V.2. Hydrochemical regulation of the lake and water chemistry of its inflow rivers

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The first data on the chemical composition of major dissolved elements in Lake Titicaca date from the beginning of the century (Neveu-Lemaire, 1906; Posnansky, 1911). These were followed by those of the Percy Sladen Trust Expedition in 1937 (Gilson, 1939–1940, 1964). Recently, more complete studies have been carried out on the Lago Grande (Richerson *et al.*, 1977) and on the whole lake (Carmouze *et al.*, 1977).

After a preliminary assessment of the main dissolved salts, a more precise assessment is given here for the Lago Grande and Lago Pequeño by means of new data on river and lake hydrology (Carmouze and Aquize Jaen, 1981) and on river water chemistry.

River water chemistry

The chemical composition of the waters of the lower courses of the main inflow rivers (Ramis, Coata, Ilave, Huancane and Suchez) and of that of secondary rivers (Pallina, Catari, Tiwanaku, Challa Jahuira, Chilla, Batallas Chicas, Keka, Huaycho and Zapatilla) was studied from samples collected between 1976 and 1979 (Table 1 and Fig. 1).

A less detailed study of the chemistry of the upper reaches of certain rivers, in relation to the geology of the corresponding part of the catchment area, enables us to make some general remarks on the origins of dissolved salts.

The Río Ramis

The mean total dissolved salt content is 5.52 mmol l^{-1}, with the following composition of main ions:

$$HCO_3 = 28.4\%,\ SO_4 = 13.94\%,\ Cl = 11.58\%,\ Na = 18.46\%$$
$$K = 1.23\%,\ Ca = 18.55\%,\ Mg = 5.72\%,\ SiO_4H_4 = 2.08\%$$

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Table 1. Mean annuual salt concentrations [i], and mean annual inputs (i) of waters from inflowing rivers and from streams along the shoreline (lit). [i] is expressed in mmol l^{-1} and (i) in mol × 10^9.

	HCO_3	(HCO_4)	$\|SO_4\|$	$^2(SO_4)$	$\|Cl\|$	(Cl)	Na	(Na)	$\|K\|$	(K)	$\|Ca\|$	(Ca)	$\|Mg\|$	(Mg)	$\|SiO_4$ Hy$\|$	(SiO_4 ^{3}Hy)
Huancané, lit. Moho	1.75	1.266	1.295	0.931	2.85	2.065	2.82	2.045	0.105	0.076	1.56	1.13	0.485	0.35	0.091	0.066
Ramis, lit. Arapa and Capachica	1.57	4.17	0.77	2.046	0.64	1.70	1.02	2.71	0.068	0.18	1.025	2.725	0.315	0.839	0.115	0.306
Ilpa	1.78	0.388	1.25	0.272	10.20	2.376	10.75	2.343	0.465	0.101	1.38	0.30	1.15	0.251	0.056	0.125
Coata, lit. Puno and Ilave	0.895	1.23	0.39	0.566	1.865	3.568	1.875	2.583	0.118	0.162	0.63	0.871	0.15	0.206	0.185	0.255
Zapatilla and lit. Juli-Tiquina	0.85	0.488	0.94	0.54	1.18	0.678	1.22	0.70	0.121	0.069	0.865	0.50	0.455	0.262	0.28	0.161
Lit. Tiquina-Desaguadero	0.29	0.059	0.40	0.103	0.025	0.006	0.12	0.030	0.065	0.008	0.28	0.072	0.15	0.038	0.218	0.058
Ilave	1.47	1.565	0.595	0.631	1.55	1.65	1.49	1.586	0.121	0.128	1.06	1.128	0.345	0.366	0.292	0.311
Lit. Desaguadero-Guaqui	1.775	0.036	0.245	0.005	0.645	0.013	1.05	0.020	0.107	0.004	0.815	0.016	0.232	0.005	0.246	0.005
Tiwanaku, lit. Taraco	1.915	0.354	0.59	0.109	0.276	0.051	0.53	0.095	0.076	0.014	1.155	0.213	0.27	0.05	0.153	0.028
Catarict Pallina	1.95	1.057	1.89	1.025	2.57	1.39	2.89	1.55	0.16	0.086	1.92	1.04	0.68	0.368	0.131	0.07
Batallas Chicas, lit. Watajata-Tiquina	0.25	0.033	0.13	0.017	0.025	0.003	0.20	0.025	0.03	0.04	0.09	0.012	0.06	0.008	0.103	0.013
Keka, lit. Tiquina-Achacachi, lit. Achacachi-Escoma	0.35	0.128	0.08	0.029	0.03	0.011	0.30	0.11	0.03	0.011	0.100	0.037	0.07	0.025	0.072	0.026
Suchez	0.64	0.151	0.251	0.059	0.025	0.006	0.19	0.043	0.032	0.007	0.305	0.071	0.16	0.038	0.06	0.014
Huaycho	0.67	0.116	0.71	0.123	0.955	0.165	1.22	0.103	0.085	0.013	0.67	0.116	0.217	0.038	0.19	0.033

