IV. CLIMATOLOGY AND HYDROLOGY
IV.1. Climatology and hydrology of the Lake Titicaca basin

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Two separate active hydrological systems are present within the endorheic basin of the Altiplano: (i) Lake Titicaca (3809.5 m altitude) which overflows via the Río Desaguadero into Lake Poopo (3686 m), which itself overflows into the Salar de Coipasa (3657 m) during periods of high water level. (ii) The Salar de Uyuni (3653 m) into which flows the Río Grande of the Lipez (Fig. 1). These two systems can communicate with one another, but only at water levels higher than those recorded in 1986. At the present day Lake Titicaca is the only large and truly perennial surface water body.

The total area of the Lake Titicaca basin, to the offtake of the Desaguadero and including the area of open water, is 57,500 km^2, a quarter lying in Bolivia and three-quarters in Peru.

The catchment area covers 49,010 km^2, or 85% of the total basin, 1/5 being in Bolivia and 4/5 in Peru. Three-quarters of the catchment area is drained by six rivers (Table 1): The Rios Ramis (31%), Ilave (15%), Coata (11%), Catari (7%), Huancane (7%) and Suchez (6%).

4% of the basin lies at an altitude of between 5000 and 6400 m. The plain of the Altiplano makes up 28%, whereas the lake itself covers 15% of the area. The average gradient of the inflow rivers can vary from 35 m km^{-1} in the upper parts of the basin to 0.8 m km^{-1} in the lower reaches. The main water courses are between 120 and 180 km long, but the Río Ramis measures 283 km long.

The lake shoreline is 915 km long. If it is assumed that the maximum inter-annual fluctuation in lake size is ± 200 m from the mean position of the shoreline around all its perimeter, this corresponds, over a total area of 8490 km^2, to a change in area of ± 2.0% for the period 1968–1987. Because this figure lacks accuracy and calibration, this correction has not been applied to the hydrological calculations on the lake.

Functioning and hydrological balance of Lake Titicaca

In addition to an annual fluctuation in level, Lake Titicaca also undergoes

C. Dejoux and A. Iltis (eds.), Lake Titicaca, 63–88.

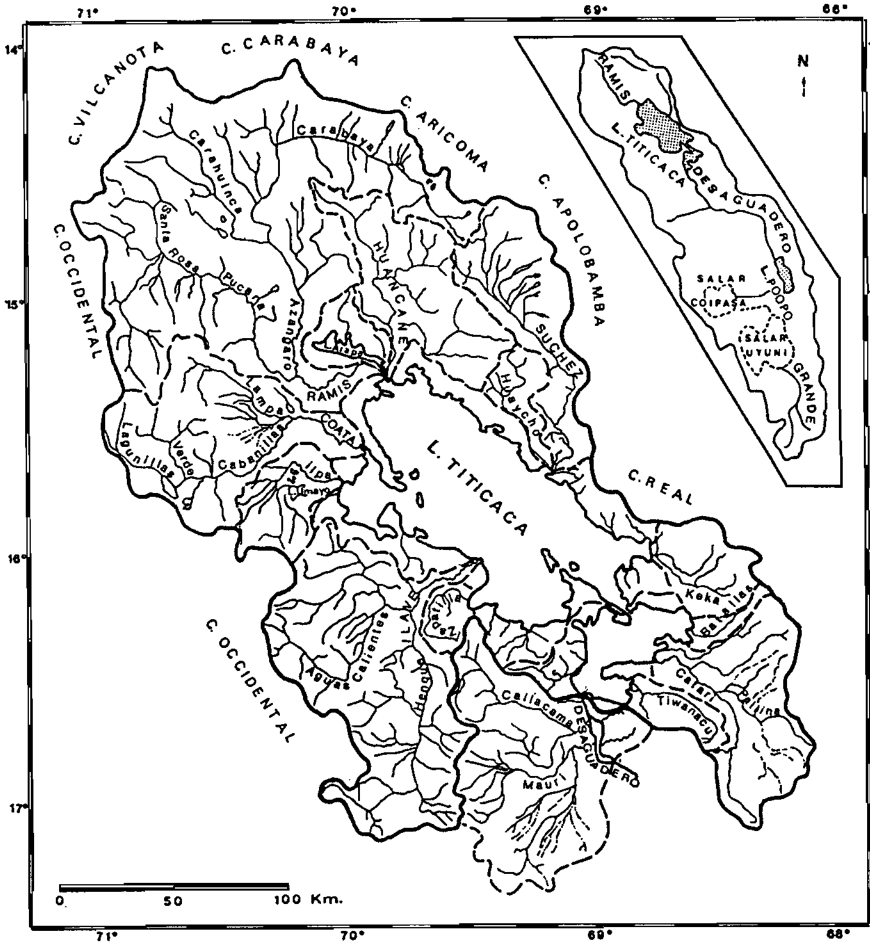

Figure 1. Hydrological systems of the Bolivian-Peruvian Altiplano. Hydrography of the Lake Titicaca basin.

changes in level of a time-scale of several years. Since 1914, the range of variation has been 6.37 metres.

Lake Titicaca is fed by inflows from the surrounding rivers around its margins and by rain falling directly onto the lake. Losses are due to evaporation and surface drainage leaving via the Desaguadero. Certain authors (Carmouze, 1981; Lozada, 1985) believe there is infiltration of water through the lake bed, which contributes to the removal of dissolved salts, in addition to removal by surface outflow via the Río Desaguadero and physico-chemical and biochemical sedimentation within the lake itself. However, the water table along the shorelines lies above the level of the open water (Guyot *et al.*, 1990) and the aquifer contributes to the lake inflows.

Variations between years in precipitation and evaporation in the basin determine the water level of the lake. Water losses are also regulated by topographical sills occurring between the start of the Río Desaguadero (at Puente Internacional) and the downstream end of a broad section of the river known as the Laguna Lucuchala, extending some 30 km from the lake (to Aguallamaya). At the exit from the lake, the cross-section of the outlet forms a V-shaped sill whose bottom lies at an altitude of about 3803 m. This does not always form the sill controlling the outflow of water, which can be further downstream. The water flowing out of the lake flows south along the course of the Desaguadero which also receives water from other catchments on the Altiplano. The hydrological system of sills and water levels which controls the outflow of water from the lake therefore seems to be complex, especially at periods of low water level.

If inputs from rainfall and rivers make the level of the Laguna Lucuchala rise more quickly than that of the lake, water can flow out from both ends of the lagoon: southwards down the Desaguadero and northwards towards the lake. This supply of water to the lake will continue until the level of the lake reestablishes a new equilibrium. The current is then reversed and the Desaguadero regains its normal course. It should be stressed that this current reversal is a rare and transient phenomenon, only involving relatively small volumes of water in terms of mean values and overall lake balance.

The hydrological balance of Lake Titicaca can be expressed as:

$$P + Qt + Qn = Qd + Qi + Qe + dH$$

where:

P = Precipitation on the lake,

Qt = Inflows to the lake from rivers $Qt = Pt - Et - Qef + n$,

where

Pt: is the precipitation on the inflow catchments,

Et: true evapo-transpiration,

Qef: any artificial exports out of the catchment, via water courses,

n: changes in the quantity of water stored in the aquifer, whose value can be positive or negative

Qn = Inflows to the lake from aquifers,

E = Evaporation from the lake surface,

Qd = Surface losses via the outflow, the Río Desaguadero,

Qi = Infiltration through the lake bed, if such exists,

dH = Changes in lake storage, whose value can be positive or negative.

