V. PHYSICO-CHEMISTRY

V.1. Physico-chemical properties of the water

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The physical and chemical properties of the water of Lake Titicaca have been subject to spot measurements during scientific expeditions and more recently have been measured over much more extended time periods. Works covering this field include Gilson (1939–40, 1964), Monheim (1956), Löffler (1960), Kessler and Monheim (1968), Widmer *et al.* (1975), Richerson *et al.* (1975, 1977), Hegewald *et al.* (1976), Lazzaro (1981), Hegewald and Runkel (1981), Carmouze *et al.* (1981, 1983, 1984), Richerson *et al.* (1986), Iltis (1987) and Quintanilla *et al.* (1987).

Although the data of these workers on the hydroclimate provide valuable information on spatial and seasonal differences, the absence of long-term measurements means that we are still uninformed at present about any between-years variation.

The water temperature, dissolved oxygen content and transparency are the three factors for which there are currently most measurements. All the data collected demonstrate marked individualities in the major morphological regions of the lake. The Lago Menor, with its shallow depth, and which is similar in many respects to the large shallow bays in the Lago Grande such as Puno Bay and Achacachi Bay, is very distinct from Lago Grande, typified by seasonal stratification and a greater thermal inertia.

Water temperature

Seasonal changes in surface temperature

The mean monthly surface temperatures measured in the Lago Grande between 1977 and 1979 (Carmouze *et al.*, 1983) varied between 11.25 and 14.35°C, the lowest temperature being in August and the highest in March (Table 1). The mean annual temperature (1977–1979) was 13.0°C.

Occasional measurements made in Lago Grande (Gilson, 1964; Iltis, 1987) give minimum values of 10.9°C (end of July) and maximum values of 17.0°C

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Table 1. Seasonal changes in air temperature, surface water temperature in the Lago Grande, wind speed at 2 m above the ground (Carmouze *et al.*, 1983), hours of sunshine per day (Boulangé and Aquize Jaen 1981) and daily total incident radiation in J cm^{-2} d^{-1} (Lazzaro, 1981). With the exception of water temperatures measured in the Lago Grande data come from the Puno (Peru) meteorological station.

Parameters	J	F	M	A	M	J	J	A	S	O	N	D	Mean
Air temp.	9.95	9.77	9.33	8.44	8.71	5.26	5.07	6.43	7.90	9.40	10.10	10.15	8.21
Water temp.	13.85	14.30	14.35	13.85	13.0	12.0	11.5	11.25	11.75	12.9	13.35	13.85	13.0
Wind speed	1.14	1.03	0.96	0.95	0.97	1.08	1.06	1.23	1.32	1.42	1.39	1.28	1.15
Solar duration	5.8	5.8	6.6	8.5	9.1	9.4	9.7	9.1	9.0	9.2	8.5	6.8	8.12
Global radiation J^{-1}	2.144	2.065	2.006	2.190	1.969	1.940	1.860	2.195	2.320	2.412	2.420	2.307	2.152

(February), whereas the extreme values recorded in the Lago Menor are 8.5°C (June) and 18.5°C (February).

In Lago Grande the annual range of mean monthly temperature has a mean value of 3.1°C with an observed maximum of 6°C. In Lago Menor, where mean monthly data are absent, the recorded range of extremes is 10°C.

The factors likely to affect changes in the water temperature over the year are the air temperature, the wind speed and the total incident solar radiation (Fig. 1). Measurements made at Puno show that the mean air temperatures range between 5.07°C in July and 10.15°C in December. Wind speeds are rather low throughout the year, the average varying from 0.95 m s^{-1} in April to 1.42 m s^{-1} in October; winter can be considered as the most windy season. Daily sunshine hours vary between 9.7 h d^{-1} in July and 5.8 h d^{-1} in January and February and total incident radiation varies between 2420 J cm^{-2} d^{-1} in November and 1860 J cm^{-2} d^{-1} in July (Lazzaro, 1981). As a result, wind

