219 mg l^{-1} in surface and 128 to 277 mg l^{-1} in deep waters with an expected seasonal trend : it was lower in summer months, increased through autumn and reached a maximum during winter months. The highest differences between surface and deep waters were obtained during July (44 mg l^{-1}). Bicarbonates were the chief constituent of the alkalinity. The seasonal trend in fluctuation of free CO_2 also corresponded with alkalinity. However, it was undetectable during summer at both the water strata. It suddenly increased in the autumn and attained high values in December. The values in deep waters were always higher than the surface waters.

Abundance of Phytoplankton Species

The variation in the density of certain important phytoplankters viz., *Chlamydomonas* sp., *Closterium acerosum*, *Eudorina elegans*, *Cosmarium* sp., *Zygnema* sp. and *Microcystis* sp. in time and space is shown in Figure 3. All the species of diatoms and the remainder

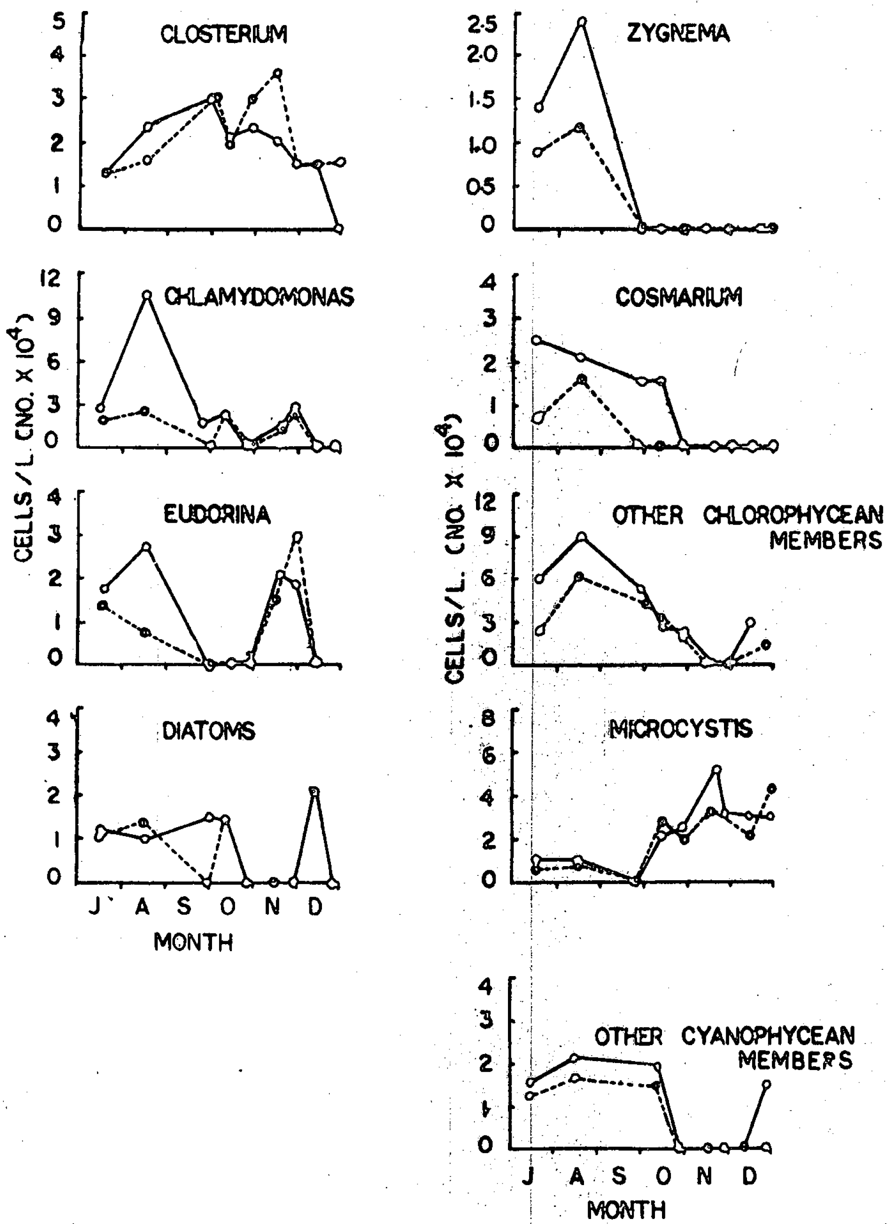

Fig. 3. Temporal variation in phytoplankton density. Solid circles connected by solid line represent surface waters and open circles connected by dotted line represent 5 m deep waters.

species of green and blue-green algae are represented as 'diatoms', other 'chlorophyceae' and 'cyanophyceae', respectively. Among the green algae, *Closterium acerosum*, and *Chlamydomonas* sp. were numerically the most important species. *Closterium acerosum* occurred from September to November and peak abundance of *Chlamydomonas* sp., was recorded in August. *Microcystis* sp. peaked during mid-November (52480 col. l^{-1}).