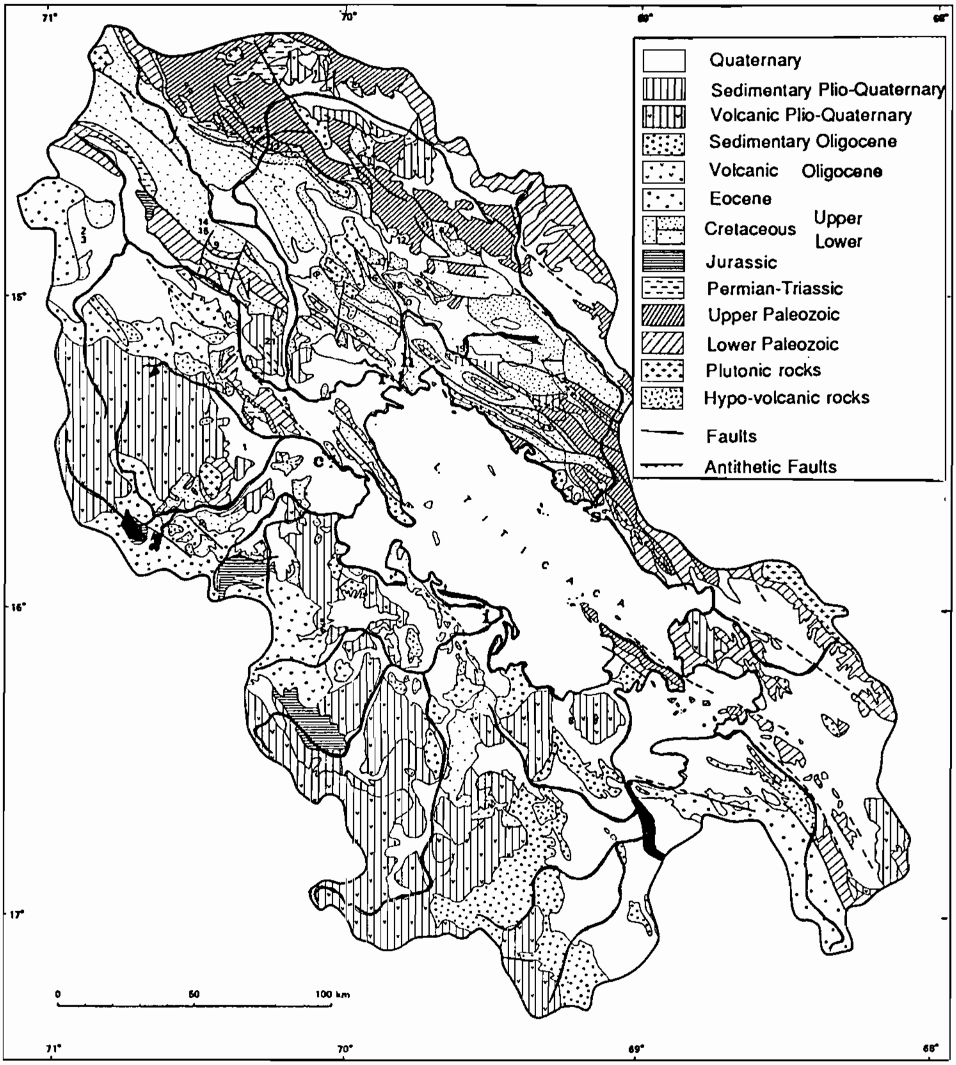

Figure 1. Geological formations in the catchment area of Lake Titicaca and water sampling locations. (r = Ramis, h = Huancane, c = Coata, i = Ilave, s = Suchez).

The calcium and bicarbonate are slightly dominant.

The total dissolved salt content shows seasonal variations, with the waters at the start of the rainy season being more heavily mineralised (10.43 mmol l^{-1}) and those at the height of the flood the least mineralised (1.27 mmol l^{-1}). The former have a double bicarbonate-calcium and chloride-sodium character, while calcium and bicarbonate dominate in the the latter.

The Río Coata

The mean total dissolved salt content of the Río Coata is 6.10 mmol l^{-1}, with sodium and chloride dominating.

HCO_3 = 14.6%, SO_4 = 6.35%, Cl = 30.58%, Na = 30.7%
K = 1.9%, Ca = 10.35%, Mg = 1.45%, SiO_4H_4 = 3.03%

Variations in dissolved salt content are both:

- very marked over the course of the year (the waters at the start of the flood reach a salt content of 18.4 mmol l^{-1} and those at the height of the flood 4.55 mmol l^{-1});
- very great from one year to another at the same season (18.4 mmol l^{-1} on 15 November 1976, 7.55 mmol l^{-1} on 26 November 1978).

There are also great seasonal changes in the chemical composition. Na + Cl make up 70% of the total dissolved salts at the start of the flood and 59 % at the height of the flood.