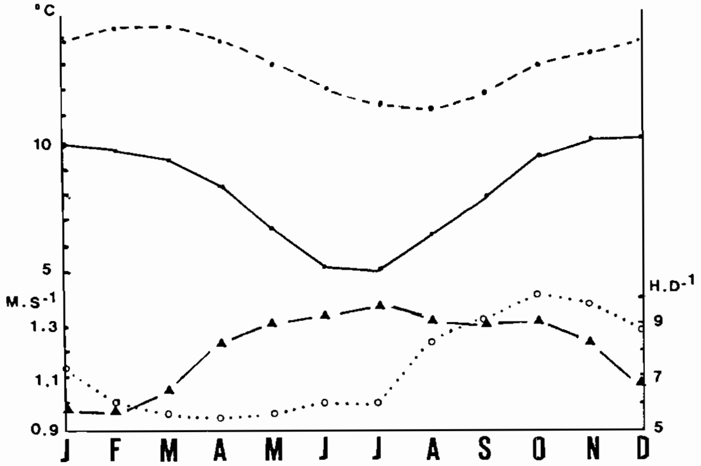

Figure 1. Seasonal changes in: top: air temperature at Puno (solid line) and surface water temperature in the Lago Grande (dashed line); bottom: sunshine hours (solid line) and wind speed at 2 m above the ground at Puno (dotted line) (from Carmouze *et al.*, 1983).

action can be considered as negligible and air temperature and incident radiation are the two factors which are most influential in causing changes in water temperature.

The seasonal range of variation at the surface is closer to that of the air in the shallower areas and particularly in the Lago Menor, because of the lower inertia related to a shallower mean depth.

Although the seasonal range and seasonal changes are closely correlated with those of the air, the fact that the mean annual temperature of both Lago Grande and Lago Menor is 13°C, whereas that of the air at Puno (1964–1978) is only of the order of 8.1°C, implies that heat exchanges and heat processes are occurring that are not found in more usual climatic and altitudinal conditions.

Horizontal variations

The different behaviours of surface temperatures are reflected in variations in temperature from one part of the lake to another: Lago Menor is colder than Lago Grande in winter and warmer in summer. Between 1985 and 1987, for example, five series of observations over the entire Bolivian part of the lake (Iltis, 1987) showed that the mean surface temperature in Lago Menor was 1°C higher in summer and 1.5°C colder in winter than in Lago Grande. These differences obviously disappear at transitional seasons (April and September-October).

Vertical variations

Published data referring to the temperature in the top hundred metres over the period 1976–1978 (Carmouze *et al.*, 1984) show that the surface waters in the Lago Grande start to warm up from October onward. This warming spreads gradually downwards until a well-defined thermocline is established in December. The thermocline gets deeper until the month of May before disappearing from June to September (Fig. 2). It would appear however that turnover does not take place right to the bottom of the lake, or else that water circulation is very slow there, because at the end of the period of mixing (September) the temperature at 180 m depth was 11 °C and the oxygen saturation was only 70%.

From the available data, Lake Titicaca can be placed in the class of warm monomictic lakes of Hutchinson's (1957) classification, the greater part of Lago Menor and the shallow bays (down to 20 m) being of the polymictic type.