The climate of Lake Titicaca basin

All the data used for both climatic and hydrological calculations are derived from records collected by the National Hydrology and Meteorology Services (SENAMHI) of La Paz and Puno.

Air temperatures

Mean annual temperatures

In areas lying below 4000 m altitude, the mean annual temperatures are between 7 and 10°C. Around the lake itself, however, they remain above 8°C. Boulangé and Aquize (1981) calculated that the mean annual temperature in the area of the lake should be 0°C and attributed the temperature difference to the thermal effects of the water body. The map of mean annual temperatures for Bolivia (Roche *et al.*, 1990) also shows values of close to 8°C over all the eastern half of the Bolivian Altiplano (7.3°C at Uyuni) and over Lake Poopo which has less thermal influence. The temperatures at stations lying between 3900 and 4000 m in the extreme south and north of the lake region are also of the order of 7°C. The lake makes the climate more temperate by decreasing the temperature range, but it does not seem to cause an increase of mean annual temperature of more than 2°C around its margins.

The isotherm map of the basin (Fig. 2) has been drawn using a correlation between temperature and altitude. Data from some stations outside the basin have also been used in order to obtain as wide a range of altitude as possible. The temperature gradient is 0.76°C 100 m^{-1}. For the area lying between 3800 and 4000 m, the temperature dispersion is great because of the effects of slope, shelter and distance from the lake. On the high peaks forming the margins of the basin, the mean annual temperature falls to below zero at around 5100 m.

Over the entire basin, the lowest temperatures occur in July, in the winter, whereas the highest temperatures occur between December and March, frequently being centred on February (Fig. 2).

Mean maximum and minimum temperature and temperature range

Figure 2 shows the changes in mean, maximum and minimum monthly temperatures and thus the temperature range over the course of the year for various stations in the basin.

The lowest mean minimum monthly temperature occurs in July. Values of 1.8°C are recorded at Copacabana (3810 m, on the lake shore) and −11.8°C at Charaña (4069 m, very far from the lake).

The mean maximum monthly temperatures for these stations are 15.3°C and 3.6°C, respectively. These occur in October or November when cloud cover is less than at the height of summer, when maximum rainfall occurs. For the same reason a second peak is recorded in March-April. In contrast the minimum temperature occurs in mid-winter since this takes place at end of night and therefore does not depend on the amount of sunshine.

Temperature range increases with distance from the lake, being 10.7°C on the shoreline.

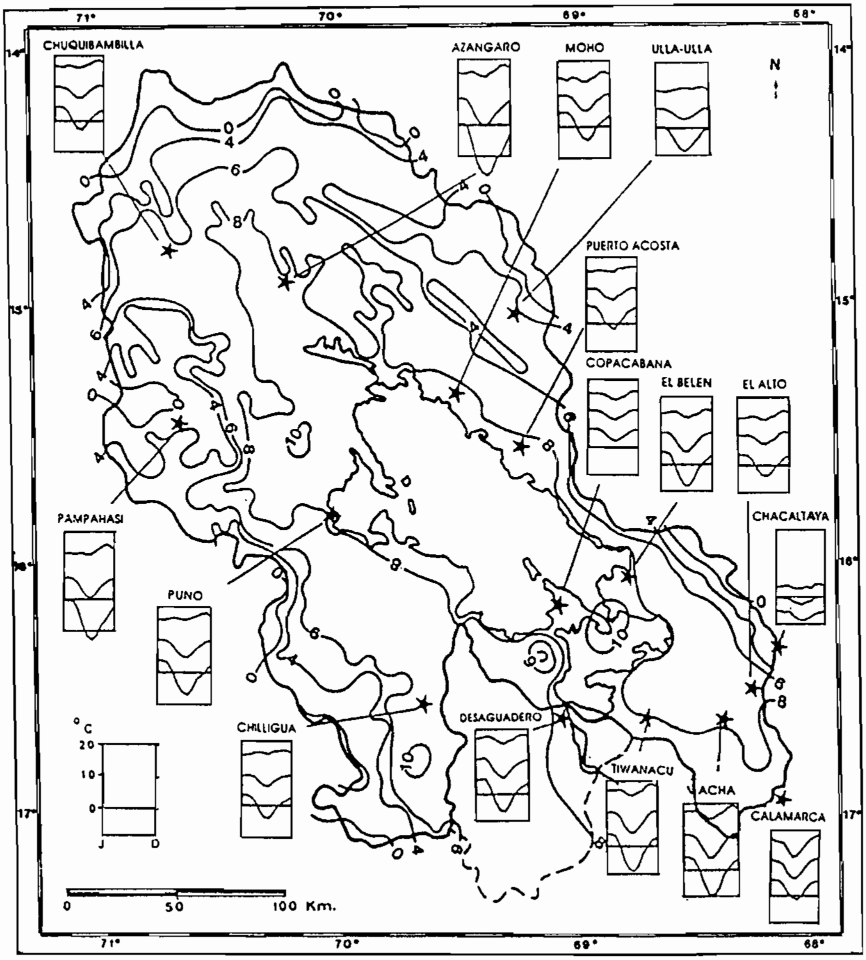

Figure 2. Map of mean annual temperatures (°C) in the Lake Titicaca basin. Seasonal changes in average monthly mean and maximum temperatures, January to December.

Relative humidity

The mean annual relative humidity around the lake varies between 50 and 65%, at temperatures of 8 to 10°C. Lower values of 50 to 45% are recorded in the south of the basin. As a general rule, humidity increases with altitude, with a maximum value of 83% at Chacaltaya (5200 m). Variation over the year follows the rainfall pattern, with a maximum in January or February and a minimum in July. The values at Copocabana for these two periods are 70% and 52%, respectively.

Sunshine duration

The annual sunshine duration near to the lake is 2915 h yr^{-1} at Belen and 3000 h yr^{-1} at Puno. Monthly minima of 167 and 180 h respectively are recorded at these two stations in January or February, during the height of the rainy season, whereas the maximum monthly values of 298 and 296 h occur in the middle of winter. The mean value for total solar luminous flux measured on the Altiplano at Viacha and Patacamaya is 8.8 mm day^{-1} (Vacher *et al.*, 1989).

Winds

The dominant winds, usually of moderate strength and often affected by local breezes, are from the north-east in the rainy season and from the west to south-west the rest of the year.

Precipitation

All the rainfall data has been homogenised on a monthly and annual basis by a spatio-temporal vector method (VECSPAT, CLIMAR2 computer program); this is a matrix calculation based on pseudo-proportionality of the data (Hiez, 1972; Roche, 1988). This method provides automatic data processing and allows missing values to be estimated or entirely calculated.

The period subject to homogenisation and used to draw up the hydrological balance is 1968–1987; there were very few meteorological stations before 1968.

Spatial distribution of precipitation and rainfall mechanisms

The map of mean isohyetes for the period in question shows the spatial distribution of precipitation (Fig. 3).

On the whole, isohyetes are concentric around the lake, in the centre of which the maximum rainfall of over 1000 mm is recorded. Rainfall tends to decrease with distance from the lake, falling to minimum values of 500 to 600 mm. It then increases again towards the summits of the Eastern Cordillera, where extreme values can exceed 800 mm and towards the west, as far as the summit of the Pecajes Caranjas chain where maximum values can exceed 1000 mm.