Total Density and Wet Biomass of Phytoplankton

Phytoplankton density exhibited only one peak during August in both the waters. Phytoplankton density varied from 8.0×10^4 to 32.6×10^4 cells l^{-1} in surface and from 6.0×10^4 to 18.0×10^4 cells l^{-1} at 5 m depth (Fig. 4a). Although, the pattern of fluctuation was similar for both the water levels, phytoplankton were more abundant in

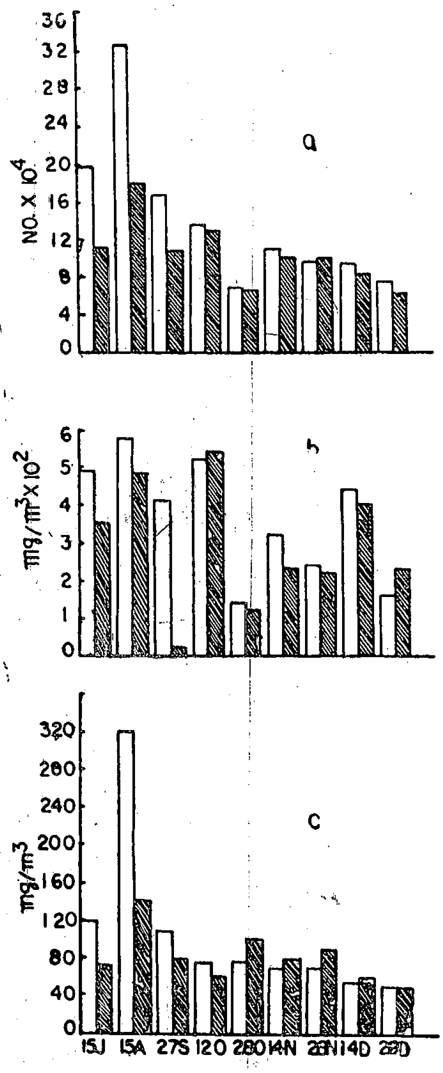

FIG. 4. Temporal variation in total abundance of phytoplankton. (*a*) density, (*b*) wet biomass, (*c*) dry biomass. Open bars represent surface waters and hatched bars represent 5 m deep water.

the surface waters ; the vertical differences were highest during summer and rainy seasons and became lower thereafter. The most marked vertical gradient in phytoplankton density existed in August (14×10^4 cells l^{-1}).

The calculated volumes of the routinely studied species of phytoplankton are given in Table 3. The biomass ranged from 2.8 to 5.8×10^2 and 0.2 to 4.8×10^2 mg m^{-3} in surface and 5 m deep waters, respectively (Fig. 4b). In contrast to density, phytoplankton biomass had two maxima, one during August and the other in October for both the water levels. The average values for the entire study period amounted to 3.95×10^2 mg m^{-3} for surface and 2.8×10^2 mg m^{-3} for the 5 m deep waters.

TABLE 3. *Calculated cell volumes of phytoplankton species*

Taxa	Volumes (μm^3)
Eudorina elegans (per colony)	314.0
Chlamydomonas sp. (per cell)	2048.0
Closterium acerosum (per cell)	560.0
Cosmarium sp. (per cell)	275.4
Microcystis sp. (per colony)	5062.0
Average for diatoms (per cell)	13220.0

Dry weight of the Plankton

The dry biomass of the plankton fluctuated from 50 to 320 mg m^{-3} at the surface and from 55 to 140 mg m^{-3} at the 5 m depth (Fig. 4c). The maximum values occurred during August, coinciding with the maximum phytoplankton density. The dry weight of plankton in deeper layers was considerably lower during August (180 mg m^{-3}). However, September onwards, it became slightly higher at the 5 m depth.