The Río Ilave

The mean total dissolved salt content of the Río Ilave is 5.50 mmol l^{-1}. The waters are of a mixed chloride-sodium and bicarbonate-calcium character:

HCO_3 = 21.2%, SO_4 = 8.57%, Cl = 22.4%, Na = 21.53%
K = 1.75%, Ca = 15.34%, Mg = 4.35%, SiO_4H_4 = 4.22%

Seasonal changes in salt content are relatively slight. The waters at the start of the flood have a salt content of 9.5 mmol l^{-1} and those at the height of the flood 4.35 mmol l^{-1}. Sodium and chloride dominate slightly in the former (Na + Cl = 51% of total dissolved salts), whereas the latter have a more marked bicarbonate-calcium character (HCO_3 + Ca = 41.4%). Nevertheless, qualitative variations in salt content are slight, irrespective of discharge.

The Río Huancane

The mean total dissolved salt content of the Río Huancane is 10.95 mmol l^{-1}. The waters are of a predominantly sodium-chloride type:

HCO_3 = 15.96%, SO_4 = 11.73%, Cl = 26.11%, Na = 25.75%
K = 0.96%, Ca = 14.24%, Mg = 4.41%, SiO_4H_4 = 0.83%

There are great seasonal variations. The waters at the start of the flood can reach a salt concentration of 26.84 mmol l^{-1}, whereas those at the height of the flood have a salt content three times lower (8.45 mmol l^{-1}). The between-years variation for any given season is also very marked because of irregularities in the hydrological regime (26.8 mmol l^{-1} in November 1976 against 10.3 mmol l^{-1} in November 1978). Variations have also been recorded on a much shorter time scale, associated with hydrological irregularities between months (23.3 mmol l^{-1} on 15 December 1976; 6.3 mmol l^{-1} on 15 January 1977; 16.9 mmol l^{-1} on 6 February 1977).

Qualitatively, the waters at the start of the flood have a clear chloride-sodium character (Na and Cl represent 70.5% of the total dissolved salts, whereas this percentage is only 46% at the height of the flood).

The Río Suchez

The waters of the Río Suchez are only very slightly mineralised. The mean total dissolved salt content is 1.66 mmol l^{-1} and the percentage composition as follows:

$HCO_3 = 88.48\%$, $SO_4 = 15.09\%$, $Cl = 1.5\%$, $Na = 11.42\%$
$K = 1.92\%$, $Ca = 18.34\%$, $Mg = 9.6\%$, $SiO_4H_4 = 3.6\%$

Bicarbonate and calcium predominate throughout the year ($HCO_3 + Ca =$ 57% of total dissolved salts). Seasonal variations in salt content are slight. The waters at the start of the flood have less than twice the salt content of those at the height of the flood (2.5 mmol l^{-1} against 1.40 mmol l^{-1}).

Secondary rivers

From results based on only two samples, the Río Zapatilla would appear to have a highly variable composition over the course of the year, both quantitatively and qualitatively. At the end of December 1976, the salt content was 7.95 mmol l^{-1} and at the start of February 1977 it was 19.95 mmol l^{-1}. At times of high discharge, chloride and bicarbonate concentrations are roughly equal ($HCO_3 = 18.6\%$, $SO_4 = 18.2\%$ and $Cl = 15.3\%$). At low discharge sodium and chloride dominate greatly ($Na + Cl = 67.5\%$).

The Ríos Challa Jahuira and Chilla have similar compositions at the time of the floods, the salt content of the former being 4.61 mmol l^{-1} and that of the latter 5.55 mmol l^{-1}. Bicarbonate and calcium dominate in both.

The Río Tiwanaku is typified by waters that change little in chemical composition over the course of the year. The salt content at the time of flood is 4.75 mmol l^{-1} and that at low water is 9.05 mmol l^{-1}. Bicarbonate and calcium predominate at all seasons.

The Ríos Pallina and Catari have relatively heavily mineralised waters. At the season of low water the salt content of the Río Pallina is 23.9 mmol l^{-1} and that of the Río Catari 9.55 mmol l^{-1}. Chloride and sodium predominate in these waters.

In the rainy season, the salt content of the waters of the Río Catari (9.55 mmol l^{-1}) are of the mixed bicarbonate-calcium and chloride-sodium type. The same must be true of the flood waters of the Río Pallina.

The Ríos Batallas Chicas and Keka are very little mineralised (0.925 mmol l^{-1} and 1.05 mmol l^{-1}, respectively); bicarbonates predominate whereas the chloride concentration is low or else is absent.

The Río Huaycho has a salt content of 4.7– 6.2 mmol l^{-1}, with bicarbonates, chlorides and sulphates all well represented.

General observations on the origins of dissolved salts in river waters

The problem of the origin of dissolved salts in the waters of the catchment area of Lake Titicaca is rather complex. The geology of the catchment contains a rather high number of different formations each with a number of distinct rock types.

This problem has been dealt with in a very simple manner by collecting water samples at the point where they run off the main formations i.e.: the Silurian-Devonian, lower Carboniferous, the lower middle and upper Cretaceous, the lower and middle Tertiary and the Pleistocene. The last two formations are of volcanic origin, whereas the others are sedimentary rocks (Fig. 1).

A certain number of observations can be made from the analyses carried out.

(a) Rivers, such as the Suchez, Keka and Batallas Chicas, flowing off granite massifs and then crossing short plains have poorly mineralised waters (1 to 2 mmol l^{-1}). Chlorides occur at low concentrations or are absent.