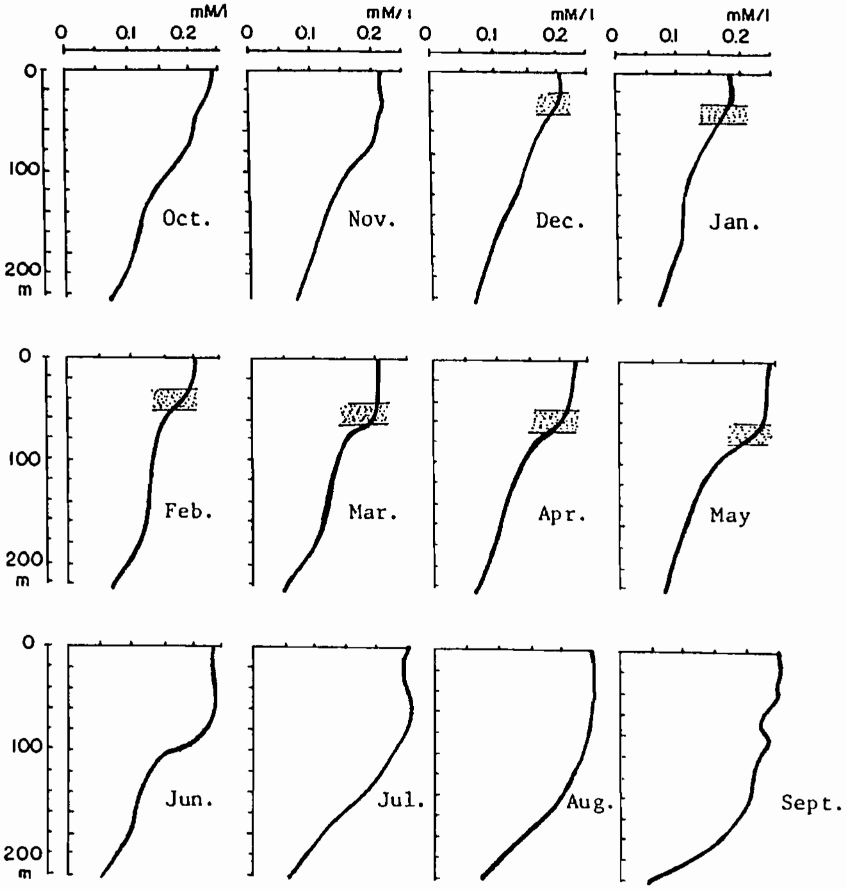

Figure 2. Mean monthly vertical profiles of dissolved oxygen concentration in the water. The shaded area indicates the position of the thermocline (Carmouze *et al.*, 1984).

Dissolved oxygen

The main factors controlling the dissolved oxygen concentration are atmospheric pressure and temperature.

The mean atmospheric pressure at the altitude of Lake Titicaca is 646 hPa (compared to about 1010 hPa at sea level). The relatively low water temperature compensates in part for this effect of pressure so that the resulting saturation concentration is of the order of 7 mg l^{-1}. A saturation curve for the range of temperature encountered in the lake, calculated from Montgomery *et al.* (1964), is given in Fig. 3.

The surface waters of the Lago Menor have concentrations close to saturation all the year round (≥95% saturation). The highest values are recorded in winter and are due to an increase in solubility of oxygen caused by the

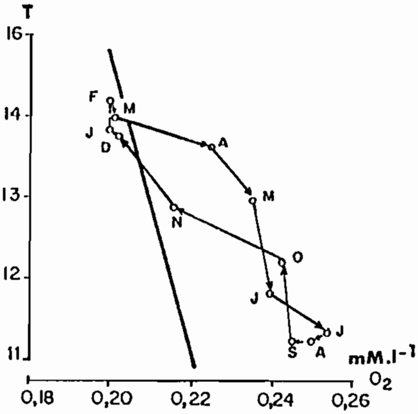

Figure 3. Relationship between mean monthly dissolved oxygen concentrations in the surface water expressed in mmol l^{-1} and water temperature in °C. The diagonal line divides the area of supersaturation to the right and under-saturation to the left (Carmouze *et al.*, 1984).

drop in water temperature. During summer stratification, the hypolimnion in the Chua Depression becomes isolated and only contains 1 to 2 mg l^{-1} (Lazzaro, 1981) with anoxia in the bottom layers in March 1979 and 1980.

Data published for Lago Grande for the period 1976–78 (Carmouze *et al.*, 1984) show an unusual temporal pattern in the percentage saturation of the surface water (Fig. 3): the water is significantly more saturated during vertical mixing than during the period of stratification. The opposite generally occurs in temperate lakes when the cold season coincides most often with the rainy season. Here, in contrast, most precipitation takes place between December and March. This possible correlation does not however explain the supersaturation that occurs in July, August and September.

The regular oxygen profile indicates that the hypolimnion in the Lago Grande becomes deficient in oxygen during the period of stratification. The vertical circulation from July to September over the period 1976–78 (Carmouze *et al.*, 1984) was insufficient to reoxygenate the deeper water layers. It is possible that variation in the main meteorological factors between years is reflected in a variable efficiency in the overturn of the water body.

Transparency

The transparency as measured by Secchi disk is greater in Lago Grande than in Lago Menor. There is however great spatial and temporal variability in both basins.

