V.5. The energy balance

JEAN-PIERRE CARMOUZE

Lake Titicaca is a unique example of a large, deep, tropical lake (between latitudes 15°25 and 16°35 south) located at 3810 m altitude. A priori one might think that this high altitude location may confer a special type of thermal regulation upon it. The various studies that have been carried out on this subject (Kessler, 1970; Carmouze *et al.*, 1983; Richerson *et al.*, 1977 and Taylor and Aquize Jaen, 1984) provide:

1) a better undertanding of the micro-climate created by the lake on the surrounding region,
2) a definition of the factors which control the temperature of the lake and its thermal stratification,
3) an estimate of the rate of evaporation which is one of the terms of the hydrological balance.

The energy balance of the water body contains two terms which should balance. The first is the algebraic sum of two components: the short wavelength radiation balance, Q_S, and the long wavelength radiation balance, Q_T. The second term represents the exchanges by conduction within the water mass Q_L, by convection at the water atmosphere interface Q_C, and by evaporation, Q_E.

The total balance is represented by:

$$Q_s + Q_T = Q_c + Q_L \tag{1}$$

The heat provided by inputs from rainfall and rivers and thermal phenomena associated with biogeochemical reactions, convection through the lake bed and geothermal energy are ignored. These various heat flows are closely related to one another. The thermal balance is subjected to the external forcing factors of solar radiation and the state of the atmosphere (temperature, air humudity, cloud cover, wind speed, etc.), the latter also being influenced by the thermal response of the water body itself, that is to say the microclimate it creates. In the final analysis, it is the water temperature (or the total heat content of the lake) which adopts a value so that the sum of the terms of the energy balance tends towards zero. The water temperature represents one of the main readjustment factors influencing the long wave-

C. Dejoux and A. Iltis (eds.), Lake Titicaca, 131–146.

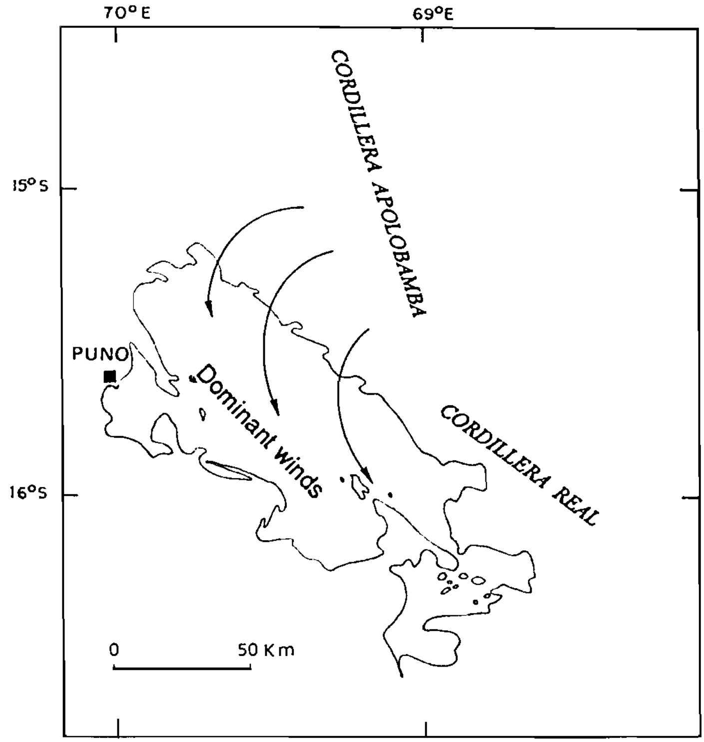

Figure 1. Location of Lake Titicaca and the Puno meteorological station. The dominant winds are indicated.

length radiation emitted by the lake, the evaporation and the thermal convection.

Because the solar radiation and the atmospheric conditions vary continuously on a daily, seasonal and annual basis, a succession of energy balances tends to becomes established at the water-atmosphere interface and within the water mass. The effect of changes in the inputs and outputs of energy at these levels, is either to draw in energy from the environment or to release energy into it, leading to changes in the total quantity of heat stored and its distribution within the lake.

In this chapter we will describe the exchanges occurring at the water-atmosphere interface and their consequences on the changes in the heat reserves of the lake. The vertical distribution of these reserves reflected in the thermal stratification is described in Chapter V.4.

Any hydrological or energy balance is typified by the period chosen. The balance that is to be described is based on meteorological data recorded at Puno (Peru) between 1954 and 1987 and temperature data in the Lago Grande collected between 1976 and 1979. It should be noted that the Puno meteorological station is exposed to the dominant winds (Fig. 1). These data are insufficient on a small time-scale for analysis of diurnal changes, and refer to too short a time period for annual variations in energy flux to be evaluated. Nevertheless, a monthly energy balance can be drawn up.

Radiation balance within the lake

Solar radiation absorbed at short wavelengths

The total solar radiation, which represents the light energy from direct and diffuse solar radiation falling on a horizontal surface, can be easily calculated in relation to the latitude of the site of observation and the state of the overlying atmospheric layer.

We have used the method of calculation developed by Perrin de Brichambaut and Lamboley (1968). These workers start with the daily total of solar radiation incident at the top of the earth's atmosphere, G_0, averaged for each month, and then calculate the solar radiation at the earth's surface in fine weather, G_{max}. This calculation requires that a certain number of assumptions be made relating to the altitude, the transparency of the atmosphere, the quantities of condensable water vapour and ozone. The following assumptions were made in the calculation of Gmax: atmospheric pressure, P = 1000 mb; quantity of condensable water vapour, w = cm, coefficient of atmospheric transparency B = 0.07.

At 15°S, the latitude of Lake Titicaca, the values for total incident radiation at sea level in J cm^{-2} d^{-1} are:

Month	J	F	M	A	M	J	J	A	S	O	N	D
G_{max}	3200	3125	2950	2650	2250	2075	2125	2375	2750	3050	3200	3250

Corrections need to be made to take into account the true environmental conditions. At the altitude of the lake (3810 m) the total radiation must be increased by 4% just because of decreased scattering from gas molecules (1% per 1000 m altitude). The quantity of condensable water vapour, w, was determined from the water vapour pressure at the lake's surface, fa, using Hann's formula:

$$w\ (\text{cm}) = 0.17 \times \text{fa}\ (\text{mb}) \tag{2}$$

fa being on average equal to 5.8 mb and $w \approx 1$ cm. This value introduces a correction of +3%. The transparency coefficient, B, which defines the quantity of aerosols contained in the column of atmosphere above the observation point is of the order of 0.025 for a pure atmosphere. This factor decreases with altitude according to the formula $Bp = B \times P/1000$, where P = the atmospheric pressure in mb. At Lake Titicaca this value must be close to 0.015. The influence of B on G_{max} is slight, because the decrease in direct radiation is partially compensated by an increase in diffuse radiation. However, because of the effect of scattering of solar radiation by the water body, this influence is indirectly increased. For an albedo of water close to 0.07 and $B = 0.015$, according to Perrin de Brichambaut and Lamboley, G_{max} must be increased by +6%. In total for Lake Titicaca, the values of G_{max} must then be increased by 13%.