(b) Rivers in the upper part of the Ramis catchment (above 4000 m) and mainly crossing Palaeozoic sedimentary formations of Silurian-Devonian and Carboniferous age (schists and marls in the former and mainly sandstones in the latter) have little or no chlorides. As the waters of the Río Ramis entering the lake have a chloride content of roughly the same magnitude as that of bicarbonates and sulphates it is therefore thought that there is an enrichment in chlorides in the lower reaches of this river.

(c) The rivers forming the Huancane mainly derive from Cretaceous formations. Their total dissolved salt content does not exceed 6.2 mmol l^{-1} in which bicarbonate and calcium dominate. In contrast the salt content of the Huancane itself is always significantly greater than this value (between 8.5 and 27 mmol l^{-1}) and chloride and sodium dominate very clearly. The waters are markedly enriched in sodium and chloride in the lower reaches. In addition, in the eastern part of the catchment there are a few small lakes which function as differential concentration basins for dissolved salts (relative enrichment in NaCl).

(d) The upper reaches of the Ríos Coata and Ilave cross lower Tertiary sedimentary formations and also middle Tertiary and Pleistocene volcanic rocks. The chemical composition of water derived from any one formation is very variable, but it seems that the waters are poorer in chlorides the closer they are sampled to the rock formation. It would therefore appear that the waters are very quickly enriched in chloride in the downstream Quaternary areas.

Hydrochemical regulation in the lake

The water flowing into Lake Titicaca has the following mean annual chemical composition in mmol l^{-1} (R = river, L = lake):

$$[HCO_3]_R = 1.31,\ [SO_4]_R = 0.76,\ [Cl]_R = 1.51,\ [Na]_R = 1.65$$
$$[K]_R = 0.11,\ [Ca]_R = 0.98,\ [Mg]_R = 0.34,\ [SiO_4H_4]_R = 0.16$$

whereas the lake's water has the following characteristics:

$$[HCO_3/CO_3]_L = 2.19,\ [SO_4]_L = 2.64,\ [Cl]_L = 7.11,\ [Na]_L = 7.78$$
$$[K]_L = 0.395,\ [Ca]_L = 1.63,\ [Mg]_L = 1.44,\ [SiO_4H_4]_L = 0.03$$

It can thus be seen that the Na concentration increases by a factor of 4.7 in the lake and that of Ca by 1.7, whereas the dissolved silica concentration decreases by a factor of 5.3.

To understand these changes in the concentrations of each of the dissolved ions in the lake the values of the fluxes at the boundaries of the lake have to be evaluated for each ion. These fluxes include those associated with water currents (river inflows and outflows, infiltration, etc.) and fluxes associated with bio-geochemical reactions. These fluxes vary in both space and time, leading to local spatial heterogeneity and temporal fluctuations.

For this reason two approximations have been made:

- to reduce the spatial variation, the lake has been divided into two environments of lower heterogenity, the Lago Mayor and Lago Menor, which are very distinct entities (identified as LM and Lm, respectively),
- by considering a long time period, the hydrochemical conditions in the lake vary around a mean state since the inputs and outputs of dissolved salts approximately balance.

We have chosen the longest time period possible in relation to the available data, i.e. 1964–1978 to establish a mean annual balance for each of the dissolved ions.

The mean annual composition of the inflow rivers was calculated from data covering the period 1976–79. The mean input of dissolved salts was calculated from this composition and values for the mean annual volumes of water covering the period 1964–79. The salt regulation figures derived from these data are certainly more representative than those that would have been obtained using just the 1976–79 data.

The terms of the annual balance are as follows:

- for the lake as a whole: $(i)_F = (i)_I + (i)_S + (i)_D + \delta(i)^L$
- for the LM: $(i)_F^{LM} = (i)_I^{LM} + (i)_S{}^{LM} + (i)_T + \delta(i)^{LM}$
- for the Lm: $(i)_F^{Lm} + (i)_T = (i)_I^{Lm} + (i)_S^{Lm} + (i)_D + \delta(i)^{Lm}$

Where $(i)_F$, $(i)_F^{LM}$ and $(i)_F^{Lm}$ are the river inputs of ions into the lake, LM and Lm, respectively; $(i)_I$, $(i)_I^{LM}$ and $(i)_I^{Lm}$ are the losses of i by infiltration from the lake, LM and Lm; $(i)_S$, $(i)_S^{LM}$ and $(i)_S^{Lm}$ are the losses by sedimentation from the lake, LM and Lm; $(i)_D$ the losses of i via the Desaguadero; $(i)_T$ the quantity of i passing from Lm to Lm via the Tiquina strait and $\delta(i)^L$, $\delta(i)^{LM}$ and $\delta(i)^{Lm}$ are variations in the reserve of i in the lake, the Lm and Lm.

Inputs of dissolved salts by the rivers

To calculate the mean annual inputs of dissolved salts into the lake, the mean annual composition of the waters in each hydrological area was first calculated. Then these were weighted in relation to the mean discharges of each river (Carmouze and Aquize Jaen 1981) (Table 1).

