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First investigation of ultraoligotrophic alpine Lake Puma Yumco in the pre-Himalayas, China

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Abstract Lake Puma Yumco is a typical alpine lake (altitude 5030 m) located in the pre-Himalayas of Tibet, China, and this study was the first limnological investigation ever conducted on it. Lake Puma Yumco (28°34′N, 90°24′E) has the following morphometric properties: maximum length 31 km, maximum width 14 km, mean width 9 km, shoreline 90 km, surface area 280 km^2, and shoreline development 1.5. Transparency was approximately 10 m, even in the thawing season. The extinction coefficient of the lake water was calculated as 0.15 m^{-1}. Annual maximum transparency was estimated from the depth of the *Chara* zone to be 30 m. Dissolved oxygen was 7 mg O_2 l^{-1} and showed saturated values, and salinity was 360 mg l^{-1}. The chemical type of the lake water was Mg-Ca-HCO_3-SO_4, and it was slightly alkaline in character. Total nitrogenous nutrients (sum of ammonia, nitrite, nitrate, and urea nitrogen), phosphate, and silicate were extremely low at 1, 0.02, and 9 μM, respectively. Dissolved organic carbon, nitrogen, and phosphorus concentrations were 160, 11, and 0.08 μM and the molar ratio was calculated as 2100 : 140 : 1. Chlorophyll *a* concentration was 0.2 mg m^{-3}. Phytoplankton and zooplankton were dominated by *Aphanocapsa* sp. and Diaptomidae. Both nitrogen and phosphorus appear to be the limiting parameters for phytoplankton growth. Organic carbon and nitrogen contents in lake sediments were low and the sediments contained a large amount of $CaCO_3$. The grain size of sediment was that of silt-sand in most cases. The present results indicate that the pre-Himalayan alpine freshwater Lake Puma Yumco is an ultraoligotrophic lake.

Key words Pre-Himalayan alpine lake · Lake morphometry · Physicochemical characteristics · Nutrients · Dissolved organic matter · Phyto- and zooplankton species · Grain size and organic matter of sediment · Lake Puma Yumco

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Introduction

The limnology of alpine lakes has been extensively studied (Anderson 1972; Blumthaler and Ambach 1990; Felip et al. 1995; McKnight et al. 1997; Sommaruga et al. 1997; Vinebrooke and Leavitt 1998; McNaught et al. 1999; Carrillo et al. 2002). There are also considerable amounts of data from lakes located on the Tibetan Plateau, China (Kato et al. 1987; Kawashima and Nishiyama 1989). However, the limnological knowledge of lake systems in extremely high altitude mountain areas is quite limited. The lake chosen for this study was a typical alpine lake (28°34′N, 90°24′E; altitude of 5030 m) formed by fault action and located in the pre-Himalayas in the southern part of the Tibetan Plateau, China. The lake lies along the upper reaches of the mighty Brahmaputra River. Lake Puma Yumco is classified as a dimictic lake. Thermal stratification is established during a short summer season and the lengthy ice-covered winter season (Zhu, personal communication). During this investigation period, the lake was about to begin a circulation phase just after the thawing season.

This is the first report of a limnological investigation in a large lake over 5000 m in altitude. In this paper, we describe the morphometric properties of the lake basin; the physical, chemical, and biological characteristics of the lake water; and the grain size and chemical properties of the lake sediment.

Materials and methods

Field investigations of the horizontal and vertical distributions of some limnological parameters were carried out in Lake Puma Yumco from April 5 to 22, 2001, during the circulation phase just after the ice-covered season but before the monsoon season (Fig. 1). Lake Puma Yumco is encircled by bare gravel, being located above the tree line. During the investigation period, the lake surface was almost frozen over; therefore, investigations were made at open water sites near the base camp. The physical, chemical, and biological parameters of the lake were observed at stations parallel to the shore line, Sta. P1 (28°35′37″N, 90°28′57″E; water depth of 24m), Sta. P2 (28°35′16″N, 90°28′55″E; 25m), Sta. P3 (28°35′13″N, 90°28′59″E; 31m), Sta. P4 (28°35′04″N, 90°28′56″E; 22m), and Sta. P5 (28°35′05″N, 90°29′10″E; 36m), and at transect stations from the shore to the offshore site, Sta. T1 (28°35′02″N, 90°28′47″E; 7m), Sta. T2 (28°35′13″N, 90°28′59″E; 31m), Sta. T3 (28°35′19″N, 90°29′12″E; 28m), Sta. T4 (28°35′28″N, 90°29′28″E; 10m), and Sta. T5 (28°35′43″N, 90°29′42″E; 4m). The parallel Sta. P3 and transect Sta. T2 are the same location.

Measurements of transparency and light penetration were made in the field with a Secchi disc and an underwater irradiance meter (Minolta, T-1M, Osaka, Japan). Turbidity was measured using a turbidimeter (Hach, 2100N, CO, USA). Water samples were collected at nine stations with a Van Dorn plastic water sampler from the surface to the bottom layer. The samples were then used for the measurement of major cation (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anion elements (Cl^-, SO_4^{2-}). The values of water temperature, pH, dissolved oxygen, and electric conductivity were taken with a multiprobe water quality monitoring system (Hydrolab, Quanta-G, CO, USA). Electric conductivity was equated to the value at 25°C. The concentrations of six major elements were determined with an ion chromatograph (Dionex, DX-120, CA, USA).