A figure for total mean radiation, G, is derived from the corrected values, taking into account the duration of sunshine. To do this Perrin de Brichambaut and Lamboley have drawn up a table of correspondence between the proportion of sunshine hours (i.e. the ratio between the mean measured hours of sunshine, S, and the maximum theoretical sunshine hours, S_{max}, for continuous fine weather) and the ratio G/G_{max}, based on Angström's formula:

$$G/G_{max} = 0.76 \times S/S_{max} + 0.24$$

S/S_{max}	0	0.2	0.4	0.5	0.6	0.8	1.0
G/G_{max}	0.24	0.42	0.58	0.65	0.73	0.86	1.0

The values of G have thus been calculated from sunshine duration data recorded at Puno (Table 1).

Part of the solar radiation, G, is dispersed in all directions by reflection and scattering from the water body surface. This fraction, or albedo, is close to 0.07 in the case of a lake. The energy absorbed by Lake Titicaca in the form of short wavelength radiation can therefore be estimated as: $Q_S = G (1 - 0.07)$.

The values obtained vary between 2628 J cm^{-2} d^{-1} in October and 1864 J cm^{-2} d^{-1} in June, the mean annual value being 2190 J cm^{-2} d^{-1} (Fig. 2).

Long wavelength radiation from the earth

This radiation includes two components of long wavelength radiation; one is the radiation emitted by the water body and the other the radiation emitted by the atmosphere away from the lake, both representing losses of energy for the lake.

Emission from the lake

Water has a behaviour close to that of a black body. The energy emitted by the lake is estimated from the Stefan-Boltzmann equation:

$$Ml = \epsilon \times \sigma \times Te^4 \qquad (3)$$

Table 1. Monthly means for: maximum and minimum air temperatures near the water body Θ_{amoy}, Θ_{amax}, Θ_{amin}; surface water temperature of the lake Θ_e; partial pressure of water vapour 1 m above the water body, f_a; saturation pressure of water vapour at the temperature Θ, F_e; atmospheric pressure, P; proportion of sunshine hours, S/S_{max}; cloud cover, N and the wind speed at 2 m above the ground, U, from daily data recorded at Puno between 1964 and 1978, with the exception of Θ_e, which come from measurements made in the Lago Grande in 1977 to 1979. (1) Θ_{amoy} was estimated from Θ_{amax} and Θ_{amin} taking into account relative lengths of night and day during the course of the year.

$\theta_{a\,max}$ in °C	14.5	14.2	14.1	14.3	13.7	13.2	13.0	13.8	14.3	15.6	15.9	15.1	–
$\theta_{a\,min}$ in °C	5.0	5.2	4.8	3.4	1.0	−0.9	−1.3	0.2	2.0	3.2	4.0	4.8	–
$\theta_{a\,mean}$ in °C (1)	9.95	9.77	9.33	8.44	6.71	5.26	5.07	6.43	7.90	9.4	10.10	10.15	8.21
θ_e in °C	13.85	14.3	14.35	13.85	13.0	12.0	11.5	11.25	11.75	12.9	13.35	13.85	13.0
f_a in num.	7.5	7.9	7.7	6.5	4.9	4.0	4.0	4.6	5.4	5.5	5.9	6.8	5.89
F_e in num.	15.90	16.34	16.40	15.90	15.02	14.06	13.60	13.38	13.82	14.06	15.34	15.90	15.05
P in num.	646	646.1	646.7	647.1	647.1	646.7	646.5	646.3	646.3	645.7	645.4	645.4	646.2
S in % $\bar{S}$ max	44	45	54	72	80	83	80	75	74	66	52	67.5	
N in octets	6.9	6.7	6.0	4.4	3.1	2.5	2.4	3.0	4.0	4.6	5.4	6.3	4.5
U in m s^{-1}	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

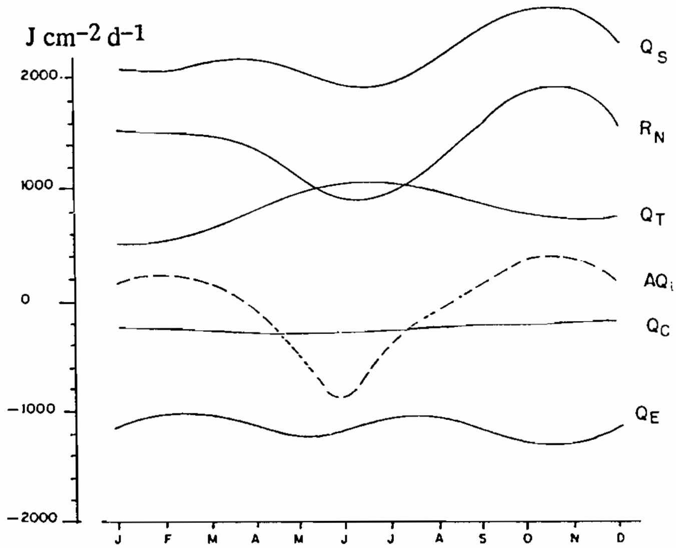

Figure 2. Mean monthly values of components of the Lake Titicaca energy balance expressed in $J\ cm^{-2}\ d^{-1}$.
Q_S = short wavelength solar radiation absorbed
Q_T = long wavelength radiation from the lake
$Q_N = Q_S - Q_T$ = radiation balance
Q_E = evaporation losses
Q_C = losses by conduction
Mean monthly changes in the heat content of the lake, expressed in $J\ cm^{-2}\ d^{-1}$: δQ_L

Where ϵ = the emissivity of water = 0.97; σ = the Stefan-Boltzmann constant = $4.9 \times 10\ J\ cm^{-2}\ K^{-4}\ d^{-1}$ and Te = the surface water temperature in °Kelvin.