The absence of data for some rivers forced us to make the following approximations:

- water draining in along the Huancane shoreline was assumed to have the same chemical composition as the waters of the Río Huancane;
- water draining in along the Arapa-Capachica shoreline was assumed to have the same chemical composition as the waters of the Río Ramis;
- water draining in along the shoreline between Puno and Tiquina was assumed to have a chemical composition intermediate between those of the waters of the Río Zapatilla and those of sampling point 8 (Fig. 1);
- water draining in along the Desaguadero-Guaqui shoreline was assumed to have a chemical composition intermediate between that of the Río Challa Jahuira and Río Chilla;
- water draining in along the Taraco shoreline was assumed to have the same chemical composition as the waters of the Río Tiwanaku;
- water draining in along the Wuatajata Tiquina shoreline was assumed to have the same chemical composition as the waters of the Río Batallas Chicas;
- water draining in along the Tiquina-Achacachi-Escoma shoreline was assumed to have the same chemical composition as the waters of the Río Keka.

The mean annual inputs to the whole lake, the Lago Mayor (LM) and Lago Menor (Lm) were than calculated for the period 1964–1978 using the mean annual volumes of water discharged by the rivers over the period 1964 and 1978 (moles × 10^9):

$(HCO_3)_F^L = 11.04$, $(SO_4)_F^L = 6.43$, $(Cl)_F^L = 12.69$, $(Na)_F^L = 13.93$
$(K)_F^L = 0.90$, $(Ca)_F^L = 8.23$, $(Mg)_F^L = 2.84$, $(SiO_4H_4)_F^L = 1.37$

$(HCO_3)_F^{LM} = 9.50$, $(SO_4)_F^{LM} = 5.167$, $(Cl)_F^{LM} = 11.23$, $(Na)_F^{LM} = 12.20$
$(K)_F^{LM} = 0.74$, $(Ca)_F^{LM} = 6.88$, $(Mg)_F^{LM} = 2.38$, $(SiO_4H_4)_F^{LM} = 1.20$

$(HCO_3)_F^{Lm} = 1.54$, $(SO_4)_F^{Lm} = 1.26$, $(Cl)_F^{Lm} = 1.46$, $(Na)_F^{Lm} = 1.72$
$(K)_F^{Lm} = 0.15$, $(Ca)_F^{Lm} = 1.35$, $(Mg)_F^{Lm} = 0.47$, $(SiO_4H_4)_F^{Lm} = 0.17$

The Lagor Mayor therefore receives on average nearly 85% of the total inputs of dissolved salts as against only 15 % for the Lago Menor.

Losses of dissolved salts by the desaguadero

Hydrological studies of the lake (see Chapter IV.1) have shown that the Desaguadero can become an inflow river in January and February in certain years. The waters which enter the lake through the Desaguadero have a chemical composition similar to that of the lake itself in neighbouring areas, since it is water of lacustrine origin stored in the adjacent flood plain that is forced back into the lake.

The net losses of dissolved salt by the Desaguadero can therefore be calculated with satisfactory precision by using the mean chemical composition of the lake water in the proximity of the Desaguadero (see Table 2) and the mean annual net volume of water flowing out over the period 1964–1978, i.e. 0.217×10^9 m^3.

The net losses in moles × 10^9 are as follows:

$(HCO_3/CO_3)_D = 0.415$, $(SO_4)_D = 0.575$, $(Cl)_D = 1.725$, $(Na)_D = 1.855$
$(K)_D = 0.095$, $(Ca)_D = 0.33$, $(Mg)_D = 0.325$, $(SiO_4H_4)_D = 0.004$

It should be noted that the mean annual input from rivers over the period 1964 to 1978 amounts 46.5 × 10^9 moles, whereas the losses from the outflow river only amount to 5.3 × 10^9 moles. The Desaguadero therefore only evacuates 11.4% of the riverine inputs, the rest being eliminated by infiltration, biogeochemical sedimentation or stored in the lake.

Table 2. Chemical composition of the waters of the whole lake $[i]^{L}$, the Lago Mayor $[i]^{LM}$, Lago Menor $[i]^{L}$m and Desaguadero $[i]^{D}$ in mmol l^{-1}. Changes in the mean annual salt reserves from 1964 to 1978 in the whole lake $\delta(i)^{I}$, the Lago Mayor $\delta(i)^{LM}$ and the Lago Menor $\delta(i)^{Lm}$ in moles × 10^9. Transport of dissolved salts through the Tiquina strait $(i)^{1}$, in moles 10^9 year^{-1}.