For a determination of the biogeochemical constituents and chlorophyll *a* concentrations in the lake water, the waters were immediately filtered through glass fiber filters (Whatman GF/F, Maidstone, UK) which were freed of organic matter by ignition at 420°C. Then the filters and filtrates were frozen solid until chemical analyses were carried out in the laboratory. The sample for the determination of silicate was filtered through a paper filter (Toyo No.5C, Tokyo, Japan) and stored at room temperature. Ammonia concentration was determined by the method of Sagi (1966), nitrite after Bendschneider and Robinson (1952), nitrate after Mitamura (1997), phosphate after Murphy and Riley (1962), and silicate by the method of Mullin and Riley (1955). Urea was determined by the method of Newell et al. (1967) with a slight modification. Dissolved organic carbon (DOC) was determined with an infrared total organic carbon analyzer (Shimadzu, TOC-5000A, Kyoto, Japan), dissolved organic nitrogen (DON) with a TN analyzer (Yanaco, TN-301P, Kyoto, Japan), and dissolved organic phosphorus (DOP) by the method of Menzel and Corwin (1965). Chlorophyll *a* and phaeopigments were determined with a fluorometer (Turner Designs, 10-AU, CA, USA).

Phytoplankton samples were collected from several depths at Sta. T2 with a Van Dorn plastic water sampler and deposited on a plastic mesh screen (10-µm mesh). Zooplankton, on the other hand, were collected with a NXX13 plankton net (mesh opening of 94µm) by hauling vertically twice at Sta. T2. After collection, the phyto- and zooplankton were immediately preserved by adding concentrated formaldehyde solution (approximately 0.2% solution as final concentration) and were stored in a refrigerator to await microscopic counting and identification of species.

Lake sediments for measurements of chemical components and grain size were collected from the upper sediment (sediment depth of about 5cm) at the transect stations using a standard Ekman–Birge grab sampler (225 cm^2). Organic carbon and nitrogen were determined with a CHN Corder (Yanaco, MT-5) after the sediments were freed of carbonate carbon using 1M HCl solution. Grain size distribution was measured with a laser diffraction particle size analyzer (Shimadzu, SALD-2000J).

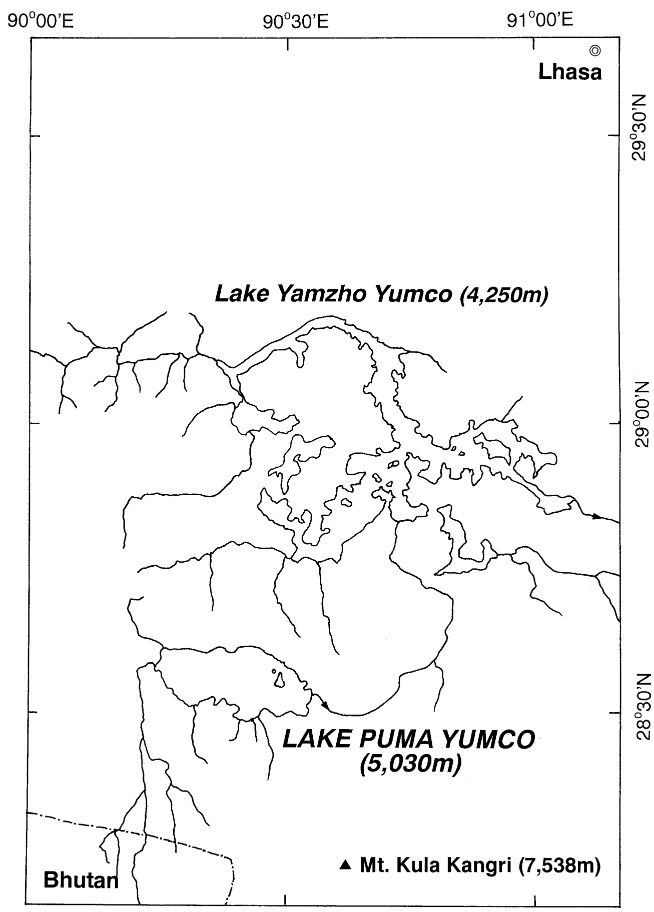

Fig. 1. Map of Lake Puma Yumco in the pre-Himalayas, China

Results and discussion

Lake morphometry

Morphometric properties of the basin, calculated from topographical maps, are shown in Table 1. The location of this lake (intersection point of maximum length and maximum width) is 28°34′N and 90°24′E. The altitude of the lake surface was 5030 m, measured using a portable GPS device (Empex FG-530, Tokyo, Japan). The maximum length of the lake surface was calculated as 31.1 km (28°37′23″N, 90°15′26″E to 28°31′20″N, E90°33′22″E). The maximum width, i.e., the maximum distance between the shores perpendicular to the maximum length line, was 14.1 km (28°37′46″N, 90°27′53″E to 28°30′47″N, 90°24′44″E), and the mean width, i.e., the value equivalent to the lake surface area divided by the maximum length, was calculated as 9.0 km. The length of the shoreline was computed as 90.3 km using a curvimeter, and the shoreline development was calculated as 1.5. The lake surface is a simple unindented oval shape. The area of the lake surface was 281 km^2 by a planimeter (Tamiya, Tokyo, Japan, Super Planix α). The catchment area of Lake Puma Yumco is 1700 km^2 and the area ratio of catchment to lake surface was calculated as 6.2. The source of the main course of river water flowing to the lake is located in the Himalayas, the Kingdom of Bhutan (28°09′N, 90°13′E; altitude 6800 m).