The mean monthly values of Ml calculated from the values of Θe, taken from Table 1, vary between $-3240\ J\ cm^{-2}\ d^{-1}$ in March and $-3102\ J\ cm^{-2}\ d^{-1}$ in August; the mean annual value being $-3181\ J\ cm^{-2}\ d^{-1}$.

Atmospheric radiation under clear skies

This is the most difficult to estimate term in the radiation balance. Among the various formulae and graphical solutions used to estimate this term, we have chosen that of Brunt, which is statistically valid in the case of clear skies. This formula considers the emission of the atmosphere to be that of a black body at the air temperature at ground level, corrected by a factor taking into account the partial pressure of water vapour at ground level, since this plays a major role in the absorption and re-emission of terrestrial radiation.

$$Ma = \epsilon \times \sigma \times Ta^4(a + b \times \sqrt{fa}) \quad (4)$$

Where: Ma = the energy emission by the atmosphere towards the lake in J cm^{-2} d^{-1}; ϵ = the emissivity of the atmosphere; σ = the Stefan-Boltzmann constant; Ta = the temperature of the air at ground level in °K, and fa = the water vapour pressure at ground level in mb. The values of the constants a and b are rather uncertain. We have used the values recommended by M. and R. Berliande (*in* Ivanoff, 1975): a = 0.61 and b = 0.051.

The mean monthly values of Ma were thus calculated from the Θa and Fa data in Table 1. Ma varies from − 2288 J cm^{-2} d^{-1} in February to − 2021 J cm^{-2} d^{-1} in July, the mean value being − 2179 J cm^{-2} d^{-1} (Table 2).

The long wavelength terrestrial radiation balance

In fine weather, the terrestrial radiation balance Q_{To} is equal to Ma − Ml. This value is reduced under cloudy conditions because the radiation by the atmosphere increases the greater the cloud cover and the lower the cloud ceiling.

Among the various proposed empirical formulae relating the mean value for terrestrial radiation under cloudy conditions, Q_T, to that of the mean value under clear skies Q_{To} and to cloud cover N, we have chosen that of Berliande (*in* Ivanoff, 1975): $Q_T = Q_{To}$ (1 − c. Nm), where m = 1.75 and c = 0.57 (value adopted for latitude 15°S). Values for cloud cover in octets, N, from Table 1, have been rescaled from 0 to 1.

The long wavelength radiation balance for each month calculated using this method shows that there is a loss of energy which is at a maximum in June (−1025 J cm^{-2} d^{-1}) and a minimum in January (−518 J cm^{-2} d^{-1}), the mean loss over the year being −782 J cm^{-2} d^{-1} (Table 2, Fig. 2).

The radiation balance

The radiation balance, R_N, which is the quantity of energy available, is equal to the difference between Q_S and Q_T. It varies from 839 J cm^{-2} d^{-1} in June to 1903 J cm^{-2} d^{-1} in November, the mean value over the whole year being 1409 J cm^{-2} d^{-1} (Fig. 2).

The heat content of the lake, evaporation, conduction

The quantity of energy in the form of radiation available at the lake surface determines the exchanges of energy between the water and atmosphere by evaporation, Q_E, and by thermal convection, Q_C, and within the water itself by changes in the energy content of the lake, δQL, according to the following equation:

$$R = \delta Q_L + Q_c + Q_E$$

The terms of this equation, including the monthly evaporation rates, E, will be calculated from values of $Q_E$and we will propose a semi-empirical formula for the estimation of E.

Changes in the heat stored in the lake

The heat content of the lake per unit area has been calculated as follows: the lake was divided into layers of equal depth in which the heat content was calculated. This content is equal to the product of the proportional area that each layer represents in terms of the total lake area, the thickness of the layer and its mean temperature. The sum of values for each layer gives the total quantity of heat contained in the lake (Dussard, 1966).

The calculation was carried out using temperature profiles that we recorded in the Lago Grande from 1977 to 1979 and the bathymetric profile drawn up for the lake by Boulangé and Aquize Jaen (1981).

After estimating the quantities of heat stored in the lake, Q_L, in each month, the changes from month to month δQ_L were calculated (Tables 2 and 3, Fig. 3). The lake has a maximum loss of heat in June of 667 J cm^{-2} d^{-1} and a maximum heat gain in October of 378 J cm^{-2} d^{-1}. It should be noted that the maximum monthly change in heat reserves of the lake is of the order of 50×10^3 J $month^{-1}$ and only represents 8% of the mean annual value of the reserves.

It is not easy to compare the changes in heat content over the course of a year from one lake to another, since these changes depend not only on the climatic conditions of the region, but also on the morphology of the lake and of its catchment. To overcome this difficulty, Taylor and Aquize Jaen (1986) have proposed a dimensionless index, S, which they call the stored heat flux:

$$S = \sigma S/\beta/T$$

Where: σS = standardised monthly changes in stored heat. β = the difference between the maximum and minimum monthly values of stored heat T = the time (months) between the month with the lowest heat content and that with the highest content. From the data in Table 3: σS = 10 417 J cm^{-2}; β = 50 995 J cm^{-2} and T = 8 months; from which S = 1.63.

Taylor and Aquize Jaen (1984) from their own data and those of Richerson *et al.* (1977), calculated values of 1.45 and 1.54, respectively, and noted that values normally found in lakes in temperate regions are lower, of the order

Table 2. Components of the mean monthly energy balance within the Lago Grande. The results are expressed in J cm^{-2} d^{-1}. Q_S = solar energy absorbed; M_L = energy emitted by the lake surface; M_a = energy emitted by the atmosphere towards the lake under clear skies; Q_T = quantity of heat lost by terrestrial radiation; R_n = radiation balance; δQL = changes in the heat content of the lake. Q_E = heat lost by evaporation; Q_C = heat lost by turbulent convection. B = Bowen ratio.