Group Composition of Phytoplankton

On the basis of density (Table 4), Chlorophyceae was the dominant contributor, throughout the study period (40 to 90% and 25 to 77% ; surface and 5 m deep waters, respectively), with the highest values occurring during July and August. Blue-green algae built high proportion of total phytoplankton crop only during October-December (10 to 75%), whereas diatoms were only abundant during monsoon (3.2—30.7%), with slight differences at the two water strata. The mean percent contributions of various groups were : Chlorophyceae, 63.0 ; Cyanophyceae, 27.0 and Bacillariophyceae, 10.0. The apportionment between individual algal groups in terms of biomass was strikingly different (Table 5) as compared to that of density. In the surface stratum, the highest proportion was made up by Cyanophyceae (38.5%), followed by Chlorophyceae (37.4%) and Bacillariophyceae (24.2%). However, at the 5 m depth, the green algae were more dominant (42.6%), followed by blue-greens (38.4%) and diatoms (24.0%).

Primary Productivity of the Plankton

The amount of organic carbon fixed by phytoplankton was assessed only in the surface water (Table 6). The highest gross primary production (GPP) was obtained

TABLE 4. *Group composition(%) of phytoplankton on the basis of density*

Month/date	Surface			5m deep		
	Chloro-phyceae	Cyano-phyceae	Bacillario-phyceae	Chloro-phyceae	Cyano-phyceae	Bacillario-phyceae
July 15.7.79	80.9	13.4	5.7	73.2	9.5	17.3
August 15.8.79	90.3	6.5	3.2	77.5	8.0	14.5
September 27.9.79	68.2	3.1	22.7	69.2	0	30.8
October 11.10.79	61.4	10.4	28.2	..	..	..
14.10.79	..	..	..	55.0	33.4	11.6
28.10.79	63.4	36.6	0	70.9	29.1	0
November 14.11.79	52.2	47.8	0	66.7	33.3	0
28.11.79	67.1	32.9	0	..	..	..
29.11.79	..	..	..	69.9	30.1	0
December 14.12.79	44.9	32.5	22.6	..	..	..
17.12.79	..	..	..	50.6	24.9	24.5
25.12.79	40.0	60.0	0	..	..	..
28.12.79	..	..	..	25.0	75.0	0

during September (875.0 mg C m^{-3} d^{-1}), whereas the highest net primary production (NPP) occurred during November (406.3 mg C m^{-3} d^{1}). The maximum community respiration (500.0 mg C m^{-3} d^{-1}) coincided with the peak value of GPP in September. December was the period of minimal activity of the phytoplankton with the values of GPP, NPP and respiration being 450.0, 268.8 and 187.5 mg C m^{-3} d^{-1}, respectively.

DISCUSSION

The remarkably lower values of water transparency (80 to 156 cm), attributable to rich phytoplankton crop and higher budgets of suspended and particulate matters, imply that the amount of organic matter should be sufficient enough in the hypolimnion (washed down from epilimnion), to create anoxic conditions in this zone. The steep decline in the oxygen levels in 5 m deep waters in the present data provides evidence to this hypothesis. Dissolved oxygen content revealed a marked seasonality with the oxygen levels approaching minimum values during winter (December 3.2 mg l^{-1} ; 32% oxygen saturation). These low values are perhaps caused by the cumulative inter-action of low insolation, low temperature, overturn of the lake water and minimal photo-synthetic activity. At this time free CO_2 attained a marked peak.

TABLE 5. *Group composition(%) of phytoplankton on the basis of wet biomass*

Month/date	Surface			5m deep		
	Chloro-phyceae	Cyano-phyceae	Bacillario-phyceae	Chloro-phyceae	Cyano-phyceae	Bacillario-phyceae
July						
15.7.79	56.58	10.62	32.80	42.60	38.40	19.00
August						
15.8.79	66.76	9.24	24.00	41.92	18.80	39.28
September						
27.9.79	50.80	0	49.20	100.00	0	0
October						
11.10.79	39.19	22.03	38.78	..	..	..
14.10.79	..	..	..	36.68	26.39	37.03
28.10.79	9.16	90.84	0	14.23	85.77	0
November						
14.11.79	15.64	84.36	0	24.47	75.53	0
28.11.79	32.41	67.59	0	..	..	..
29.11.79	..	..	..	31.13	68.87	0
December						
14.12.79	1.92	63.30	34.78	..	..	..
17.12.79	..	..	..	2.04	70.96	27.00
25.12.79	5.24	94.76	0	..	..	..
28.12.79	..	..	..	0	100.00	0