This spatial distribution is determined by the regional air circulation patterns, by the influence of orography and by the major body of water formed by the lake.

On occasions, and almost exclusively during the rainy season, humid

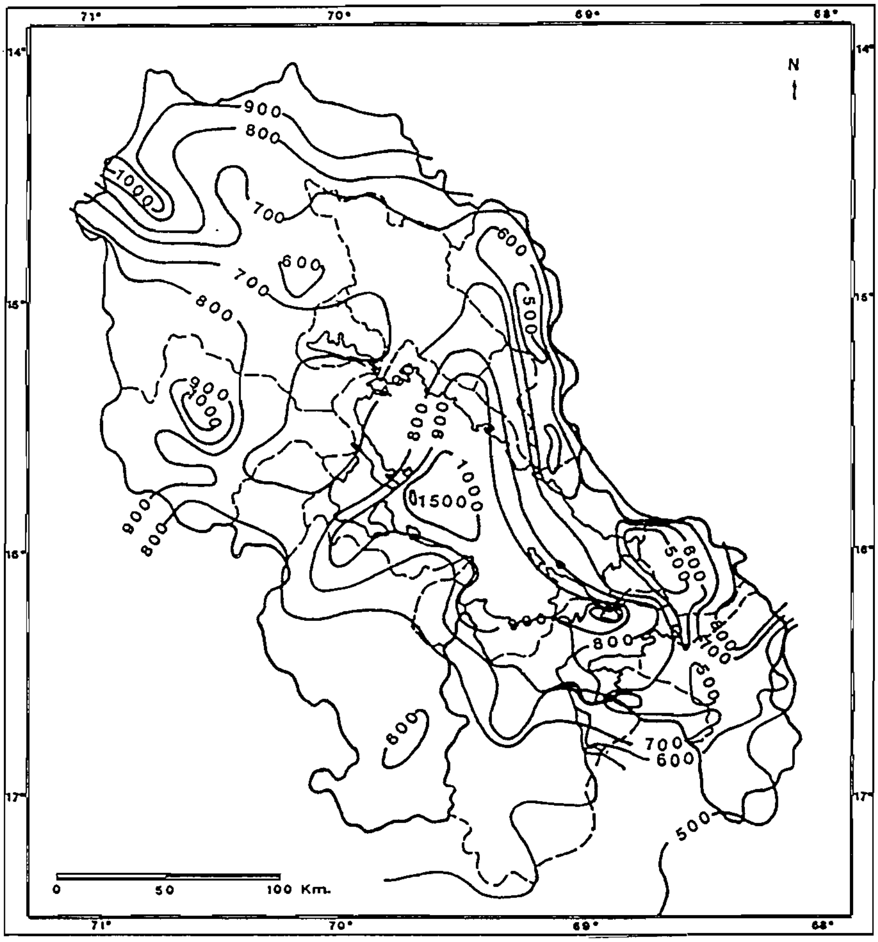

Figure 3. Mean annual precipitation (mm) for the Lake Titicaca basin (period 1968–1987).

Amazonian air spills over the peaks of the Eastern Cordillera which rise to between 4500 and 6400 m. The north-east trade winds thus bring considerable quantities of water into the hydrological system, although much smaller quantities fall on the Altiplano than on the Amazonian slopes. As the air descends towards the lake, its pressure and temperature increase, leading to a decrease in relative humidity and a decrease in rainfall.

The rain shadow effect produced by the highest summits is particularly noticeable. The humid Amazonian airmass frequently remains blocked behind the highest mountains but manages to pass over the lower crests around the rest of the basin. The area around Suchez, sheltered by the Cordillera Apolobamba rising to over 6000 m, is for example particularly dry. The lowest rainfall in the basin occurs to the south-west of Illampu and the Cordillera Apolobamba, where Escoma has only 507 mm and Belen 452 mm.

The influence of the lake is due to its extremely large surface area and its large volume caused by its depth. Its strong capacity to absorb solar radiation leads to water temperatures that are significantly higher (10 to 14°C) than those of the surrounding air and land. The lake is therefore continuously giving out heat to its surroundings. Air passing over the lake is warmed and picks up water vapour at the same time. It is subject to strong convection, particularly during the night when the temperature difference is accentuated, leading to thunderstorms which are heavier over the lake than on the land. Rainfall over the lake is greater than 800 mm and can reach 1000 mm. The maximum recorded is on Taquili Island; but the value of 1535 mm, much higher than elsewhere in the basin, would appear to be excessive – the calculated value is only 1272 mm. The humid air from the Lago Grande can cross the Yunguyo-Copocabana isthmus or the Tiquina Strait into the Lago Huiñaimarca, so that rainfall is also high over the western part of this basin, such as at Desaguadero (797 mm) and Tiquina (1050 mm). In contrast, in the south-eastern parts of the lake, the NE winds are deviated by the Illampu massif or are affected by down-drafts along its western flank and do not cross or only partially cross the Lago Grande, so the south-eastern parts of both the Lago Grande and Lago Huiñaimarca are relatively dry.

Weighted mean precipitation over the catchment areas and on Lake Titicaca

The quantities of monthly, annual and long-term rainfall were calculated by computer, by weighting the rainfall recorded at each meteorological station by its area of influence (Thiessen polygons), over the 20 year period (1968–1987). These quantities were calculated for each of the 82 individual catchments and for the main grouped catchments, using homogenised data in which missing data had been estimated and using entirely calculated data. Only the former will be presented in detail.

The lowest long-term average rainfall in this data set was 585 mm yr^{-1} for the catchment of the Río Keka and the highest was 811 mm yr^{-1} for the Río Coata catchment and 889 mm yr^{-1} over the Lago Grande. The long-term mean precipitation for the main catchments are given in Table 1.

The average precipitation over the whole basin is 758 mm yr^{-1}, or a total volume of 43.6×10^9 m^3 yr^{-1}. The long-term average rainfall over the entire lake is 880 mm yr^{-1}, or a total volume of 7.47×10^9 m^3 yr^{-1}, equivalent to a discharge of 236.7 m^3 s^{-1}. The long-term average rainfall of the Lago Grande is 889 mm yr^{-1} and that of the drier Lago Huiñaimarca 829 mm yr^{-1}. In terms of volumes, these values (6.42 and 1.05×10^9 m^3 yr^{-1}) mean that 86% and 14% respectively of the total inputs to each of the two parts of the lake come from rainfall.