	J	F	M	A	M	J	J	A	S	O	N	D	Annual mean
Q_S	2.070	2.046	2.132	2.171	2.025	1.864	1.947	2.142	2.399	2.628	2.581	2.296	2.190
M_L	−3.215	−3.236	−3.240	−3.215	−3.177	−3.135	−3.114	−3.102	−3.122	−3.148	−3.194	−3.215	−3.181
M_a	2.290	2.288	2.267	2.203	2.100	2.027	2.021	2.083	2.155	2.206	2.243	2.268	2.179
Q_T	−518	−552	−637	−809	−956	−1.025	−1.016	−914	−803	−737	−678	−741	−782
R_n	1.552	1.494	1.494	1.361	1.065	839	930	1.228	1.596	1.890	1.903	1.554	1.409
ΔQ_l	190	232	182	−53	−478	−667	−399	−73	169	378	349	182	–
B	0.192	0.226	0.243	0.241	0.259	0.258	0.282	0.227	0.190	0.155	0.145	0.168	0.215
Q_E	−1.142	−1.029	−1.055	−1.139	−1.225	−1.197	−1.036	−1.060	−1.199	−1.309	−1.357	−1.174	−1.160
Q_C	−219	−232	−256	−274	−317	−309	−292	−240	−228	−203	−197	−197	−248

Table 3. Heat content of the Lago Grande in the first month, Q_L, and the mean monthly changes δQ_L. The results are expressed in $J\,cm^{-2}$. (Note that the monthly values of δQ_L are expressed in mean daily values for each month in Table 2).

	J	F	M	A	M	J	J	A	S	O	N	D
Q_l	613.310	619.205	625.750	631.395	629.815	615.015	595.015	582.650	580.400	585.475	597.190	607.665
ΔQ_L	5.895	6.545	5.645	−1.580	−14.800	−20.000	−12.370	−2.250	5.075	11.715	10.475	5.645

of 1.15, thus underlining the wider range of changes in heat content in tropical lakes.

Exchanges by evaporation and convection

Exchanges by evaporation and convection are difficult to estimate. Various semi-empirical formulae exist, but one of the best ways of estimating them is to derive the sum of their values from the energy balance, and then calculate their separate values from Bowen's ratio, B. This ratio reflects the fact that the coefficients of the transfers of water vapour and of heat at the air-water interface are very close to another.

$$B = Q_c/Q_E = C_p.P/0.621.L \times \Theta_e - \Theta_a/F_e - f_a$$

Where: Θ_a = the air temperature; Θ_e = the water temperature; C_P = the specific heat capacity of air at atmospheric pressure = $1005\ J\,g^{-1}$; L = the latent heat of evaporation of water in $J\,g^{-1}$ (This is a function of the surface water temperature Θ_e: $L = 2495 - 2.38\ \Theta_e$); P = the atmospheric pressure; F_e = the partial pressure of water vapour at saturation at the temperature Θ_e and f_a = the actual pressure of water vapour in the air just above the lake's surface.

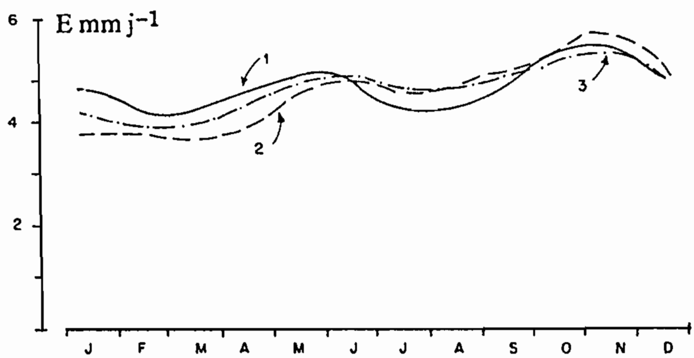

Figure 3. Mean monthly values for evaporation rates from Lake Titicaca in $mm\ d^{-1}$.
(1) Curve obtained from the energy balance
(2) Curve derived from the relationship $E = 0.477\ (F_e - f_a)\ U_{2m}$
(3) Curve derived from the relationship $E = 0.17 + U_m\ (F_e - f_a)$
E being the mean monthly evaporation rate in $mm\ d^{-1}$, $F_e - f_a$ the humidity deficit in mb and U_{2m} the wind speed 2 m above ground level in $m\ s^{-1}$.

The mean monthly values of $Q_E + Q_C$ were thus calculated from equation (1) and those of B from data presented in Table 1. The separate values of Q_E and Q_C (Table 2) were obtained from equation (5).

Losses by evaporation range from $-1357\,J\,cm^{-2}\,d^{-1}$ in November to $-1029\,J\,cm^{-2}\,d^{-1}$ in February and those by turbulent convection from $-309\,J\,cm^{-2}\,d^{-1}$ in June to $-197\,J\,cm^{-2}\,d^{-1}$ in November (Fig. 2).

Evaporation rates derived from the energy balance, semi-empirical formulae

The mean monthly evaporation rate, E, was derived from the relationship $E = Q_E/L$; where E is expressed in $cm\,d^{-1}$; Q_E in $J\,cm^{-2}$ and L, the latent heat of evaporation in $J\,g^{-1}$.

The results (Fig. 3) show that the evaporation rates range from 4.2 to 5.3 mm d^{-1}, the minimum being in May and the maximum in November. The mean annual rate of 1720 mm is very close to the value of 1740 mm/year obtained from the hydrological balance of the Lago Grande by Carmouze and Aquize Jaen (1981).

Kessler (1970) and Richerson *et al.* (1977) have also calculated rates of evaporation of 1714 and 1900 mm/year, respectively, from the heat balance and values of 1480 and 1344 mm/year from the hydrological balance. The most recent estimate made by Taylor and Aquize Jaen (1984) from the heat balance is 1350 mm/year.

The semi-empirical formulae which are used to calculate the evaporation rates are mostly derived from the approximate expression for this variable derived from the general aerodynamic model:

$$E = D_a/A_a \times C_Z\, 0.622/P\, (F_e - f_a)\, U_Z$$
$$P$$

Where: D_a = the coefficient of turbulent diffusion of the atmosphere in the vertical plane; A_a = the coefficient of turbulent viscosity of the atmosphere in the vertical plane; C_Z = the friction coefficient at distance Z at which the wind speed, U_Z, is measured.

These variables are difficult to measure. Jacobs (1951) chose to determine a mean value for this group of variables by combining the energy balance method giving QE and equation (6):

$$E = Q_E/L = k(F_e - f_a).U_{6m} \qquad (7)$$

Taking the 4 oceanic regions, he obtained values of k varying between extremes of 0.11 and 0.20 (E being expressed in mm d − 1, F and f in mb and U in m s − 1 at 6 m above the water surface). Using the same method for Lake Titicaca, a mean annual value of k of 0.477 was obtained. It should be noted that these values of k are not directly comparable, because for

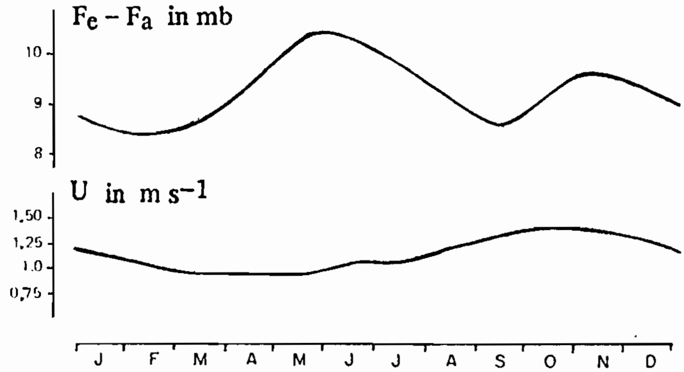

Figure 4. Monthly values for the humidity deficit of the air, $F_e - f_a$, at Puno and the wind speed at 2 m above ground level.