Physicochemical features

The physicochemical characteristics of the lake are shown in Table 2. Water temperature ranged from 3.3° to 3.7°C (3.6° ± 0.1°C average with standard deviation). The water exhibited slightly alkaline properties, showing a pH value of 8.3–8.7. Dissolved oxygen concentration was 5.3–8.6 mg O_2 l^{-1}. The lake waters were almost completely saturated with dissolved oxygen that averaged 109% from the surface to the bottom layer. Electric conductivity was 45–48 mS m^{-1}. The vertical distribution of these physicochemical parameters showed almost constant values and there were no differences among the nine stations. Transparency, as determined with a Secchi disc, was 8.5–10.5 m. Figure 2 shows the comparative light penetration of photosynthetically active radiation in the lake. The extinction coefficient of the lake water was calculated as 0.15 m^{-1}, according to Smith (1975). The turbidity of the water was 180–277 NTU, and averaged 230 NTU. The water was a clear blue color, even in the thawing season with silty particles in suspension. A large biomass of Charophyta was observed at the stations with water depths of 28 m or less. Thus, the annual maximum Secchi transparency can be estimated as 30 m from the depth of the *Chara* zone, making Lake Puma Yumco one of the clearest lakes in the world.

Table 1. Lake basin characteristics and morphometry of Lake Puma Yumco

Location	28°34′N, 90°24′E
Altitude	5030 m
Maximum length	31.1 km
Maximum width	14.1 km
Mean width	9.0 km
Shoreline	90.3 km
Area	281 km^2
Catchment area	1700 km^2
Catchment area: surface area	6.2
Shoreline development	1.5

Composition and concentration of major ionic elements

Figure 3 shows the distributions of major cation (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anion (HCO_3^-, Cl^-, SO_4^{2-}) concentrations.

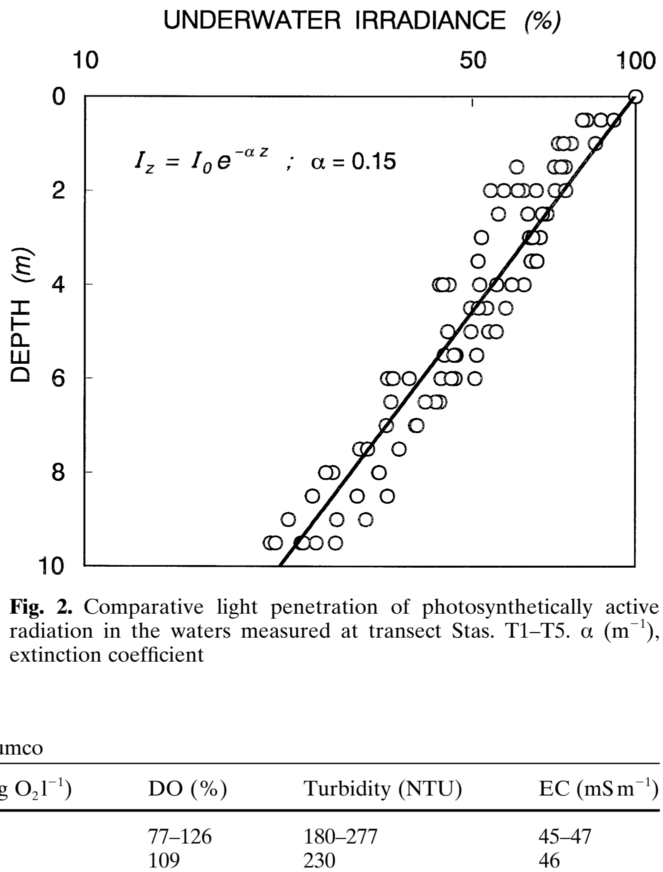

Fig. 2. Comparative light penetration of photosynthetically active radiation in the waters measured at transect Stas. T1–T5. α (m^{-1}), extinction coefficient

Table 2. Distributions of physicochemical parameters in Lake Puma Yumco

	Tr (m)	WT (°C)	pH[a]	DO (mg $O_2 l^{-1}$)	DO (%)	Turbidity (NTU)	EC (mS m^{-1})
Range	8.5–10.5	3.3–3.7	8.3–8.7	5.3–8.6	77–126	180–277	45–47
Average	9.4	3.6	8.5	7.5	109	230	46
SD	0.6	0.1	0.1	0.5	8	28	0.3
CV (%)	6	2	1	7	7	12	1

Tr, transparency; WT, water temperature; DO, dissolved oxygen; EC, electric conductivity; SD, standard deviation; CV, coefficient of variation
[a] Average, SD, and CV were arithmetically calculated from the pH values