The extreme values recorded in Lago Menor are 1.2 and 9 metres (Lazzaro, 1981; Iltis, 1987), with lower transparencies in summer and autumn and higher values in winter. As an example, five series of measurements, each carried out at 28 stations in the Lago Menor gave mean values of 4.7 m in June 1985, 4.5 m in December 1985, 5.6 m in April 1986, 5.4 m in October 1986 and 3.2 m in February 1987.

The relationship between Secchi disc transparency (S in metres) and the photosynthetic available radiation m^{-1} K (PAR, Ln base, flat receptor) is K.S = 1.12.

The euphotic depth therefore reaches to the bottom over most of the Lago Menor, except in the deepest areas (the Chua Depression). At Chua, light attenuation is closely correlated with the phytoplankton concentration. In other, shallower stations, other particles in suspension also play an important role (Lazzaro, 1981).

In the Lago Grande, Richerson *et al.* (1977) give Secchi disc values of between 4.5 and 10.5 m. Observations made in 1982 gave a maximum value of 13.3 m, whereas in 1984–85, the mean value was 15.7 m (Alfaro and Roncal, unpublished data). Five series of measurements, each taken at 19 stations in the Bolivian part of Lago Grande, gave mean values of 11.8 m in June 1985, 11.9 m in December 1985, 13.2 m in April 1986, 12.4 m in October 1986 and 13.9 m in February 1987 (Iltis, 1987). These values are in agreement with those of a series of 4 observations (Quintanilla *et al.*, 1987) made between August 1984 and May 1985 where the means were between 11.3 and 14.6 metres.

Chemical properties

pH

The pH values of the surface waters are relatively stable. Lazzaro (1981) recorded values of between 8.55 and 8.65 in the Lago Menor in 1979–80. Mean values at 28 stations between 1985 and 1987 gave mean values of 8.68 in December 1985, 8.40 in April 1986, 8.38 in October 1986 and 8.31 in February 1987; the extreme values were 8.06 and 9.38 (Iltis, 1987).

Richerson *et al.* (1977) gave pH values of 8.6 in the stratified period and 8.5 in the period of isothermy in the Peruvian part of the Lago Grande. The means recorded at 19 stations in the Bolivian part of the lake were 8.48 in December 1985, 8.30 in April 1986, 8.31 in October 1986 and 8.20 in February 1987 (Iltis, *loc. cit.*).

pH is therefore on average a little higher in the Lago Menor than in the Lago Grande, possibly because of the greater photosynthetic activity of phytoplankton and very abundant benthic macrophytes.

Total dissolved solids (TDS)

This has been measured in terms of the electrical conductivity at 25°C. The mean of 16 measurements made in April 1985 in the Lago Menor was 1343

Table 2. Ionic composition (in mg l^{-1}) of the waters of Lake Titicaca published by various workers (the dates given are the sampling dates).

	NEVEU-LEMAIRE 1903	POSNANSKY 1908	GILSON 1937	LÖFFLER 1954	RICHERSON *et al.* 1973	HEGEWALD *et al.* 1974-77	CARMOUZE *et al.* 1977
Ca	64,6	68,7	65,4	54,3	64,0	62,0	65,2
Mg	18	16	34,5	41	36	36,4	35
Na	261	240	167,7	176	-	205,0	178,9
K	8	4	14,9	14	-	21,7	15,4
SO_4	392	285	246,2	251	282	265,7	253,4
Cl	287	339	247	244	260	272,0	253,8

μS cm^{-1}. A later series of 28 measurements gave the following values: 1521 in December 1985, 1368 in April 1986, 1490 in October 1986 and 1366 in February 1987. The means recorded at 19 stations in the Bolivian part of the Lago Grande were 1501 μS cm^{-1} in December 1985, 1448 in April 1986, 1490 in October 1986 and 1409 in February 1987 (Iltis, *loc. cit.*).

As for temperature, the means recorded showed more marked changes in Lago Menor, where dilution by water in the rainy season and evaporation during the dry season had greater effects than in Lago Grande. At intermediate seasons such as in October 1986, the conductivity was identical in both basins. Stations situated close to the mouths of the Rios Catari, Tiwanaku and Suchez had conductivities 100 to 300 μS lower than those of other stations.