TABLE 6. *Primary production and respiration (mg C m^{-3} d^{-1}) due to phytoplankton in surface waters*

Month/date	Net production	Gross production	Respiration
July			
15.7.79	390.0	625.0	..
August			
15.8.79	440.0	650.0	..
September			
27.9.79	375.0	875.0	500.0
30.9.79	375.0	875.0	500.0
October			
12.10.79	500.0	750.0	250.0
18.10.79	375.0	875.0	500.0
28.10.79	312.5	687.5	375.0
November			
8.11.79	375.0	875.0	500.0
17.11.79	375.0	750.0	375.0
19.11.79	500.0	1125.0	625.0
29.11.79	375.0	625.0	250.0
December			
5.12.79	375.0	625.0	250.0
13.12.79	437.5	740.0	312.5
19.12.79	187.5	312.5	125.0
24.12.79	75.0	125.0	62.5

Dissolved oxygen had significant correlations with transparency, temperature, free CO_2 and gross primary production (GPP) in the surface waters, according to the following linear regressions : Transparency ; $Y=165.95-52.73X$; $(r=-0.77$; $p<0.01)$, where Y=transparency (cm) and X=dissolved oxygen (mg l^{-1}), Temperature ; $Y=1.29+0.71\ X$; $(r=0.70$; $p<0.01)$, where Y=dissolved oxygen (mg l^{-1}) and X=temperature (°C), Free CO_2 ; $Y=-65.83-5.99\ X$; $(r=-0.80$; $P<0.01)$, where Y=free CO_2 (mg l^{-1}) and X=dissolved oxygen (mg l^{-1}). GPP ; $Y=237.1+36.3\ X$; $(r=0.66$; $p<0.01)$. where Y=GPP (mg C $m^{-3}d^{-1}$) and X=dissolved oxygen (mg l^{-1}). Bicarbonates were the predominant constituent of alkalinity in the lake. According to Freiser and Fernando (1966), bicarbonate system prevails in water bodies having high alkalinity ; waters are highly buffered and generally remain alkaline. Further, the marked variation in the pH and alkalinity in time and depth are perhaps tied with the biological activity. On the basis of alkalinity, the lake water can be categorized as 'hard water type' after Moyle (1946). The above physico-chemical characteristics strongly suggest the remarkably high trophic status of the lake and indicate that community metabolism should be sufficiently intense and steep short-term variations should occur in the lake.

Phytoplankton density (cell numbers) had only a single maximum during August, whereas biomass, in addition to this peak, had one additional peak. This discrepancy was caused by peak growth of colonial blue-green alga, *Microcystis* sp. which has a higher cell volume and hence builds a larger biomass. Since a colony was counted as a single unit, its contribution in terms of density was less revealing. Similar pattern has been observed in Lake Lanao (Lewis 1978). The peak dry weight of the plankton (including the suspended material and the zooplankton) coincided with the August peak of the phytoplankton density and wet biomass. However, it did not peak during the secondary pulse of wet biomass in October. In spite of these discrepancies, phytoplankton density was significantly correlated with wet biomass and dry weight, according to the following regression equations : Fresh weight ; $Y_1=57.68+21.18X$; $(r=0.77$; $P<0.01)$; Dry weight : $Y_2=-2.21+0.09\ X$; $(r=0.9$; $p<0.01)$; where Y_1=fresh weight (mg m^{-3}); Y_2=dry weight (mg m^{-3}) and X=density (cells l^{-1}). Similarly, fresh weight had also a significant relationship with dry weight of the plankton. The regression equation was : $Y=22.18+0.32\ X$; $(r=0.64$; $p<0.01)$; where Y=fresh weight (mg m^{-3}) and X=dry weight (mg m^{-3}) of the plankton. As one would expect, the bloom of blue-green algae in Naini Tal lake was natural due to rich stock of organic matter, bicarbonates, NO_3—N and PO_4—P. Water systems having high community metabolism are usually dominated by volume specific—standing crops of blue-green algae (Lewis and Weibezahn 1976). The wide variations of physico-chemical and biological parameters in space and time both indicate the intense metabolism in Lake Naini Tal. Consequently diatom population was remarkably underdeveloped, which prefer to grow in soft waters (Patrick 1948).