Titicaca, U was measured at 2 m above ground level. Equation (7) thus becomes:

$$E = 0.4777\ (F_e - f_a).U_{2m}$$

The mean monthly evaporation rates were calculated from this equation using the data presented in Table 1. The graph obtained shows wide deviations from that obtained from the energy balance (Fig. 3). The deviations are to a large extent due to the variable U, because the slope of the monthly evaporation curve given by the balance method (Fig. 3) is close to that of $F_e - f_a$ and different from that of U (Fig. 4). To obtain a better agreement between the two methods it is therefore necessary to use formulae giving less weight to the wind factor, such as: $E = (k1 + k2\,U_{2m}) \times (F_e - f_a)$. A satisfactory adjustment was obtained by taking the following values for k1 and k2:

$$k1 = 0.17,\ k2 = 0.30$$

which give

$$E = (0.17 + 0.30\ U_{2m}) \times (F_e - f_a) \qquad (9)\ (\text{Fig. 3})$$

Note that Laevastu (*in* Ivanoff, 1975) used values of k1 = 0.26, k2 = 0.077 in oceanic environments. These values are different from ours, but they referred to wind speeds at 10 m above the water surface and not at 2 m as in our case. It is therefore probable that the use of meteorological data from another station around the lake would lead to a change in values of k1 and k2.

The unusual nature of the energy balance

– Because of its high altitude situation, Lake Titicaca receives 13% greater solar radiation during fine weather than it would receive if it were at sea level. On the other hand, the sunshine duration (245 h $month^{-1}$) is not very high; at the same latitude higher values can occur, such as at Lake Chad at 13°N which has 288 h $month^{-1}$. However, this increase in sunshine only amounts to an increase in solar energy of 3 to 4%. In total, the solar radiation received by Lake Titicaca, with a mean annual value of 2190 J cm^{-2} d^{-1}, is higher than that received by other environments at approximately the same latitudes.

The seasonal variations in solar radiation are in part attenuated by the fact that in the season when the solar radiation reaching the top of the atmosphere is at its lowest (i.e. June-July-August) the sunshine hours are at their greatest. The between-month variation in incident radiation, which amounts to 42% of the mean value in fine weather, is reduced to 32% because of seasonal changes in cloud cover.

– The losses by terrestrial long wavelength radiation, Q_T, at the lake surface are greatest when the difference between the surface water temperature, Θ_e and the temperature of the overlying air, Θ_a, is slight. However, in the case of Lake Titicaca, the difference between Θ_e and Θ_a (expressed as the daily average) varies between 3.5°C and 5°C throughout the year. If the water temperature were to fall to that of the air, the radiation losses would be 20% less. In addition, Θ_e and Θ_a are on average 10 to 15°C lower than they would be at sea level at the same latitude. Under the conditions occurring at low altitude, the terrestrial solar radiation losses would be reduced by 10 to 15%.

Overall, at Lake Titicaca, again because of its high altitude, the long wavelength radiation losses are 30 to 35% higher than those which would occur if it were situated at sea level. Seasonal variations in terrestrial radiation are very pronounced, with extreme values differing by + 32% from the annual mean value. These variations are nevertheless attenuated by the fact that the differences in water and air temperatures are greatest when the partial pressure of water vapour is at its lowest in the southern winter, whereas the reverse occurs in summer. The seasonal variations are still much less than the diurnal changes (which are not dealt with in this chapter) due to the wide range of Θe and especially Θa over the 24 hours.

– The radiation balance provides the value for the energy available within the water body. In the case of Lake Titicaca, the increase in the gain in short wavelength radiation (ca. 10%), because of its situation at 3800 m altitude, is roughly compensated for by an increase in losses by long wavelength radiation (ca. 30 to 35%). This implies that the sum of the losses by evaporation and conduction is of the same order of magnitude as that recorded in low-altitude lakes.

– The energy losses by evaporation, averaging 1160 J cm^{-2} d^{-1} over the year, correspond to an evaporation rate of 1720 mm $year^{-1}$. This value is of the same order of magnitude as that recorded in other tropical lakes. It should be recalled that the evaporation rate is mainly a function of the water vapour deficit, $F_a - f_e$, and of the wind speed U. $F_a - f_e$ is on average 9.16 mb, a relatively high value, although the water and air temperatures are low compared to those occurring at low altitudes. This value is explained by the low relative humidity (the mean annual value of fe = 50%) and by the fact that the daily mean water temperature is always 4 to 5°C above that of the air. A simple calculation shows in fact that if the water temperature were reduced to that of the air, the water vapour deficit, $F_a - f_e$, would be 5.15 mb, a value that when substituted in formula (8) would lead to a decrease in the evaporation rate of 40 to 45%. The wind speed, which is not very high on average (1.15 m s^{-1} at 2 m above ground level), has nevertheless an effective action in renewing the air mass which would otherwise tend to become saturated on contact with the water, since the temperature gradient at the surface of the water body is such that it leads to the formation of an unstable stratification for most of the time.

The changes in evaporation rates over the year reflect those in the humidity deficit, $F_a - f_e$, the wind speed playing a minor role. However, the winds, which are lighter in May-June, tend to reduce the increase in evaporation at this period due to the strong humidity deficit.

– Exchanges by thermal convection represent losses of heat from the lake throughout the year, when the day is taken as the time unit.

The Bowen ratio, B, is inversely proportional to the atmospheric pressure (see equation (5)). At 3800 m altitude, however, this is only 640 mb, so that the value of B is 36% lower than what it would be at the normal pressure of 1000 mb. But the relatively low air and water temperatures have the reverse effect. By taking the example of a tropical lake at low altitude with the same difference between the air and water temperatures of 4.5°C, but with values of around 26°C and the same relative humidity (50%), it can be seen from formula (4) that B decreases by 40%. In general, the altitude factor on its own does not systematically favour heat exchanges by evaporation in a lake compared to those by thermal convection and vice versa.