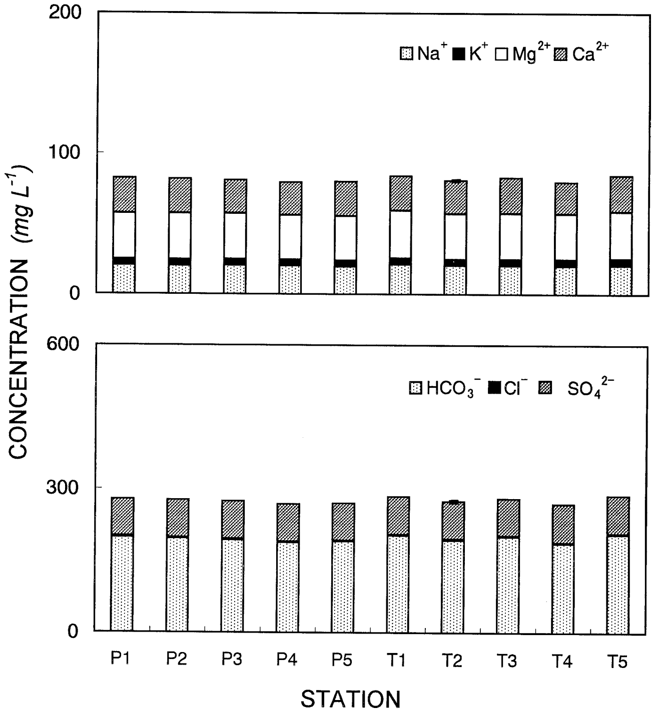

Fig. 3. Distributions of major cation (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anion (HCO_3^-, Cl^-, SO_4^{2-}) concentrations. *Bars* at Sta. T2 indicate the SD values of total cation or anion concentrations obtained in vertical observations

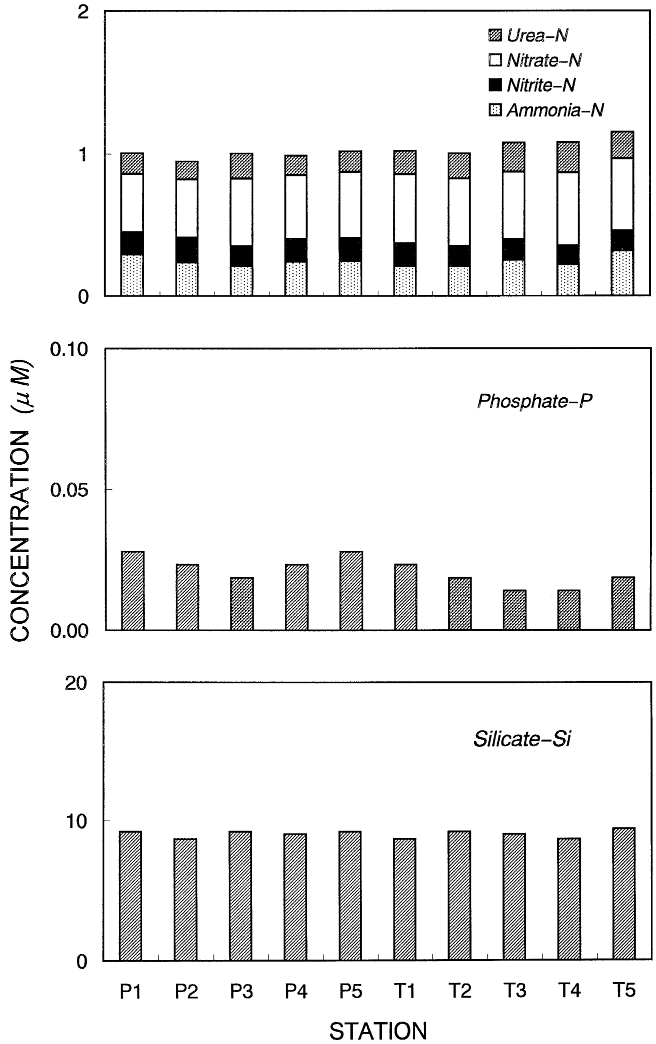

Fig. 4. Horizontal distributions of nitrogenous nutrient concentrations (ammonia, nitrite, nitrate, and urea) and phosphate and silicate concentrations

These values were relatively conservative and exhibited only minor changes from biological activities within the lake, except for bicarbonate and sulfate ions. The concentrations of each ionic element were Na^+, 20.6 ± 0.4 mg l^{-1} (average value with SD); K^+, 4.3 ± 0.1 mg l^{-1}; Mg^{2+}, 32.9 ± 0.6 mg l^{-1}; Ca^{2+}, 25.0 ± 1.1 mg l^{-1}; Cl^-, 2.3 ± 0.1 mg l^{-1}; and SO_4^{2-}, 78.9 ± 1.3 mg l^{-1}. High concentrations of Mg^{2+} and SO_4^{2-} were observed. The concentration of HCO_3^- was estimated as 199 ± 7 mg l^{-1} from the ionic balance between the cation and anion equivalent values. The chemical type of the lake water was Mg–Ca–HCO_3–SO_4, based on 25% or more of cation or anion equivalence. The water was characterized by a high concentration of Mg. These values showed a uniform vertical distribution due to the absence of thermal stratification. Average salinity was estimated as 363 mg l^{-1} from the sum of the major ionic elements. In contrast, the water in Lake Yamzho Yumco (28°55′N, 90°45′E; altitude 4250 m; lake surface 621 km^2), located in the lower reaches of Lake Puma Yumco, contained 1.9 g l^{-1} of major ionic constituents, and its chemical type was Mg–Na–SO_4–HCO_3. Lake Yamzho Yumco is a saline lake according to the report of Hammer (1986). Thus, Lake Puma Yumco had a fairly low salinity and a different chemical type compared with Lake Yamzho Yumco.