$M \times 10^3$	$(i)^{L}$ $M \times 10^3$	$(i)^{L}_{A}$ %	R^{I} Years	T^{L} $M \times 10^3$	$(i)^{LM}_{A}$ $M \times 10^3$	$(i)^{LM}$ %	R^{LM} Years	T^{LM} $M \times 10^3$	$(i)^{Lm}$ $M \times 10^3$	$(i)^{Lm}_{A}$ %	R^{Lm} Years	T^{Lm}
HCO_2/CO_3	1964	11.60	0.59	169	1940	9.66	0.49	200	24	1.57	6.5	1
So^{+}	2365	6.65	0.28	355	2330	5.36	0.23	435	35	1.30	3.7	27
Cl	6370	13.30	0.21	479	6275	11.73	0.19	537	95	1.57	1.6	60
Na	6970	14.60	0.21	382	6865	12.78	0.19	537	105	1.84	1.7	57
K	355	0.93	0.26	174	348	0.77	0.22	452	5.5	0.15	2.7	37
Ca	1460	8.37	0.57	435	1441	7.00	0.48	206	19	1.37	7.2	14
Mg	1290	2.97	0.23	20	1271	2.49	0.20	510	19	0.49	2.6	39
SiO_4H_4	27	1.37	5.1		7.35	1.20	0.16	6	0.10	0.17	170	0.6

Losses by infiltration

We assume that infiltrating water has a mean chemical composition similar to the water of the lake itself (Table 2). The mean volume of water infiltrating has been estimated from the Cl balance (Carmouze and Aquize Jaen, 1981). This volume is equal to 1.36 × 10^9 m^3 $year^{-1}$ for the whole lake, 0.93 × 10^9 m^3 $year^{-1}$ for the LM and 0.44 × 10^9 m^3 $year^{-1}$ for the Lm, which give the following losses in 10^9 moles for the whole lake $(i)^L$, the LM $(i)^{LM}$ and Lm $(i)^{Lm}$:

$(HCO_3/CO_3)_I^L = 2.985$, $(SO_4)_I^L = 3.595$, $(Cl)_I^L = 9.68$, $(Na)_I^L = 10.59$

$(K)_I^L = 0.54$, $(Ca)_I^L = 2.22$, $(Mg)_I^L = 1.96$, $(SiO_4H_4)_I^L = 0.041$

$(HCO_3/CO_3)_I^{LM} = 2.035$, $(SO_4)_I^{LM} = 2.43$, $(Cl)_I^{LM} = 6.53$, $(Na)_I^{LM} = 7.139$

$(K)_I^{LM} = 0.36$, $(Ca)_I^{LM} = 1.510$, $(Mg)_I^{LM} = 1.325$, $(SiO_4H_4)_I^{LM} = 0.022$

$(HCO_3/CO_3)_I^{Lm} = 0.825$, $(SO_4)_I^{Lm} = 1.175$, $(Cl)_I^{Lm} = 3.190$, $(Na = 3.530$

$(K)_I^{Lm} = 0.180$, $(Ca)_I^{Lm} = 0.645$, $(Mg)_I^{Lm} = 0.640$, $(SiO_4H_4)_I^{Lm} = 0.013$

Overall, infiltration eliminates 40% of the dissolved salts brought in by the rivers. It accounts for 56% of the losses of Na and Cl, 43% of the loss of K, 40% of the loss of SO_4, 34% of the loss of Mg, 20% of the losses of HCO_3/CO_3 and Ca and scarcely 2% of the losses of SiO_4H_4.

Losses by biogeochemical sedimentation

These are obtained by subtraction using the balance equations:
- for the lake as a whole: $(i)_S^L = (i)_F^L - (i)_I^L - \delta(i)^L$
- for the LM: $(i)_S^{LM} = (i)_F^{LM} - (i)_I^{LM} - (i)_T - \delta(i)^{LM}$
- for the Lm: $(i)_S^{Lm} = (i)_F^{Lm} + (i)_T = (i)_I^{Lm}\ (i)_D + \delta(i)^{Lm}$

The values of $(i)_T$, $(i)^L$, $(i)^{LM}$ and $(i)^{Lm}$ must first be calculated. The quantity of salts passing through the Tiquina strait is equal to $(i)_T = (v)_T \times [i]^{GL}$, where $(v)_T$ = the volume of water flowing through Tiquina = 0.515 m^3 × 10^9 $year^{-1}$ (Carmouze and Aquize Jaen, 1981). The results are given in Table 2.

The variations of the reserves of i in the lake, LM and Lm are: $\delta(i)^L = \delta\ (v)^L \times [i]^L$, $\delta(i)^L = \delta\ (v)^{LM} \times [i]^{LM}$ and $\delta(i)^{Lm} = \delta(v)^{Lm} \times [i]^{Lm}$, respectively. $\delta\ (v)^L$, $\delta\ (v)^{LM}$ and $\delta(v)^{Lm}$ which represent the changes in the volume of the entire lake, the Lm and Lm are equal to 0.18, 0.15 and 0.03 × 10^9 m^3, respectively (results in Table 2).