Table 1. Water balance of the catchments of rivers flowing into Lake Titicaca (1968–1987)

	AREAS km²	RAINFALLS mm	MODULE $m^3 s^{-1}$	$10^6 m^3$	%	mm	$l s^{-1} km^{-2}$	KE %	DE mm
Ramis*	15 060	795.4	78.1	2464.1	29.0	163.6	5.2	22.2	632
Coata*	4 650	885.5	46.6	1470.9	17.3	316.4	10.0	35.7	569
Ilave*	7 290	699.6	42.7	1346.2	15.8	184.8	5.9	26.4	515
Huancane*	3 580	714.4	20.8	655.7	7.7	183.3	5.8	25.7	531
Zapatilla*	440	823.2	2.3	71.3	0.9	161.7	5.2	19.6	661
Peruvian basin*	31 010	769.0	190.4	6007.3	70.6	193.7	6.1	25.2	575
Complement	18 000	628.4	79.3	2501.1	29.4	139.0	4.4	22.0	489
Total basin	49 010	736.2	269.7	8508.4	100.0	173.6	5.5	23.6	563

* observed

Rainfall in the Bolivian part of the catchment amounts to 664 mm yr^{-1}, of which 635 mm yr^{-1} falls on the land and 753 mm yr^{-1} on the Bolivian part of the lake. Similarly, the Peruvian part of the catchment receives 786 mm yr^{-1}, of which 762 mm yr^{-1} falls on the land and 964 mm yr^{-1} on the Peruvian part of the lake. Expressed in terms of volume these values are equivalent to 9.01×10^9 m^3 yr^{-1}, 6.48×10^9 m^3 yr^{-1} and 2.54×10^9 m^3 yr^{-1} for Bolivia and 34.5×10^9 m^3 yr^{-1}, 29.4×10^9 m^3 yr^{-1} and 4.94×10^9 m^3 yr^{-1} for Peru. It can thus be seen that the Bolivian and Peruvian parts of the lake receive 34% and 66% respectively of the quantity of rainfall falling directly on the water surface.

The five catchments in Peru for which the discharge is known, together have a mean long-term precipitation of 769 mm yr^{-1}, whereas the rest of the basin receives 682 mm yr^{-1}.

Seasonal distribution of precipitation

The rainy season is centred on January (Fig. 4). The rains usually start in December and end in March. The middle of the dry season, which lasts from May to August, is in June. Two transitional periods separate these seasons, one in April and the other from September to November. Figure 4 shows the monthly variation in long-term average rainfall for the main catchments. Depending on the individual catchment, 65 to 78% of the annual precipitation falls during the four months of the rainy season, but only 3 to 8% in the dry season. The two intermediate periods account for 18 to 29%. Over the entire dry land part of the catchment, these values are 70%, 5% and 25%, respectively. They are the same for the lake itself and therefore for the entire Lake Titicaca basin.

The maximum monthly rainfall recorded over the lake reaches values of 300 to 450 mm, depending on the station, with a weighted mean of 353 mm in January 1984, a particularly rainy month.

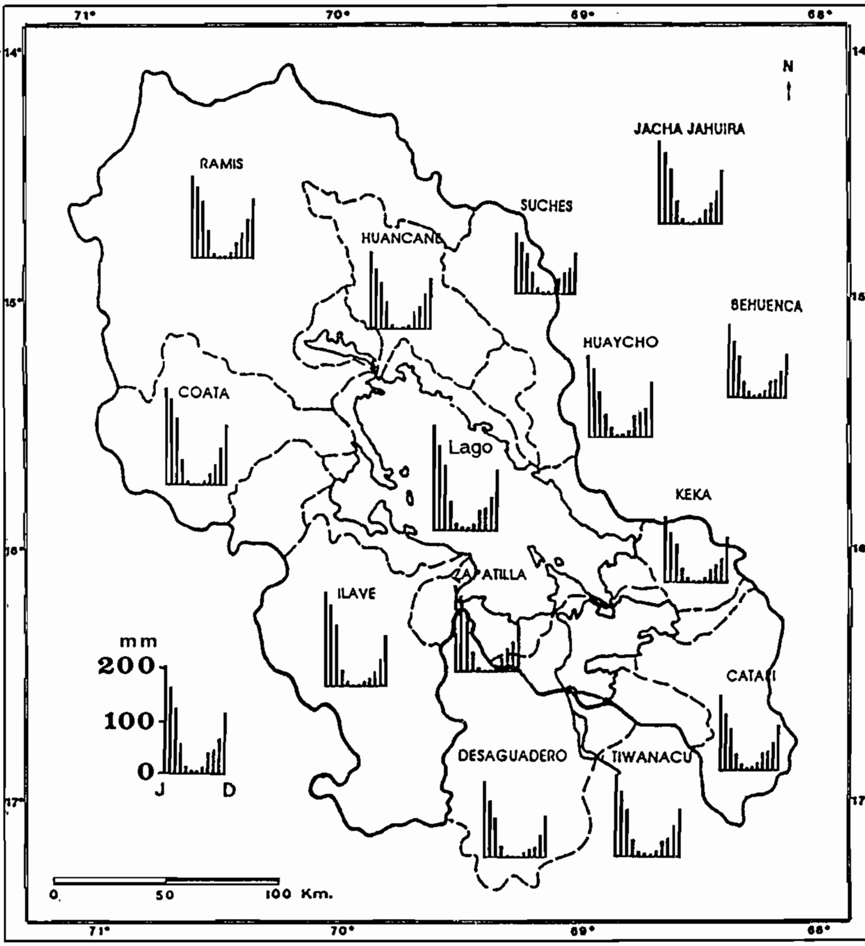

Figure 4. Monthly rainfall distribution in the Lake Titicaca basin (period 1968–1987).

Hydrology of the Lake Titicaca basin

The hydrology of Lake Titicaca, and particularly the inputs and outputs of its water balance, have been studied previously by several workers (Monheim, 1956; Bazoberry, 1968; Kessler, 1970; Richerson *et al.*, 1977 and Carmouze *et al.* 1977, 1982). The balance can produce very different results depending on the precision of the data, its processing and on the period taken into consideration.