Williams (1964) classified water as saline if its salt concentration was in excess of 3 g l^{-1}; water below this level was freshwater. Hammer (1986), on the other hand, categorized lakes into five groups according their salinity, i.e., fresh (less than 0.5 g l^{-1} salinity), subsaline (0.5–3 g l^{-1}), hyposaline (3–20 g l^{-1}), mesosaline (20–50 g l^{-1}), and hypersaline (more than 50 g l^{-1}). Using the above classifications, Lake Puma Yumco can be considered a freshwater lake. Kawashima and Nishiyama (1989) reported the chemical features of 27 lakes on the Tibetan Plateau. They determined the major chemical elements in lake waters and discussed the relationship between the salinity or chemical type and the climate. They indicated that the salinity was lower in the south than in the arid north of the plateau, and that of the chemical type of lake waters was Na–Cl and/or Na–SO_4 in the north but Na–HCO_3 (with the exception of one Ca–HCO_3) in the south. Our results, showing a high Mg concentration in Lake Puma Yumco, however, revealed a considerably different chemical type.

Distribution of biogeochemical parameters

Horizontal and vertical distributions of nitrogenous nutrients (ammonia, nitrite, nitrate, and urea) and phosphate and silicate concentrations are shown in Figs. 4 and 5. The

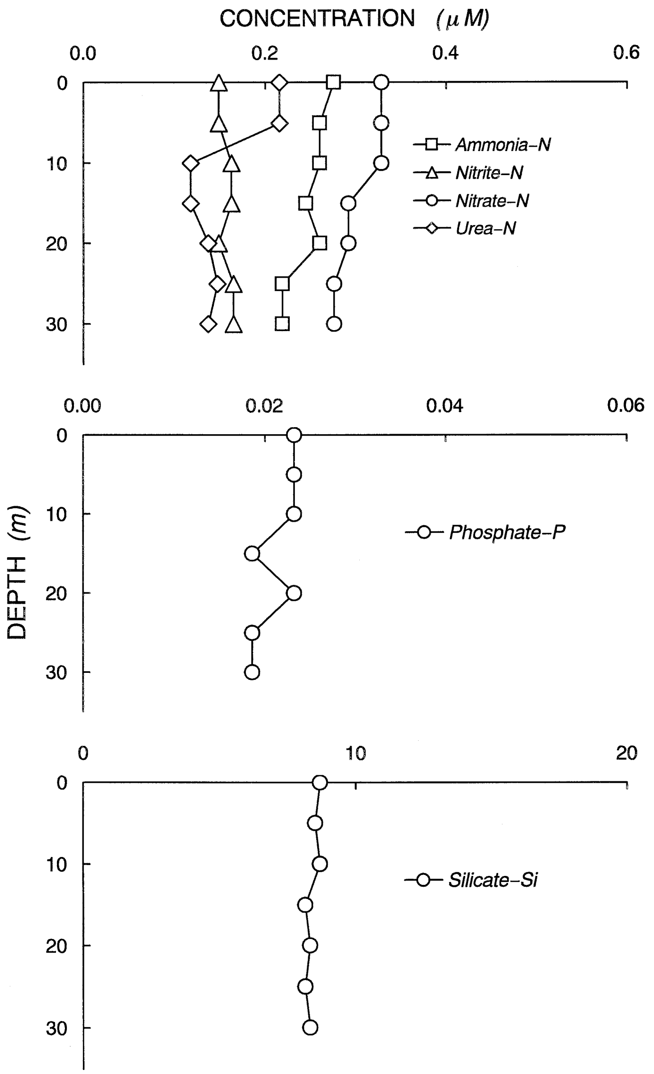

Fig. 5. Vertical distribution of nitrogenous nutrients, phosphate, and silicate concentrations at Sta. T2

concentration of ammonia was 0.25 ± 0.03 μM and constituted 24%–37% of dissolved inorganic nitrogenous nutrients (DIN, the sum of ammonia, nitrite, and nitrate nitrogen). A much lower concentration of nitrite, namely 0.16 ± 0.01 μM (15%–25%), was observed. The nitrate concentrations, on the other hand, were 0.39 ± 0.09 μM (41%–59%). The concentrations of DIN were extremely low compared with those generally observed in natural lakes. This indicates that the loading of these nitrogenous compounds from the lake watersheds is considerably low. The greater part of DIN in Lake Puma Yumco was nitrate, suggesting that the nitrification rate in this lake exceeded the microbial mineralization rate of organic nitrogen or the zooplankton excretion rate during the investigation period. There were no appreciable differences in the level of these inorganic nitrogenous nutrient concentrations among stations and these parameters showed an almost uniform vertical distribution. The present results indicate that Lake Puma Yumco during the investigation period was in its circulation phase.