– The last term of the energy balance to be analysed is that of the changes in the heat reserves of the lake provoked by the uneven distribution of solar energy over the course of the year. These changes (631 500 J cm^{-2} at the end of March against 580 500 J cm^{-2} at the end of August) represent thermal control by the lake since they result from the absorption of excedent solar energy in summer and its restitution in winter, the season of deficit in winter, thus attenuating the fluctuations caused by the other energy fluxes.

Thermal regulation is a function of the amplitude of seasonal changes in solar radiation, directly related to the latitude of the site, and also of the capacities of the lake itself to exchange heat energy with the atmosphere. This capacity is related to the depth of the water column involved in heat exchanges at different seasons. In deep lakes the transport of heat with depth depends on the intensity of vertical mixing, whereas in shallow lakes it is limited by the depth of the water body itself. So, at the same latitude, deeper lakes have a greater degree of thermal regulation. The intensity of vertical mixing is a function of a large number of factors including the morphology of the site, the wind speed and fetch, the horizontal circulation of water, Coriolis force and the resistance to mixing when there is a vertical density gradient (thermal or chemical stratification). These factors will not be analysed here, but in order to determine the reasons for the uniqueness of Lake Titicaca, it is interesting to demonstrate the fact that a high altitude tropical lake has a greater heat regulation than that of a low-altitude tropical lake under the same conditions. In fact, if one considers the density gradients created by temperature gradients, it takes twice as much mechanical energy to mix two masses of water, one at 24°C and the other at 26°C (water temperatures typical of low-altitude tropical lakes) than to mix two water masses at 11.5°C and 13.5°C (water temperatures in Lake Titicaca). In other words, all things being equal, the resistance to thermal diffusion created by the penetration of the temperature front is half as great in Lake Titicaca than it would be at sea level at the same latitude, the thermal regulation is thus increased and the micro-climate created by the lake is reinforced.

Conclusions

The analysis of the various terms of Lake Titicaca's energy balance has enabled the following points to be elucidated:

- the high altitude has the effect of increasing the solar radiation by 10 to 15% by inducing decreases in atmospheric transparency, scattering by gas molecules and in the thickness of condensable water vapour traversed. Because of this, the radiation emitted by the atmosphere is reduced, increasing the losses of long wavelength radiation by 30 to 35%. The sum of these opposing effects is that the energy balance, or the energy available at the lake's surface is of the same order of magnitude as for other lakes at the same latitude, but at low altitudes (1400 to 1450 J cm^{-2} d^{-1}).
- on an annual basis, the heat exchanges between the lake and the atmosphere by convection and evaporation are approximately equal to the energy balance. As a result, they have about the same value as those recorded at sea level at the same latitude (mean values: evaporation = 1160 J cm^{-2} d^{-1}, thermal convection = 248 J cm^{-2} d^{-1}). Because of the altitude, a decrease in evaporation losses might have been expected, because for the same quantity of water vapour, the deficit in the partial pressure of water vapour (to which evaporation is directly proportional) decreases with increasing air and water temperatures. A decrease in losses

by convection may also have been expected since these are directly proportional to atmospheric pressure. In practice, because of a major difference between the air and water temperatures (4 to 5°C), which maintains the local atmospheric circulation for most of the year (dominance of cold winds coming from the Western Cordillera), the thermal exchanges over a year are comparable with those recorded at sea level at the same latitude.
- changes over the course of the year in the heat content of Lake Titicaca, which result from seasonal disequilibria between the inputs and losses of energy within the water body, are very pronounced. As we have seen this is due to its great depth (100 m average) and the low water temperatures for a tropical lake (11–14°C).

The heat gains reach a maximum in October and November (378 and 349 $J\ cm^{-2}\ d^{-1}$, respectively) whereas the losses are greatest in June ($-667\ J\ cm^{-2}\ d^{-1}$). Taking into account its size (8448 km^2), the lake releases 16.9×10^{17} J of energy during the cooling period in the month of June alone and absorbs 18.7 × 1017 J during the warming period between October and November. These figures give some idea of the heat regulation of Lake Titicaca and of the major thermoregulatory role that it has on the surrounding environment (Boulangé and Aquize Jaen, 1981). These workers showed that the mean annual temperature of the air and the maximum and minimum temperature values become lower the further from the lake shore. As an example, the mean annual temperature at Puno on the lake shore is 8.5°C compared to 6.5°C at Chuquibambilla 60 km to the north-west and the annual temperature range is 12°C at Puno compared to 18°C at Chuquibambilla.

References of chapter V

BAXTER (R.M.), PROSSER (M.V.), TALLING (J.F.), WOOD (R.R.), 1965. Stratification in tropical African lakes at moderate altitudes (1,500 to 2,000 m). *Limnol. Oceanogr.*, 10: 510–520.

BAZOBERRY (Q.), 1968. Balance hídrico del Lago Titicaca. Dir. de Irrig. Min. Fom., Lima.

BOULANGE (B.), AQUIZE JAEN (E.), 1981. Morphologie, hydrographie et climatologie du lac Titicaca et de son bassin versant. *Revue Hydrobiol. trop.*, 14 (4): 269–287.

BOULANGE (B.), VARGAS (C.), RODRIGO (L.A.), 1981. La sédimentation actuelle dans le lac Titicaca. *Rev. Hydrobiol. trop.*, 14 (4): 299–309.

CARMOUZE (J.P.), AQUIZE JAEN (E.), 1981. La régulation hydrique du lac Titicaca et l'hydrologie de ses tributaires. *Rev. Hydrobiol. trop.*, 14 (4): 311–328.

CARMOUZE (J.P.), MIRANDA (I.), 1978. Estudio de los factores de control de los carbonatos disueltos en las aguas del lago Titicaca. Proceso de precipitación de calcita. *Rev. Boliviana de Química*, 2 (1): 57–67.

CARMOUZE (J.P.), ARZE (C.), QUINTANILLA (J.), 1977. Circulación de materia (agua, sales disueltas) a través del sistema fluvio-lacustre del Altiplano. *Cah. ORSTOM., sér. Géol.*, 10 (1): 49–68.

CARMOUZE (J.P.), ARZE (C.), QUINTANILLA (J.), 1977. La régulation hydrique des lacs Titicaca et Poopó. *Cah. ORSTOM., sér. Hydrobiol.*, 11 (1): 269–283.