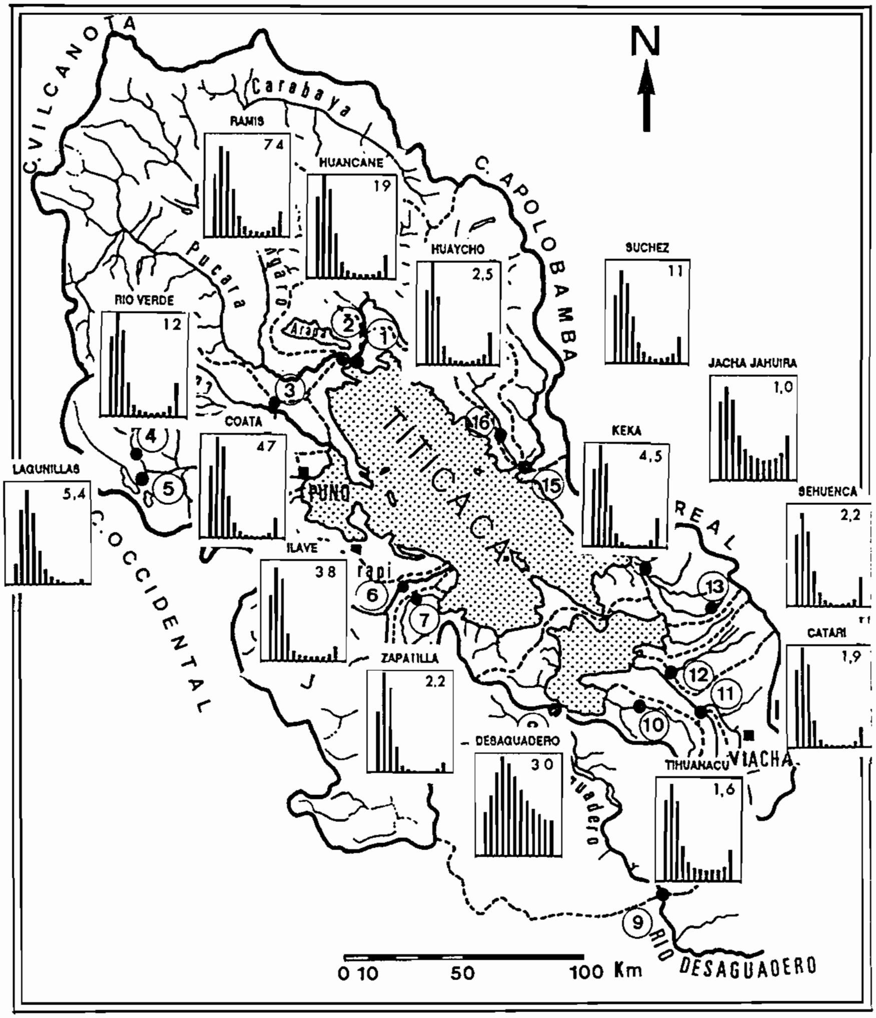

Figure 5. Map of the hydrographic network in the Lake Titicaca catchment and location of gauging stations. A histogram of the mean monthly discharge and the value for the mean annual discharge ($m^3\ s^{-1}$) calculated over the observation period is shown for each station.

Discharges of the inflow rivers

Spatial distribution of riverine inputs to the lake

Mean monthly discharges are available from seven gauging stations in Peru, five of them providing direct measurements of river inputs into the lake. These stations are on the Río Ramis, Río Ilave, Río Huancane at Puente Carretera, Río Coata at Maravillas and the Río Zapatilla at Puente Carretera (Fig. 5). The first four measure the discharges of the most important water courses of the system. Two stations within the Coata catchment are installed on the Río Lagunillas at Lagunillas and on the Río Verde at Verde. The proportion of the catchments gauged in comparison to the total catchment area in Peru is 80.3%, and is 63.5% of the entire terrestrial catchment of the lake. Measurements generally started in 1956.

Seven catchments have been taken into consideration in Bolivia: The Río Suchez at Escoma, the Río Huaycho at Puerto Acosta, the Río Keka at Achacachi, the Río Catari at Tambillo, the Río Sehuenca at Villa Iquiaca, the Río Jacha Jahuira at Hichu Kkota and the Río Tiwanacu at Tiwanacu (Fig. 5). These data cover shorter periods than those from Peru. Bolivia gauges 6470 km^2 of the catchment at these stations, of which 1630 km^2 is in Peru. Bolivia therefore obtains measurements on 47.4% of the catchment lying within its own territory and 13.3% of the total lake catchment. Overall, discharges are recorded for 76% of the total catchment in the two countries.

For the rest of the area for which no direct measurements are available, 4400 km^2 are occupied by river catchments similar to those monitored (Rios Pallina, Batallas, etc.) and 7100 km^2 are made up of small coastal catchments for which run-off was calculated from rainfall. Using this method of calculation, the volume flowing into the lake each year between 1968 and 1978 varied from 3.11×10^9 m^3 yr^{-1} in 1983 to 15.78×10^9 m^3 yr^{-1} in 1986, the mean being about 8.90×10^9 m^3 yr^{-1}. On the basis of the discharges measured in the five main catchments, the mean inflow over the period 1956–1987 was 8.09×10^9 m^3 yr^{-1}, equivalent to a mean discharge of 256 m^3 s^{-1}.

Another method of calculation was also used. After homogenising the data using the VECSPAT method, the unknown discharges were calculated from those of the gauged Peruvian catchments, by taking into account the ratios of their areas, rainfall and the given annual run-off coefficients. The values obtained, assuming a mean run-off coefficients of 22% for the non-measured catchments, gave an annual mean inflow over the period 1968–87 of 8.51×10^9 m^3 yr^{-1}, equivalent to 270 m^3 s^{-1}, a value close to the previous calculation. The proportion of the total discharge actually measured is therefore 71%. This river inflow represents a water depth of 1002 mm over the entire lake surface. The results in Table 1 which should be compared with those of Table 2 have therefore been obtained for different groupings of catchments. The estimated discharges with run-off percentages of 15 to 25% for those catchments not measured directly, varies between 250 and 290 m^3 s^{-1}, equivalent to a depth of water of between 930 and 1080 mm over the entire lake surface.

Run-off and specific discharge

The mean run-off coefficient over all the gauged catchments in Peru is 25.2%, with a maximum of 38.3% in the Coata catchment and a minimum of 19.6% in the Zapatilla catchment. Previous assessments have given a mean run-off coefficient for the whole lake catchment of 23.6%.

In terms of specific discharges the catchments can be divided into two areas:

- The north and west where the specific discharges are close to 5.5 l s^{-1} km^{-2}, with the exception of the Coata which has a specific discharge of 10 l s^{-1} km^{-2}.
- The south and east, covering mostly the area within Bolivia, where the specific discharges are of the order of 3 to 4 l s^{-1} km^{-2}, with the exception of the Sehuencas which reaches 6 l s^{-1} km^{-2}.

The lowest inputs come from the driest areas situated on the eastern fringes and from catchments situated on the Altiplano where the low gradients favour infiltration and evapotranspiration rather than run-off. In the heavy rainfall catchments with steep gradients, the specific discharges are of the order of 15 l s^{-1} km^{-2}. In high altitude catchments such as that of the Suchez this discharge can be relatively low however (3.7 l s^{-1} km^{-2}), because of the low rainfall and the heavy retention of water by the fluvio-morainic soils and by peat. Relief therefore has an influence on run-off, both by the gradient and by the head of water it produces. This explains why the discharge per unit area of the Río Sehuencas, which runs directly off the Cordillera into the lake, is higher than that of the Río Keka which wanders over the plain.

Despite the relief, the maximum daily specific discharges are not very high. For a median year they range between 20 and 60 l s^{-1} km^{-2}. The spatial distribution of discharges per unit area is identical to that of river discharges.

Temporal variation in discharge

The histogram of mean monthly discharges (Fig. 6) shows a maximum in February, except for the Río Ramis, where a slight peak is evident in the month of March. 80% of the lake inputs occur between January and April. Late or early rains have practically no effect on run-off.

Year-to-year variation in annual discharge (Fig. 7) shows the low values for the periods 1956–1958, 1964–1967 and especially 1983, a year affected by an exceptional El Niño event. Similarly, the high discharges of the years 1962–1963, 1974–1976 and 1984–1986, when inputs were 1.5 to 2 times higher than the mean, are also evident. Together with the amount of rain falling directly on the lake, these variations in river input to the lake influence long-term changes in lake level. The period 1956–1987 was a dry period which lasted until 1974 and was followed by a much wetter period, particularly from 1984–1986.

Statistical analysis of the distribution of mean annual discharges over the period 1956–1987 provides estimates of the various return times (Table 2).