It is therefore possible to calculate $(i)^L_S$, $(i)^{LM}_S$ and $(i)^{Lm}_S$; the results, expressed in moles × 10^9, are as follows:

$(HCO_3/CO_3)^L_S = 7.245$, $(SO_4)^L_S = 1.785$, $(Cl)^L_S = 0.0$, $(Na)^L_S = 0.04$
$(K)^L_S = 0.195$, $(Ca)^L_S = 5.385$, $(Mg)^L_S = 0.295$, $(SiO_4H_4)^L_S = 1.32$

$(HCO_3/CO_3)^{LM}_S = 6.00$, $(SO_4)^{LM}_S = 0.98$, $(Cl)^{LM}_S = 0.0$, $(Na)^{LM}_S$
$= 0.0$
$(K)^{LM}_S = 0.12$, $(Ca)^{LM}_S = 4.28$, $(Mg)^{LM}_S = 0.10$, $(SiO_4H_4)^{LM}_S = 1.15$

$(HCO_3/CO_3)^{Lm}_S = 1.38$, $(SO_4)^{Lm}_S = 0.785$, $(Cl)^{Lm}_S = 0.0$, $(Na)^{Lm}_S$
$= 0.08$
$(K)^{Lm}_S = 0.065$, $(Ca)^{Lm}_S = 1.17$, $(Mg)^{Lm}_S = 0.20$, $(SiO_4H_4)^{Lm}_S = 0.15$

It is assumed that Cl is not sedimented. The sedimentation values given for Na are not significant taking into account the uncertainties in the terms in the balance equation. The losses by sedimentation of HCO_3/CO_3, SO_4, K, Ca, Mg and SiO_4H_4 are 65.6%, 27.7%, 21.6%, 67.8%, 10.2% and 96.3% of the river input, respectively. Sedimentation of SiO_4H_4, HCO_3/CO_3, Ca, K and SO_4 is 7.7, 5.3, 4.6, 2.9 and 2.25 times greater in the LM than in the Lm, respectively, but that of Mg is twice as great in the Lm than in the LM.

Overall, losses by sedimentation represented 28.5% of the river input between 1964 and 1978, 77.5% occurring in the LM and 25% in the Lm.

The partial removal of SiO_4H_4 in the lake is to a great extent due to use of silica by diatoms and the removal of HCO_3 and Ca is mainly due to the precipitation of calcium carbonate (Carmouze and Miranda, 1978; Boulangé *et al.*, 1981). SO_4 is partially reduced under reducing conditions. K and Mg are taken up by macrophytes and it should be noted that the sedimentation of Mg was greater in the Lm than in the LM where macrophyte development is less extensive.

Although they were calculated separately, the sum of the balances for the LM and Lm is close to the balance for the lake as a whole.

The stocks of dissolved salts in the lake and their turnover rate and retention time

The stocks of dissolved salts in the lake are continually being renewed, their annual turnover rate being equal to the quantities of salts brought in $(i)_A$ or eliminated $(i)_P$ each year divided by the corresponding stocks (i). The inverse of this value, T, is the mean retention time of the dissolved substance in the lake; it is another way of giving an idea of the time taken for matter to circulate through the environment.

The calculation is simple

- For the whole lake $(i)^L = (v)^L \times [i]^L$; $R^L_i = (i)^L_A/(i)^L = (i)^L_P/(i)^L$; $T^L_i = 1/R^L_i$

Table 3. Stocks of dissolved salts (i), mean annual inputs or losses $(i)^{\wedge}$, annual turnover rate of the stocks R^i and retention time T^i in the whole lake, LM and Lm. (from Carmouze *et al.*, 1981).

	HCO_3/CO_3	SO_4	Cl	Na	K	Ca	Mg	SiO_4H_4
$(i)^L$	1964	2365	6370	6970	355	1460	1290	27
$(i)^L_A$	11.60	6.65	13.30	14.60	0.93	8.37	2.97	1.37
R^L (%)	0.59	0.28	0.21	0.21	0.26	0.57	0.23	5.10
T^L (Years)	169	355	479	479	382	174	435	20
$(i)^{LM}$	1940	2330	6275	6865	348	1441	1271	20
$(i)^{LM}_A$	9.66	5.36	11.73	12.78	0.77	7.00	2.49	1.20
R^{LM}	0.49	0.23	0.19	0.19	0.22	0.48	0.20	0.16
T^{LM}	200	435	537	537	452	206	510	6
$(i)^{Lm}$	24	35	95	105	5.5	19	19	0.10
$(i)^{Lm}_A$	1.57	1.30	1.57	1.84	0.15	1.37	0.49	0.17
R^{Lm}	6.5	3.7	1.6	1.7	2.7	7.2	2.6	170
T^{Lm}	15	27	60	57	37	14	39	0.6

- For the LM $(i)^{LM} = (v)^{LM} \times [i]^{LM}$; $R_i^{LM} = (i)_A^{LM}/(i)^{LM} = (i)_P^{LM}/(i)^{LM}$; $T_i^{LM} = 1/R_i^{LM}$
- For the Lm $(i)^{Lm} = (v)^{Lm} \times [i]^{Lm}$; $R_i^{Lm} = (i)_A^{Lm}/(i)^{Lm} = (i)_P^{Lm}/(i)^{Lm}$; $T_i^{Lm} = 1/R_i^{Lm}$

The results are given in Table 3. Over the period in question $(i)_A^A$ was slightly greater than a $(i)_P$, so an intermediate value was used in the calculations.

The mean annual turnover rates of dissolved salts are low in the LM, with the exception of SiO_4H_4. They vary between 0.5 and 0.2% for all dissolved ions, except for SiO_4H_4 for which it is 16%. These rates are about 10–12 times higher in the Lm. In other terms, the retention time for a substance is 10–12 times shorter in the Lm than in the LM, being 30 years on average for the Lm and 350 years in the LM.