CARMOUZE (J.P.), ARZE (C.), QUINTANILLA (J.), 1981. Régulation hydrochimique du lac Titicaca et l'hydrochimie de ses tributaires. *Rev. Hydrobiol. trop.*, 14 (4): 329–348.

CARMOUZE (J.P.), ARZE (C.), QUINTANILLA (J.), 1984. Le lac Titicaca: stratification physique et métabolisme associé. *Rev. Hydrobiol. trop.*, 17 (1): 3–12.

CARMOUZE (J.P.), AQUIZE JAEN (E.), ARZE (C.), QUINTANILLA (J.), 1983. Le bilan énergétique du lac Titicaca. *Rev. Hydrobiol. trop.*, 16 (2): 135–144.

CARNEY (H.J.), 1984. Productivity, population growth and physiological responses to nutrient enrichments by phytoplankton of Lake Titicaca, Peru-Bolivia. *Verh. Internat. Verein. Limnol.*, 22: 1253–1257.

CARNEY (H.J.), RICHERSON (P.J.), ELORANTA (P.), 1987. Lake Titicaca (Peru/Bolivia) phytoplankton: Species composition and structural comparison with other tropical and temperate lakes. *Arch. Hydrobiol.*, 110: 365–385.

CHURUTA SALLUgA (J.), MAMANI HUANcA (L.A.), 1977. Hidrología de la cuenca del río Ramis. Tesis Ing. Agron. UNTA, Puno: 173 p.

CSANADY (G.T.), 1973. Turbulent diffusion in the environment. Reidel, Dordrecht, 248 p.

DERKOSCH (I.), LÖFFLER (H.), 1960. Spektrochemische Spurenanalyse Südamerikanischer Binnengewässer. *Ark. Geofysik*, 3: 337–345.

DUSSART (B.), 1966. Limnologie. L'étude des eaux continentales. Gauthiers-Villars, Paris, 677 p.

ELSER (J.J.), MARZOLF (E.R.), GOLDMAN (C.R.), 1990. Phosphorus and nitrogen limitation of phytoplankton growth in freshwaters of North America: a review and critique of experimental enrichments. *Can. J. Fish and Aquat. Sci.*, 47: 1468–1477.

GILSON (H.C.), 1939–40. The Percy Sladen Trust Expedition to Lake Titicaca in 1937. *Trans. Linn. Soc. London*, ser. 3, 1: 1–357.

GILSON (H.C.), 1964. Lake Titicaca. *Verh. Internat. Verein Limnol.*, 15: 112–127.

GOLDMAN (C.R.), 1981. Lake Tahoe: two decades of change in a nitrogen deficient oligotrophic lake. *Verh. Internat. Verein. Limnol.*, 21: 45–70.

GOLDMAN (C.R.), JASSBY (A.), POWELL (T.), 1989. Interannual fluctuations in primary production: meteorological forcing at two subalpine lakes. *Limnol. Oceanogr.*, 34: 310–323.

GOLTERMAN (H.L.), 1975. Physiological limnology. Elsevier Scientific, Amsterdam, 489 p.

GUYOT (J.L.), BOURGES (J.), HOORELBECKE (R.), ROCHE (M.A.), CALLE (H.), CORTES (J.), BARRAGAN (M.C.), 1988. Exportation de matières en suspension des Andes vers l'Amazonie par le Rio Béni, Bolivie. Proc. Porto Alegre Symposium, December 1988. IAHS, n° 174: 443–451.

GUYOT (J.L.), CALLE (H.), CORTES (J.), PEREIRA (M.), 1990. Transport de matières dissoutes et particulaires des Andes vers le Rio de La Plata par les tributaires boliviens (rios Pilcomayo et Bermejo) du Rio Paraguay. *J. Sci. Hydrol.*, 35 (6): 653–665.

GUYOT (J.L.), ROCHE (M.A.), NORIEGA (L.), CALLE (H.), QUINTANILLA (J.), 1990. Salinities and sediment loads on the Bolivian Highlands. *J. Hydrol.*, 113: 147–162.

GUYOT (J.L.), BOURGES (J.), Calle (H.), CORTES (J.), HOORELBECKE (R.), ROCHE (M.A.), 1991. Transport of suspended sediments to the Amazon by an andean river: the River Mamore, Bolivia. Fourth Internat. Symposium on River Sedimentation, Beïjing, November 1989 (in press).

HECKY (R.E.), KILHAM (P.), 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: A review of recent evidence on the effects of enrichment. *Limnol. Oceanogr.*, 33: 796–822.

HEGEWALD (E.), ALDAVE (A.), HAKULI (T.), 1976. Investigations on the lakes of Peru and their phytoplankton. 1: Review of literature, description of the investigated waters and chemical data. *Arch. Hydrobiol.*, 78 (4): 494–506.

HEGEWALD (E.), RUNKEL (K.H.), 1981. Investigations on the lakes of Peru and their phytoplankton. 6: Additionnal chemical analyses. *Arch. Hydrobiol.*, 92 (1): 31–43.

HEIL (G.W.), WERGER (M.J.A.), de MOL (W.), van DAM (D.), HEIJNE (B.), 1988. Capture of atmospheric ammonium by grassland canopies. *Science*, 239: 764–765.

HOWE (M.R.), TAIT (R.I.), 1969. Some observations of the diurnal heat wave in the ocean. *Limnol. Oceanogr.*, 14: 16–22.

HUTCHINSON (G.E.), 1957. A treatise on Limnology. I. Geography, Physics, and Chemistry. John Wiley & Sons, New York, 1015 p.

HUTCHINSON (G.E.), LÖFFLER (H.), 1956. The thermal classification of lakes. *Proc. Nat. Acad. Sci.* USA, 42: 84–86.

ILTIS (A.), 1987. Datos sobre la temperatura, el pH, la conductibilidad eléctrica y la transparencia de las aguas de superficie del lago Titicaca boliviano (1985–1986). UMSA-ORSTOM, La Paz, Informe 3: 19 p., multigr.

IVANOFF (A.), 1975. Introduction à l'Océanographie. Tome II. Vuibert. Paris, 340 p.

JACOBS (W.C.), 1951. The energy exchange between sea and atmosphere and some of its consequences. *Bull. Scrips Inst. of Oceanogr. Tech. Ser. Univ. of Calif.*, 6: 27–122.

KESSLER (A.), 1970. Über den Jahresgang des potentiellen Verdunstung im Titicaca-Becken. *Arch. Met. Geoph. Biokl.*, Ser. B, 18: 239–252.