Statistical analysis of the annual mean monthly maximum discharges gives

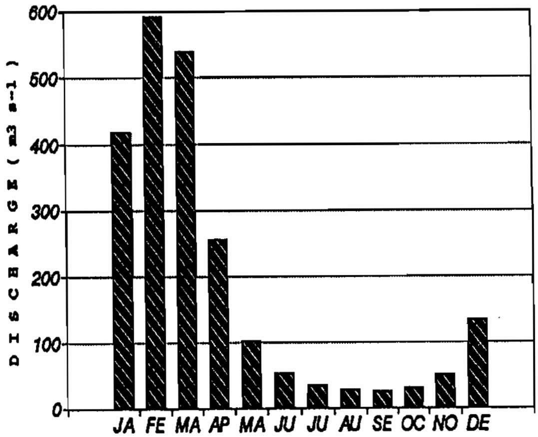

Figure 6. Variation in the total mean monthly discharges ($m^3 s^{-1}$) for the lake's five largest inflow rivers (Ramis, Coata, Ilave, Huancane and Suchez) over the period 1956–1987.

an indication of the probability of exceptional discharges (Table 3) and shows in the case of the Ilave and the Ramis, which have the same median value, that the value for the 100–year flood is twice as high in the former although its catchment area is only half that of the latter.

Discharge of the outflow from Lake Titicaca

The many gaps in the measurements of the discharge of the Desaguadero made at Puente Internacional at the outflow from the lake have been filled

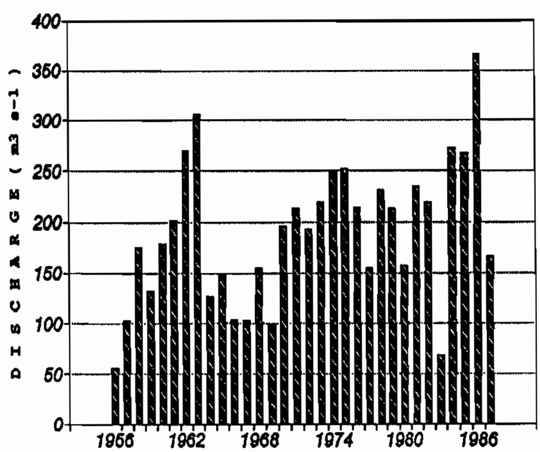

Figure 7. Total mean annual discharges ($m^3 s^{-1}$) for the lake's five largest inflow rivers (Ramis, Coata, Ilave, Huancane and Suchez) over the period 1956–1987.

Table 2. Measured and adjusted mean annual discharge ($m^3 s^{-1}$) for the period 1956–1987.

	Ramis	Ilave	Coata	Huancané	Suchez
Surface (km²)	15 060	7 290	4 650	3 580	3 170
Minimum	25	10	11	5	4
Medium	74	38	47	19	11
Maximum	121	90	99	40	20
Dry fifty	36	13	15	8	6
Middle	70	37	36	19	12
Wet fifty	140	100	90	42	24

by interpolation. The mean annual discharge over the period 1968–1987 has thus been estimated at 30.6 $m^3 s^{-1}$.

The discharge has been correlated with the lake level at Puno over the period 1957–1988, then reconstituted as a function of the level to reduce the strong heterogeneity that exists between periods. The mean annual discharge for the period 1968–1987 based on this correlation is 48.5 $m^3 s^{-1}$.

In order to overcome the inaccuracy of the discharge values measured at this station, discharges were also estimated from those measured at Calacoto, situated 150 km downstream, after making allowances for the inputs from the intervening catchments. The mean annual discharge estimated this way for the same period is 37.5 $m^3 s^{-1}$.

It should be noted that the discharges measured directly at the lake outflow and those estimated by one of the above two methods can differ by a factor of two. Figure 8 shows the changes in mean annual discharge from the lake for the period 1956 to 1987.

The annual outflow increased in successive cyles over the entire observed time scale to reach a maximum mean annual discharge of 169 $m^3 s^{-1}$ in 1986. The maximum recorded daily discharge of 250 $m^3 s^{-1}$ occurred in April of the same year. The discharge is highly variable and can be almost zero or even negative in some years (1971–1973), whereas it can exceed 100 $m^3 s^{-1}$ in other years (1986–1987) when the lake level is high. The mean therefore only has relative significance, because if the four highest years from 1985 to 1988 are excluded, the value is reduced to 19.5 $m^3 s^{-1}$.

The period 1956–1989, and especially from 1974 onwards, was a wet one in comparison to the entire period for which records are available, which starts in 1916 and includes the particularly dry years from 1935 to 1945. The median value for the outflow discharge is 15 $m^3 s^{-1}$ for the period 1956–1989 but falls to less than 5 $m^3 s^{-1}$ when the entire period is taken into consider-

Table 3. Return frequencies of maximum daily discharges ($m^3 s^{-1}$) for the period 1956–1987.

	Ramis	Ilave	Coata	Huancané	Suchez
Average	350	350	270	130	60
20 years	550	800	580	240	140
100 years	660	1 130	810	320	220

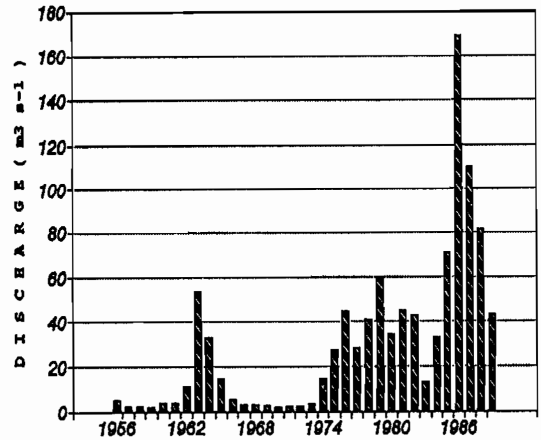

Figure 8. Mean annual discharge ($m^3\ s^{-1}$) calculated for the Desaguadero at the exit from Lake Titicaca (Puente Internacional) for the period 1956–1989.

ation. The mean annual discharge of 10 $m^3\ s^{-1}$ would only be reached in one year out of three. Statistical analysis of the discharges gives a 100–year maximum value of 250 $m^3\ s^{-1}$. For the maximum daily discharge the 100–year value is 350 $m^3\ s^{-1}$.

Because of the lake inertia and meteorological conditions, the maximum outflow discharge occurs in April (Fig. 9), the month of highest lake level, whereas the maximum for inputs from the catchment is in February. The fall in lake level is therefore gradual, so that the volume flowing out in May is greater than in March. Because of this regulatory effect of the lake, only

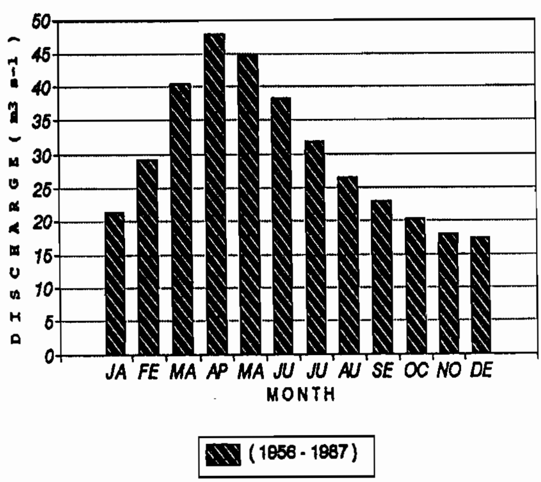

Figure 9. Seasonal changes in mean monthly discharge ($m^3\ s^{-1}$) calculated for the Desaguadero at the exit from Lake Titicaca (Puente Internacional) for the period 1956–1989.

60% of the total annual volume flows out down the Desaguadero between January and June, whereas river inputs over the same period amount to 85% of the annual total.