Fluctuations in the chemical composition of the water between years

Comparison between the data on the chemical composition of the waters of Lake Titicaca obtained from the beginning of the century by the workers cited in the introduction and those of the present day shows that there are no significant differences, if allowance is made for the different methods of analysis used. In other words, the major changes in water level of the lake have hardly affected the chemical composition of the water. This can be verified by a rough calculation and a comparison between analyses made at a time of low water level (1971) and high water level (1978), compared to a normal situation (1967).

(*a*) *Low water level*

From 1967 to 1971 the volume of the lake fell from 896 × 10^9 m^3 to 887 × 10^9 m^3. The stocks of dissolved salts decreased by a quantity approximately equal to the product of the deficit in river discharge, i.e. 4.5 × 10^9 m^3 and the mean chemical composition of the river waters.

Stocks of dissolved salts at low water level $(i)_d$ in moles × 10^3:

$(HCO_3/CO_3)_d = 1958$, $(SO_4)_d = 2360$, $(Cl)_d = 6359$, $(Na)_d = 6958$,
$(K)_d = 354$, $(Ca)_d = 1455$, $(Mg)_d = 1288$, $(SiO_4H_4)_d = 26.27$

The corresponding concentration in mmol:

$[HCO_3/CO_3]_d = 2.21$, $[SO_4]_d = 2.26$, $[Cl]_d = 7.17$, $[Na]_d = 7.84$
$[K]_d = 0.40$, $[Ca]_d = 1.64$, $[Mg]_d = 1.45$, $[SiO_4H_4]_d = 0.029$

(*b*) *At high water level*

From 1967 to 1978 the volume increased from 896 × 10^9 m^3 to 904 × 10^9 m^3. River discharge had an excess of 4.0 × 10^9 m^3.

Stocks of dissolved salts at high water level $(i)_c$ in moles × 10^3:

$(HCO_3/CO_3)_c = 1970$, $(SO_4)_c = 2369$, $(Cl)_c = 6380$, $(Na)_c = 6980$,
$(K)_c = 356$, $(Ca)_c = 1464$, $(Mg)_c = 1292$, $(SiO_4H_4)_c = 27.65$

The corresponding concentration in mmol:

$[HCO_3/CO_3]_c = 2.18$, $[SO_4]_c = 2.62$, $[Cl]_c = 7.06$, $[Na]_c = 7.72$
$[K]_c = 0.393$, $[Ca]_c = 1.62$, $[Mg]_c = 1.43$, $[SiO_4H_4]_c = 0.035$

From these results it can be seen that the chemical composition of the water varies little between periods of high and low water level, at least in the LM. The changes in concentration do not exceed 2%. In the Lm, however, judging just from the change in volume of water, these must reach 10–15%.

Conclusions

The total dissolved salt contents of the rivers flowing into Lake Titicaca are usually between 5 and 10 mmol l^{-1}. These are relatively high values compared to the mean value of 2 mmol l^{-1} given for inland waters by Meybeck (1979). They reflect heavy chemical erosion.

Most of the water originates from volcanic and sedimentary formations and has total dissolved salt contents of between 5 and 20 mmol l^{-1}, with strong seasonal variations. Concentrations can be three times higher at low water than during floods, but no one chemical ion dominates. HCO_3 SO_4 and Cl are present in roughly equal proportions. Nevertheless, at low water or at the start of the rainy season chloride and sodium may dominate due to a clear enrichment in sodium chloride in the lower reaches of the rivers.

Water coming directly off the Eastern Cordillera is less mineralised (less than 5 mmol l^{-1}). The dominance of bicarbonates, calcium and sodium is characteristic of chemical erosion of crystalline rocks.

The hydrological regime of the lake is such that the dissolved salts in the river waters should on average be enriched by a factor of 4.7. This is true for Na and Cl, but for other dissolved ions this factor is lower because of chemical sedimentation. This mainly affects dissolved silica (used by diatoms), bicarbonate, carbonate and calcium (precipitated as $CaCO_3$), and to a lesser extent sulphate (reduction in deep stratified water), potassium and magnesium (uptake by macrophytes).

Overall, sedimentation losses amounted to 28.5% of the riverine inputs between 1964 and 1978. 77.5% of this sedimentation occurred in the Lago Mayor and 22.5% in the Lago Menor. Losses by infiltration amounted to 40% of the riverine input: 68% in the Lago Mayor and 32% in the Lago Menor. The Desagaudero only removed 11.4% of the riverine inputs.

The annual turnover of the stocks of dissolved salts is very low in the Lago Mayor; for the major ions it varies between 0.20 % (Na and Cl) and 0.50% (Ca and HCO_3). It is much higher in the where it varies between 1.6–1.7% (Na and Cl) and 6.5–7.2% (Ca and HCO_3).

As a consequence Lake Titicaca is a very stable environment. Irregularities in the inputs of water and dissolved salts do not change the composition of its waters to any notable extent, at least in the Lago Mayor.

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