The directly measured TDS in Lake Titicaca vary according to sources from 1.2 g l^{-1} (Lazzaro, 1981), to 1.03 (Hegewald *et al.*, 1976) and 0.78 g l^{-1} (Richerson *et al.*, 1977).

Chemical composition of the water

This has been measured by various workers: Neveu-Lemaire (1906), Posnansky (1911), Gilson (1964), Löffler (1960), Richerson *et al.* (1977), Hegewald *et al.* (1976, 1980) and Carmouze *et al.* (1981) (Table 2).

The waters are dominated by chloride, sulphate and sodium ions, the ranking of cations being Na > Ca > Mg > K.

The concentrations of nitrate and phosphate are the subject of a separate chapter (Chapter V.6).

For silica, the majority of published values lie between 0 and 2.6 mg l^{-1}, with a representative mean value of 1.8 mg l^{-1} (Carmouze *et al.*, 1981). Concentrations of silica in the top five metres of the water column in Lago

Menor vary between 0.2 and 1.8 mg l^{-1} over the annual cycle. Maximum values occur during the winter turnover in deep stations. In areas where the depth is less than 5 metres, the concentrations remain low throughout the year.

Löffler (1960) gave values varying of between 0.5 and 1 mg l^{-1} SiO_2 for Puno Bay. Richerson *et al.* (1977) measured silica concentrations throughout the annual cycle in the Peruvian part of the Lago Grande and found that concentrations in the epilimnion were between 0.49 and 1.18 mg l^{-1} from January to the end of May, but then fell rapidly to 0.18 mg l^{-1}. Concentrations in the hypolimnion in this period (January to 15 June) varied between 1.82 and 2.60 mg l^{-1}. In July, at the onset of isothermal conditions, the silica concentration of the surface waters was between 0.28 and 0.46 mg l^{-1}, whereas the concentration in the deep waters fell to 0.34 mg l^{-1}. The silica concentration in the surface waters then increased slowly from September to the end of the year but in the deeper water this increase was faster and the highest value (3.7 mg l^{-1}) was reached at 150 m depth at the end of the year.

Among the trace elements, Derkosh and Löffler (1961) mentioned the presence of boron, iron and lead and traces of chromium, manganese, aluminium and arsenic. Cobalt, nickel and vanadium were absent. Gilson (1964) recorded the presence of lithium (0.9 mg l^{-1}) and aluminium (0.4 mg l^{-1}). Hegewald *et al.* (1976) and Hegewald and Runkel (1981) recorded traces of iron, copper and zinc and 0.26 mg l^{-1} of aluminium in the water of Puno Bay.

Conclusions

Analysis of the physico-chemical properties of the waters of Lake Titicaca shows a low seasonal variability. The lake environment can thus be considered as fairly stable.

The range of variation of surface temperature during the year is rather low (3°C) in comparison with that recorded in African lakes at the same latitude (Talling, 1969). This is partly explained by the altitude, but also by the climate: the rainy season and maximum cloud over occur in the summer and thus winter sunshine partly compensates for the lowering of the air temperature.

The deep areas (Lago Grande, Chua Depression) behave as warm monomictic lakes, whereas the shallow areas (Lago Menor and Puno Bay) can be classified as rather independent environments with a polymictic cycle and with more marked seasonal changes.

There are few data on the oxygen concentration at the bottom of the Lago Grande and at Chua in the Lago Menor for periods of more than a year. The variation between years in the oxygen concentrations at the bottom, both in periods of stratification and isothermy, is therefore unknown.

The rather high total dissolved salt concentration is attributed to heavy chemical weathering of the catchment area. Its stability is a result of the long retention time of water in the lake.

The range of variation in the values of some variables can be greater in the vast shallow areas such as the Lago Huiñaimarca and Puno Bay, which are relatively isolated from the central body of water in the Lago Grande, especially as these regions are influenced by special local conditions (such as inflow rivers and the presence or absence of macrophytes), which makes them spatially heterogeneous. As a result, most of the variables studied have a greater range than in the Lago Grande.

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