Lake Titicaca levels

Figure 10 shows the changes in daily records of lake level at Puno from 1914 to 1989. The zero datum on the scale is at 3809.93 m altitude.

Changes over the year are determined by the balance between water inputs and losses. The maximum level is generally centred on April, at the end of the rainy season and the period of high river inputs. The minimum usually occurs in December, just before the start of the rains.

Over the entire period the total inter-annual range in level has been 6.37 m, with an absolute minimum of − 3.72 m below datum in December 1943 and an absolute maximum of 2.56 m above datum in April 1986.

The annual range of level has varied between 1.80 m (in 1986) and 0.04 m (in 1983);

Differences in level during a month are usually maximum in February, with a mean value of 0.26 m. This corresponds to the major rise in water level caused by the maximum inputs from rivers and direct rainfall. The minimum monthly differences in water level generally occur in December and April, corresponding to the stable periods of annual minimum and maximum levels. The rise in water level occurs more quickly than the fall because the inputs are concentrated almost exclusively over 5 months, whereas the losses by evaporation are more evenly spread over the year.

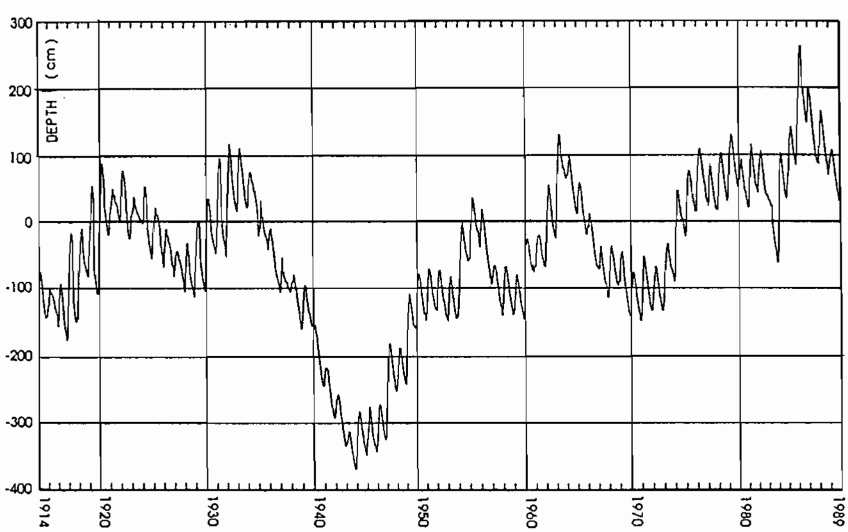

Figure 10. Changes in the level of Lake Titicaca at Puno.

Volume of water in Lake Titicaca

Boulangé and Aquize Jaen (1981) estimated the volume of the lake to be 895.9×10^9 m^3 during the period 1964–1979 when the water level was on average 0.46 m lower than during the period 1968–1987. The increase in level is equivalent to 3.89×10^9 m^3. We therefore adopt a lake volume of 900×10^9 m^3 for this latter period. Taking into account the mean inputs, the turnover rate for the water is 1.79%, or an average retention time of 55.8 years. The volume of the Lago Grande (887.5×10^9 m^3) is much greater than that of the Lago Menor (12.5×10^9 m^3).

The actual evapotranspiration and evaporation are generally the most difficult terms to measure in the hydrological cycle. This is the case for Lake Titicaca and its basin where uncertainties exist in the values to be used. The spot measurement or estimation of these terms and their extension to the whole catchment are very complicated. One of the interests in calculating the water balance is to provide an estimate of the losses other than those due to surface flows from the basin. Such losses are considered as an approximate value for evaporation. From the balance equation (paragraph 2), these losses are equal to the algebraic sum of the other terms.

In the case of Lake Titicaca and its basin, the interest is all the greater because it involves the evaluation of the actual evaporation from a very large body of water and the actual evapotranspiration from a high-altitude mountainous soil-vegetation complex lying within the tropics.

Any losses by infiltration through the lake bed and any inputs to the lake from aquifers could also be included in the balance without problems, if their values were known. This is not the case, since these phenomena are poorly understood, although it is likely that subterranean inputs such as those from aquifers surrounding the lake and which are evident in the form of springs and seepages, are greater than any underground losses under the Desaguadero in the direction of Lake Poopo. These possible inputs and losses have not therefore been taken into consideration in the calulations. Any input from aquifers would tend to lead to an under-estimate of overall losses and therefore of the approximate value for evaporation. The opposite is true in the case of infiltration.

Various attempts have been made to estimate evaporation on the Altiplano using several methods. Among these were Carmouze and Aquize Jaen (1981) who, from a water balance, estimated total losses at 1880 mm yr^{-1} and after estimating infiltration of 160 mm yr^{-1} from a dissolved chloride balance, calculated an evaporation of 1720 mm yr^{-1}. Carmouze *et al.* (1983) arrived at a figure of 1720 mm yr^{-1} for evaporation based on a heat balance. In contrast, Vacher *et al.* (1989), after measuring the terms of the radiation balance, calculated potential evapotranspiration on the Altiplano using the Penman formula and arrived at figures of 1300 mm yr^{-1} at Belen and 1350 mm yr^{-1} at Patacamaya. These values are lower than those above because of the low net radiation.

Mariaca (1985) using type A tanks obtained values of 1860 mm yr^{-1} and 1955 mm yr^{-1} for Desaguadero (Peru) and Patacamaya, respectively. These values were reduced to 1490 mm yr^{-1} and 1565 mm yr^{-1} after applying a tank correction factor of 0.8. At Belen evaporation is lowest in June, with a value of 110 mm and highest in October with 154 mm. The annual total at this site is 1692 mm. At Isla del Sol, on the lake itself, but at a height of 150 m above the lake level, the annual value is 1606 mm. After applying the tank correction factor, these two values become 1355 mm and 1285 mm.

Actual evapotranspiration of the Lake Titicaca catchment

Overall, the terrestrial part of the catchment receives 736 mm yr^{-1} of rain, or a volume of 36.1×10^9 m^3 yr^{-1} (Table 2).

Over the long term, the actual evapotranspiration over the catchment is equivalent to the difference between rainfall and run-off. In the case of Titicaca, however, an uncertainty remains because account has to be taken of changes in the groundwater reserves in the catchment. As is the case with the lake, it is likely that the volume of groundwater has increased up to the end of the period in question, as a result of the very wet period from 1984 to 1986. Evapotranspiration calculated from a water balance would therefore be overestimated. Actual evapotranspiration in the various river catchments varies between 490 and 660 mm yr^{-1}, with a value of 563 mm for the entire terrestrial part of the catchment (Table 2). This represents a volume of 27.6×10^9 m^3 yr^{-1}, or a loss of 76.4%, the highest component of losses in the catchment.

The terms of the water balance and actual evaporation from Lake Titicaca

As has been shown above, several methods have been used to evaluate each term in the water balance, each giving significantly different results. It is worth mentioning these various results on a long-term average scale, since the method of estimation, used for the first time, provides an estimate of the degree of uncertainty that is attached to the final accepted values.