As shown in Figs. 4 and 5, urea nitrogen in the lake ranged from 0.12 to 0.22 μM (0.16 ± 0.03 μM). Low concentrations of urea were indicated and the urea concentration displayed no change horizontally or vertically. Urea nitrogen was lower than that of ammonia and nitrate, but comparable to nitrite. An appreciable amount of urea nitrogen in the total nitrogenous nutrient level (TNN, sum of ammonia, nitrite, nitrate, and urea nitrogen) was observed, ranging from 13% to 22% of TNN. In freshwater lakes, urea makes an appreciable contribution to the nitrogenous nutrients (Satoh et al. 1980; Mitamura and Saijo 1981; Mitamura and Hino 1997). Moreover, the importance of urea as a nitrogen source for phytoplankton has been pointed out by several studies of freshwater lakes (McCarthy et al. 1982; Mitamura and Saijo 1986; Mitamura et al. 1995; Mitamura 2001). The present results indicate that the urea in the euphotic zone of Lake Puma Yumco is one of the principal nitrogenous compounds serving as a nitrogen source for phytoplankton, although the activity of nitrogen uptake seems to be considerably low.

The phosphate (DIP) concentration was limited (Figs. 4 and 5), with values of 0.02 ± 0.004 μM. There was no appreciable change either with station or with depth. The concentrations at pelagic stations displayed somewhat higher values than those at littoral stations. The molar ratios of DIN to DIP and TNN to DIP were calculated as 30–63 and 36–77, respectively. This seems to indicate that both nitrogen and phosphorus nutrient compounds were the limiting parameters for phytoplankton growth during the investigation period.

The concentrations of dissolved reactive silica (DRSi) were 8.1–9.4 μM (8.8 ± 0.4 μM) and uniform horizontal and vertical distributions were observed. Low DRSi concentrations suggest that the biomass of diatoms in phytoplankton populations is considerably low, as shown in the microscopic analysis of lake water and sediment samples, and contributes merely to primary productivity in Lake Puma Yumco.

Distributions of dissolved organic carbon (DOC), nitrogen (DON), and phosphorus (DOP) concentrations are shown in Table 3. The concentrations of DOC in surface waters at nine stations ranged from 162 to 173 μM (165 ± 4 μM). The DON concentration was 10.6 ± 0.4 μM. An extremely low concentration of DOP, namely 0.08 ± 0.02 μM, was observed. There were no regular horizontal variations, although the coefficient of variation in DOP showed a considerably higher value (30%) than those for DOC (2%) and DON (4%). This seemed to be caused by the analytical error in the DOP determination. No appreciable differences in the DOC and DON concentrations with depth were observed; however, low DOP concentrations were revealed in the deeper layer. The concentrations of dissolved organic matter in Lake Puma Yumco were relatively lower than those generally observed in oligotrophic lakes located in flatland regions. The average molar ratio of DOC:DON:DOP in surface waters was calculated as 2100:140:1. The DOC:DOP and DON:DOP ratios displayed markedly high values. Holm-Hansen et al. (1976) obtained a DOC:DON:DOP molar ratio of 500:40:1 in Lake Tahoe,

Table 3. Distributions of dissolved organic carbon (DOC), nitrogen (DON), phosphorus (DOP), and urea concentrations; the molar ratio of DOC:DON:DOP; and the percentage of urea carbon (DUC) in DOC and urea nitrogen (DUN) in DON

	DOC (μM)	DON	DOP	Urea	DOC:DON:DOP (molar ratio)	DUC/DOC (%)	DUN/DON
Horizontal							
Average	165	10.6	0.078	0.08	2100:135:1	0.051	1.6
SD	3.8	0.4	0.021	0.02			
CV (%)	2.3	3.8	27	18			
Vertical							
Average	161	10.3	0.042	0.08	3870:247:1	0.048	1.5
SD	3.1	0.3	0.009	0.02			
CV (%)	1.9	2.6	22	25			

Horizontal and vertical indicate the values in surface water from nine stations and seven depths (from the surface to the bottom layer at Sta. T2), respectively

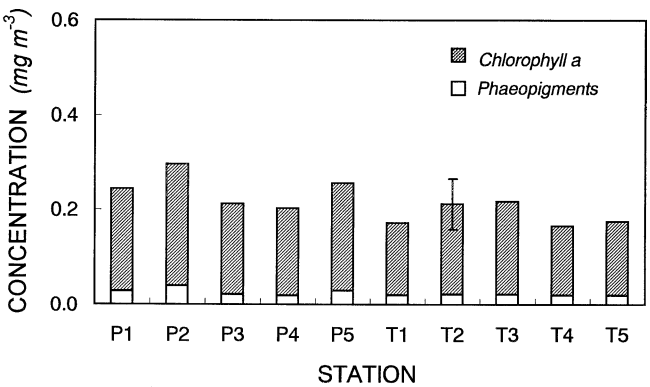

Fig. 6. Distributions of chlorophyll *a* and phaeopigments. *Bar* at Sta. T2 indicates the SD value of total chlorophyll (sum of chlorophyll *a* and phaeopigments) obtained in vertical observations

and Mitamura and Saijo (1981) reported an average ratio of 840:36:1 at a station in the deep north basin of Lake Biwa. In a mesotrophic tropical lake, Mitamura and Hino (1997) obtained an average value of 340:77:1. The DOC:DON ratios in the present study are similar to those in the previous reports on temperate lakes. On the other hand, the DOC:DOP and DON:DOP ratios seen in the current study are extremely high, as compared with those obtained in previous reports.