Pant *et al.* (1981) reported that amounts of N and P in Naini Tal lake are far higher than what is required to trigger the production of algal blooms. Notwithstanding the fact that algal blooms are a conspicuous feature of the Naini Tal lake (Pande and Singh 1978), the phytoplankton biomass obtained in the present study (395 mg m^{-3}) for surface waters is remarkably low. One would instantly conclude that the majority of the phytoplankton population should be smaller in size than the pores (0.064 mm) of the net which was used to obtain the plankton samples and in this way, most of the phytoplankton crop might have been eliminated. Further, most of the phytoplankton in the algal community of the lake are smaller in size than 64 μm and hence, their population was poorly represented. Pechlaner (1971) found that 73% of the total population was eliminated through a net in a mountain lake. In view of this, an additional sample from surface water was simultaneously taken on 14 December. The sample was centrifuged and census of the population was done in a haemocytometer (see Table 7). According to this method, the total biomass amounted to 10.0 g m^{-3} as compared to that obtained through the net (0.4 g m^{-3}) on the same date. The former value is 25 times higher than the latter. If the above factor is applied, the mean phytoplankton biomass for the study period would be $395 \times 25 = 9875$ mg m^{-3}. This value falls in the range set for eutrophic/productive waters ($\geq$ 8 g m^{-3}), Vollenweider 1968). The diversity (Shannon—Weiner information function) of this sample came to 1.68 which is too low as is the case in fertile waters (Wetzel 1975). The above data are also substantiated by Chlorophyll *a* (determined during October and November; Table 8), which is considered as an index of phytoplankton abundance, according to Vollenweider (1968). Chlorophyll *a* content (11.3 to 28.4 mg m^{-3}) is higher than many of the productive lakes, e.g. Lake Huron (0.9 to 14.5 mg m^{-3}), as reported by Schelske *et al.* (1974). The amount of organic production by autototrophs too is very high as described later. Obviously, the true picture of the phytoplankton dynamics is exposed in this way and the use of a net for getting plankton samples could be highly questionable.

TABLE 7. *Density and biomass of phytoplankton, as obtained by centrifuging the sample on 14 December 1979*

Taxon	Density (cells g^{-1})	Biomass (mg m^{-3})
Microcystis sp.	1 96 250*	2 940.0
Closterium acerosum	4 02 500	644.0
Eudorina elegans	31 250*	136.3
Chlamydomonas sp.	20 69 500	4 966.8
Oocystis irregularis	32 000*	57.6
Coelastrum microporum	63 250	134.4
Other species (< 10 μ)	2 01 250	100.6
Amphora ovalis	62 250	124.5
Navicula sublinearis	1 69 500	33.9
Cymbella lanceolata	51 000	816.0
Pinnularia sp.	12 500	46.3
Total	32 91 250	10 000.4

*The values are colonies^{-1}.

TABLE 8. *Chlorophyll content (mg m^{-3}) of surface waters*

Month	Chlorophyll *a*	Chlorophyll *b*	Chlorophyll *c*
October	11.298	17.439	38.475
November	28.35	18.75	17.4

The influence of environmental factors on primary production is well documented (Lewis 1974). In this study, phytoplankton production had a significant relationship with water transparency, according to the following regressions :

Y=1135.20—4.31 X ; (r=0.58 ; p<0.01) where Y=gross primary production (mg C $m^{-3}d^{-1}$) and X=Secchi transparency (cm).

Goldman and Wetzel (1963) and Efford (1967) also found a close relationship between light penetration and productivity. However, productivity was not significantly related to phytoplankton abundance. This could be accounted or by the activites of nannoplankton which significantly contribute to total primary productivity (Gliwice 1967, Malone 1971). Gilmartin (1964) observed that in a British Columbia fjord nannoplankters accounted for ≥92% of the primary production. Thus the high productivity recorded in the present case at times when phytoplankton abundance was low may be due to nannoplankton as indicated by centrifuge biomass data for 14 December discussed earlier. The nannoplankton in this sample constituted about 84% of the total phytoplankton biomass.

Sufficiently high values of primary production (GPP, 450-1125 mg C m^{-3} d^{-1}), truly reflect the trophic status of Naini Tal lake. The values of community respiration were also higher suggesting a marked consumption of oxygen by bacteria and other heterotrophs (zooplankton). The respiration was 51% of the total gross primary production. Ganf (1972, 1974) concluded that values of community respiration ≥40% are a characteristic of eutrophic waters.

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