- Two values for average precipitation over the lake have been obtained using the Vecspat method: 7.47×10^9 m^3 yr^{-1} with missing values estimated and 7.07×10^9 m^3 yr^{-1} with calculated values.
- Two values are given for river inputs: firstly 8.90×10^9 m^3 yr^{-1} based on the observed results plus correlations and the other 8.51×10^9 m^3 yr^{-1} with missing values estimated by Vecspat and with a run-off coefficient of 22% for the non-measured catchments. The discharges calculated by Vecspat give the same overall results. The values vary between 7.86×10^9 m^3 yr^{-1} and 9.11×10^9 m^3 yr^{-1}, if a range of values for run-off coefficient of between 15 and 25% is used for the non-measured part.

Table 4. Mean annual hydrological balance for Lake Titicaca over the period 1968–1987.

Units	Rainfalls	Rivers	Effluent	Evaporation	Lake storage
Height mm	880	1 002	160	1 628	94
Volume 10^9 m^3	7.47	8.51	1.36	13.82	0.80
%	46.8	53.2	8.9	91.1	

- The value for the volume flowing out by the Desaguadero derived from actual data plus interpolation for missing values is 0.965×10^9 m^3 yr^{-1}, that obtained by correlations with lake levels is 1.53×10^9 m^3 yr^{-1} and that estimated from the disharge at the Calacoto gauging station (Bourges *et al.*, 1991) is 1.18×10^9 m^3 yr^{-1}.
- Changes in lake volume derived from 5 day running means of lake level give an annual increase in volume of 0.802×10^9 m^3 yr^{-1}, or 94 mm per year over the 20 year period in question.

Different combinations of the results given above could thus be applied to the calculation of overall losses resulting from the balance.

A minimum figure of 12.6×10^9 m^3 yr^{-1}, or 1485 mm is obtained by taking the lowest values for inputs and the highest figure for the Desaguadero discharge and a maximum value of 14.8×10^9 m^3 yr^{-1} or 1745 mm is obtained by doing the converse. The mean of these two values is 1615 mm with an error of ± 8%.

Two estimates based on the median and mean of the available values of each term give figures for overall losses of 14.0×10^9 m^3 yr^{-1} and 13.9×10^9 m^3 yr^{-1} or 1650 mm and 1630 mm, respectively.

On the basis of discharge by Vecspat, outflow discharge deduced by correlations with lake levels, and rainfall figures with estimated missing values, the overall losses are estimated at 13.6×10^9 m^3 yr^{-1} or 1610 mm and those from calculated rainfall figures at 13.2×10^9 m^3 yr^{-1} or 1560 mm, the mean of these two figures being 1585 mm.

From measured discharge values with missing values calculated by correlations, outflow measurement estimated from discharge at Calacoto and rainfall with missing values calculated by Vecspat, the overall losses are estimated at 14.4×10^9 m^3 yr^{-1}, or 1695 mm. The same calculation, but using rainfall values calculated by Vecspat gives overall losses of 14.0×10^9 m^3 yr^{-1}, or 1645 mm.

If we had to give one value for the terms of the water balance, we would adopt rainfall and discharges with missing values estimated by Vecspat and the mean of the two calculated values for the Desaguadero (Table 4). For the overall losses other than those leaving by the Desaguadero, a volume of 13.8×10^9 m^3 yr^{-1}, or 1628 mm yr^{-1} is therefore proposed. By taking into account a margin of uncertainty of ± 3%, a value is obtained which is close to most estimates of actual evaporation.

The overall hydrological balance of the basin

Using the values for the terrestrial part of the basin and for the lake, the total precipitation over the basin was 43.6×10^9 m^3 yr^{-1}. A volume of 0.80×10^9 m^3 yr^{-1} was stored in the lake and 41.4×10^9 m^3 yr^{-1} was evaporated. Exportation out of the basin towards Lake Poopo by the Desaguadero was 1.36×10^9 m^3 yr^{-1}. Evaporation and evapotanspiration therefore represent 96.8% of the water losses whereas surface outflow was only 3.2%.

Conclusions

The climate of the Lake Titicaca basin, temperate by day and cold at night, is that of a high mountain region subjected by its geographical situation to a tropical regime. The influence of the impressive body of water is felt by a reduction in temperature range and to a lesser extent by higher mean temperatures than those that should occur at such altitudes. The lake, with water warmer than the surrounding air also influences precipitation, which is greatest at the lake's centre. Rain falls almost exclusively between December and March and amounts can vary by a factor of two from one year to another.

The hydrological regime is therefore tropical, but river discharges are spread out over the year in the eastern rivers where glaciers cover the higher summits. Mean annual discharge can vary by a factor of three between years, reflecting in an amplified manner the inter-annual irregularity in rainfall. The maximum river inputs occur in the second half of summer one to two months after the rainfall peak; 80% of run-off occurs in 4 months.

The irregularity of rainfall and river inputs between years, combined with a relative stability in evaporation and a slight surface outflow, are the cause of the great variations recorded in lake level. The range of ± 3.18 m recorded since 1914 has led to a change in lake volume of ± 3%. Because of the great difference in their volumes, this variation accounts for ± 2.6% in the Lago Grande and ± 33% in the Lago Menor. The stability of the lake environment is therfore very variable according to the particular area.

Direct rainfall onto the lake amounts to 880 mm, or 7.47×10^9 m^3 yr^{-1}, whereas inputs from rivers are equal to 1002 mm, or 8.51×10^9 m^3 yr^{-1}. Evaporation (including unknown groundwater inputs or losses) removes 1628 mm ± 3%, or 13.8×10^9 m^3 yr^{-1}, whereas the Desaguadero only drains away 160 mm yr^{-1}, or 1.36×10^9 m^3 yr^{-1}. Direct rainfall therefore accounts for 47% of the inputs and the inflow rivers 53% of inputs. Evaporation accounts for 91% of the total losses and outflow via the Desaguadero only 9%. The up-to-date, entirely computerised way of processing the rainfall and hydrological data guarantees a better precision of the values. It is certain that the period 1968–1987 was wetter than those periods studied previously by other workers and that this has led to changes in the relative importance of the terms in the water balance by increasing the contribution of the inflow rivers and that of the Desaguadero and decreasing that of direct rainfall and evaporation. In comparison Carmouze (1982) for the period 1956–1978, which was drier than 1968 to 1987, gave a figure for evaporation of 1720 mm and of 0.22×10^9 m^3 yr^{-1} for outflow via the Desaguadero.

Lake Titicaca, because of its area and volume and its situation at high altitude within the tropics, remains a hydrological site unique in the world.

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C. DEJOUX and A. ILTIS / Editors

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A Synthesis of Limnological Knowledge

Kluwer Academic Publishers

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KLUWER ACADEMIC PUBLISHERS

DORDRECHT / BOSTON / LONDON

Library of Congress Cataloging-in-Publication Data

Lake Titicaca : a synthesis of limnological knowledge / edited by C.
Dejoux and A. Iltis.
p. cm. -- (Monographiae biologicae ; v. 68)
Includes indexes.
ISBN 0-7923-1663-0 (HB : alk. paper)
1. Limnology--Titicaca Lake (Peru and Bolivia) 2. Aquatic
resources--Titicaca Lake (Peru and Bolivia) I. Dejoux, Claude.
II. Iltis, A. III. Series.
QP1.P37 vol. 68
[QH128]
574 s--dc20
[574.5'26322'098412] 92-7958

ISBN 0-7923-1663-0

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Kluwer Academic Publishers incorporates
the publishing programmes of
D. Reidel, Martinus Nijhoff, Dr W. Junk and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed on acid-free paper

Printed in the Netherlands