The percentage of urea carbon in DOC ranged from 0.04% to 0.07% and that of urea nitrogen in DON was calculated as 1.1%–2.1% (Table 3). Only a small amount of the DOC was provided by urea. The contributions in the present results were lower compared with those reported by Mitamura and Saijo (1981) and Mitamura and Hino (1997). Thus, in Lake Puma Yumco, the urea seems to have an insignificant impact on the DOC and DON variation.

As shown in Fig. 6, chlorophyll *a* valves were 0.15–0.34 $mg\,m^{-3}$ (0.22 ± 0.05 $mg\,m^{-3}$). On the other hand, low concentrations of phaeopigments were obtained, namely 0.03 ± 0.01 $mg\,m^{-3}$. Uniform distributions in the concentrations of these parameters were observed both horizontally and vertically. The ratios of phaeopigments to chlorophyll *a* concentration ranged from 0.09 to 0.15. Low ratios indicate that the phytoplankton in Lake Puma Yumco during the investigation period possessed a high potential for photosynthetic activity, although the primary productivity seemed to be limited by low concentrations of nitrogen and phosphorus nutrients.

Composition and distribution of phyto- and zooplankton

Tables 4 and 5 show the composition and vertical distribution of phytoplankton and zooplankton species during the investigation period. A varied community of three species of Cyanophyceae, eight or more species of Bacillariophyceae, twelve or more species of Chlorophyceae, and one species of Dinophyceae, was observed. Predominant among the epilimnetic phytoplankton was a blue–green alga *Aphanocapsa* sp. and a green alga *Oocystis borgei*. The vertical profiles of phytoplankton seemed to reveal the existence of preferential depths for each species, although most species were present at all depths.

Two species of Copepoda and two of Branchiopoda, on the other hand, comprised our zooplankton sample. The zooplankton were dominated by free-living copepods *Diaptomus* sp. (first dominant) and Nauplii (second dominant). Very little biomass of the Cladocera species was observed. It is noteworthy that the adult and copepodit Diaptomidae shown in Table 5 are likely to represent endemic species. The composition of phyto- and zooplankton as shown by the present results confirms the oligotrophic character of Lake Puma Yumco.

Chemical characteristics of lake sediment

Visual observation of samples taken from the Ekman-Birge grab sampler showed that the sediments at transect Stas. T1–T4 had the grain size of sand with clay, while at littoral Sta. T5 it was mainly composed of pebble-cobble gravel with sand and clay. Sediments from the shallow stations of 30 m depth or less were covered with a macrophyte, *Chara* sp. At Stas. T4 (10 m depth) and T5 (4 m) a large biomass was verified. The benthic animals (including shellfish) in the bottom sediment taken in the single grab collection could not be identified.

The physical and chemical characteristics of the interstitial waters in the upper sediments were as follows. Water temperature ranged from 3.3° to 3.7°C, and showed almost

Table 4. Vertical distribution of phytoplankton species at Sta. T2

Species	0 m	5 m	10 m	15 m	20 m	25 m
Cyanophyceae						
Aphanocapsa sp.	+++	C	C	++	+++	C
Chroococcales	+	+	+	+	+	r
Oscillatoriaceae	++					
Bacillariophyceae						
Cyclotella spp.	+	+	+	+	+	+
Pinnularia sp.	r					
Navicula spp.	r					
Cymbella sp.	r					
Amphora sp.		r				
Chlorophyceae						
Elakatothrix gelatinosa	+	r		+	+	+
Tetrasporales	++	+	+	++	++	+
Dictyosphaerium ehrenbergianum	+	++	+	++	++	+
Oocystis borgei	++	++	++	++	++	++
Pediastrum duplex v.*reticulatum*					+	
Coelastrum reticulatum	+	+				
Crucigenia sp.						+
Oedogoniaceae						+
Cosmarium spp.		r	r			r
Chlorophyceae	+	+	+	++	+	+
Dinophyceae						
Gymnodiniaceae	r	r	r	r	r	

C, >30%; +++, 20%–30%; ++, 10%–20%; +, 1%–10%; r, <1%

Table 5. Vertical distributions of zooplankton species at Sta. T2

Species	0–5 m	5–10 m	10–15 m	15–20 m	20–25 m
Rotifera					
Filinia longiseta	0	0	0	57	6
Cladocera					
Daphnia sp.	3	3	0	11	17
Copepoda					
Diaptomidae adult	14	120	150	410	160
Diaptomidae copepodit	14	160	200	1030	570
Cyclopoida copepodit	0	3	11	23	28
Nauplius of copepode	34	150	690	1510	180

Values are expressed as individuals m^{-3}

the same values as those of the lake water. The pH values were 7.4–7.9. It is worth noting that the pH values in the contact/interstitial water on the sediments were low compared with those of the lake water (8.3–8.7). The concentrations of dissolved oxygen varied from 1.8 to 7.0 mg O_2 l^{-1} (27%–106% of saturated value), showing that the surface sediments in Lake Puma Yumco showed an anoxic character, despite their large grain size and low levels of organic matter.

Distributions of carbon and nitrogen in sediments are shown in Table 6. Organic carbon ranged from 0.5% to 6.2%, and high values were obtained at the littoral station. At Sta. T4, the >500-μm fraction was large and the organic carbon content in this fraction was much higher than those at the offshore stations. This observation seemed to be caused by large numbers of Charophyta on the sediment at Sta. T4, as described above. The nitrogen content was 0.08%–0.59% and the distribution showed a similar tendency to that of organic carbon. Both carbon and nitrogen levels in the present results, except for the values at Sta. T4, were considerably lower than those generally observed. This indicates that in oligotrophic Lake Puma Yumco, the autochthonous organic production and the allochthonous input from its watershed above the forest limit were quite limited. The molar ratio of organic carbon to nitrogen was calculated as 8.1–12.4. The high ratio was observed at Sta. T4 and was caused by the macrophyte population.

A considerably high level of inorganic carbon was observed, with values of 2.9%–3.6%. There were no appreciable differences among stations. It was estimated by chemical analyses that almost all the inorganic carbon was in the form of $CaCO_3$ from the inorganic elements in sediment. $CaCO_3$ accounted for 22%–34% of sediment. The contribution of $MgCO_3$ was considerably low, although high concentrations of Mg^{2+} were observed in lake water. The high $CaCO_3$ values seem to be caused by the abundant supply of allochthonous inorganic substances resulting from heavy rain, snow, or glacier flooding from the watershed, and suggest that the chemical characteristics of the lake basin originated in the formation of the Himalayas.

Table 6. Carbon and nitrogen contents of lake sediments at transect stations

Station	Fraction	Organic carbon (%)	Nitrogen (%)	Organic C/N (molar ratio)	Inorganic carbon (%)
T1	Total	0.6	0.09	8.1	3.5
	<500 μm	0.5	0.08	8.1	
T2	Total	1.4	0.19	8.2	2.9
	<500 μm	1.2	0.17	8.4	
T3	Total	1.9	0.22	9.9	3.4
	<500 μm	1.6	0.21	8.8	
T4	Total	6.2	0.59	12.4	3.6
	<500 μm	3.9	0.34	13.2	

Table 7. Frequency distribution (ϕ grade scale) of sediment grain size in Lake Puma Yumco

	Sta. T2	Sta. T3	Sta. T4
Frequency (%)			
Sand (<ϕ2)	2	4	7
(ϕ2–4)	40	47	55
Silt (ϕ4–6)	41	35	30
(ϕ6–8)	14	13	7
Clay (ϕ8–10)	2	2	0
(>ϕ10)	0	0	0
Average (ϕ)	4.5	4.2	3.7
Average ± SD (μm)	44 ± 0.5	53 ± 0.5	74 ± 0.4
Median (ϕ)	4.3	4.0	3.5
Median (μm)	49.2	63.2	88.1

Grain size distribution

Table 7 shows the frequency distribution of grain size in sediments taken from three stations along the transect line. These sediments were generally of silt and sand particles. At offshore Sta. T2, the average grain diameter was 44 ± 0.5 μm; whereas at inshore Sta. T4, a larger size (74 ± 0.4 μm) was observed. At Sta. T2, the median diameter was 49 μm (ϕ4.3; phi grade scale), i.e., silt; at Sta. T3 it was sand of 63 μm (ϕ4.0); and at Sta. T4 it was sand of 88 μm (ϕ3.5). Even at Sta. T2, with its finer sediments, the clay made up only 2% of the total (sum of clay, silt, and sand percentages). Generally the sediments were of large grain size compared with those observed in temperate and tropical lakes located in low altitude regions. The present results indicate that the supply of allochthonous organic matter from the Lake Puma Yumco watershed was extremely low, and that the sedimentation of autochthonous organic matter originating from primary productivity was also poor because of the low photosynthesis levels of phytoplankton.

Wetzel (2001) established a trophic classification of lakes and reservoirs in relation to nitrogen and phosphorus concentrations in water, based on the relationship of lake productivity and the biogeochemical parameters demonstrated by Vollenweider (1968). Lakes with low concentrations of DIN (<200 $\mu g l^{-1}$) and total phosphorus (<5 $\mu g l^{-1}$) are defined as ultraoligotrophic (Wetzel 2001). In the present study, extremely low concentrations of nitrogenous nutrients, phosphorus nutrients, and chlorophyll *a* were obtained. This seems to confirm that Lake Puma Yumco can be classified as a harmonic ultraoligotrophic lake based on its high transparency, low extinction coefficient, distribution of *Chara* in deep water, low organic matter content, large sediment grain size, and low levels of nutrients.

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