KESSLER (A.), MONHEIM (F.), 1968. Der Wasserhaushalt Titicacasees nach neueren Messergebnissen. *Erdkunde, Arch. für Wissenschaft. Geogr.*, Bonn, 22 (4): 275–283.

KITTEL (T.), RICHERSON (P.J.), 1978. The heat budget of a large tropical lake, Lake Titicaca (Perú-Bolivia). *Verh. Internat. Verein. Limnol.*, 20: 1203–1209.

LAZZARO (X.), 1981. Biomasses, peuplements phytoplanctoniques et production primaire du lac Titicaca. *Rev. Hydrobiol. trop.*, 14: 349–380.

LAZZARO (X.), 1985. Poblaciones, biomasas y producciones fitoplanctónicas del Lago Titicaca. *Rev. Inst. Ecol.*, La Paz, 7: 23–64.

LEWIS (M.W., Jr.), 1973. The thermal regime of Lake Lanao (Philippines) and its theoretical implications for tropical lakes. *Limnol. Oceanogr.*, 18: 200–217.

LEWIS (M. W., Jr.), 1983. Temperature, heat and mixing in Lake Valencia, Venezuela. *Limnol. Oceanogr.*, 28: 273–286.

LÖFFLER (H.), 1960. Limnologische Untersuchungen an Chilenischen und Peruanischen Binnengewassern. *Ark. Geofysik*, 3: 155–254.

MEYBECK (M.), 1979. Concentrations des eaux fluviales en éléments majeurs et apports en solution aux océans. *Rev. Géol. Dynam. et Géogr. Phys.*, 21 (3): 215–216.

MONHEIM (F.), 1956. Beiträge zur Klimatologie und Hydrologie des Titicacabeckens. *Selbstverl. d. Geograph. Heidelberg*: 152 p.

MONTGOMERY (H.A.C.), THOM (N.S.), COKBURN (A.), 1964. Determination of dissolved oxygen by the Winkler method and the solubility of oxygen in pure water and sea water. *J. Appl. Chem.*, 14: 280–296.

NEALE (P.J.), RICHERSON (P.J.), 1987. Photoinhibition and the diurnal variation of phytoplankton photosynthesis – I. Development of a photosynthesis-irradiance model from studies of *in situ* responses. *J. Plank. Res.*, 9: 167–193.

NEVEU-LEMAIRE (M.), 1906. Les lacs des hauts-plateaux de l'Amérique du Sud. Imprimerie nationale, Paris, 197 p.

PAERL (H.W.), 1982. Factors limiting productivity of freshwater ecosystems. In: Advances in microbial ecology, Marshall ed.; Plenum Press, New York, 6:75–110.

PERRIN de BRICHAMBAUT (C.), LAMBOLEY (G.), 1968. Le rayonnement solaire au sol et ses mesures. Cahiers de l'AFEDES: 111 p.

PICK (F.), LEAN (D.R.S.), 1987. The role of macronutrients (C, N, P) in controlling cyanobacterial dominance in temperate lakes. *New Zeal. J. Mar. Freshw. Res.*, 21: 425–434.

POSNANSKY (A.), 1911. El clima del Altiplano y la extensión del Lago Titicaca con relación a Tihuanacu en épocas prehistóricas. Tipografía comercial de Ismael Argote, La Paz, 29 p.

POWELL (T.), KIRKISH (M.H.), NEALE (P.J.), RICHERSON (P.J.), 1984. The diurnal cycle of stratification in Lake Titicaca: eddy diffusion. *Verh. Internat. Verein. Limnol.*, 22: 1237–1242.

QUINTANILLA (J.), CALLICONDE (M.), CRESPO (P.), 1987. La química del lago Titicaca y su relación con el plancton. Documento de pesca 004, Oldepesca, Lima, 321 p., multigr.

QUISPE ZAPARA (L.L.), AMAN UI (A.A.), 1978. Caracterización hidrológica de la cuenca del río Coata. Tesis Ing. Agron. UNTA, Puno: 143 p.

REYNOLDS (C.S.), 1984. The ecology of freshwater phytoplankton. Cambridge University Press, Cambridge, 384 p.

RICHERSON (P.J.), WIDMER (C.), KITTEL (T.), 1977. The limnology of lake Titicaca (Peru-Bolivia). Univ. California, Davis. Inst. Ecology, 14, 78 p., multigr.

RICHERSON (P.J.), WIDMER (C.), KITTEL (T.), LANDA (A.), 1975. A survey of the physical and chemical limnology of lake Titicaca. *Verh. Internat. Verein. Limnol.*, 19: 1498–1503.

RICHERSON (P.J.), NEALE (P.J.), WURTSBAUGH (W.A.), ALFARO TAPIA (R.), VINCENT (W.F.), 1986. Patterns of temporal variation in Lake Titicaca, a high altitude tropical lake. 1: Background, physical and chemical processes and primary production. *Hydrobiologia*, 138: 205–220.

SCHINDLER (D.W.), 1977. The evolution of phosphorus limitation in lakes. *Science*, 195: 260–262.

SMITH (V.H.), 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: an empirical and theoretical analysis. *Limnol. Oceanogr.*, 27: 1101–1112.

SMITH (V.H.), 1983. Nutrient dependence of primary productivity in lakes. *Limnol. Oceanogr.*, 28: 1051–1064.

S.N.D.C. G.T.Z., 1981. Programa de irrigación Altiplano/valles. Estudio de factibilidad Huarina. Salzgitter Consult GmbH, La Paz, multigr.

TALLING (J.F.), 1969. The incidence of vertical mixing and some biological and chemical consequences in tropical African lakes. *Verh. Internat. Verein. Limnol.*, 17: 998–1012.

TALLING (J.F.), 1969. The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). *Internat. Rev. ges. Hydrobiol.*, 51: 545–621.

TAYLOR (M.), AQUIZE JAEN (E.), 1984. A climatological energy budget of Lake Titicaca (Peru/Bolivia). *Verh. Internat. Verein. Limnol.*, 22: 1246–1251.

TEJADA CARI (A.), 1977. Caracterización hidrológica de la cuenca del río Ilave. Tesis Ing. Agron. UNTA, Puno, 104 p.

VALLENTYNE (J.R.), 1957. Principles of modern limnology. *American Scientist*, 45 (3): 218–244.

VINCENT (W.F.), 1989. Cyanobacterial growth and dominance in two eutrophic lakes: review and synthesis. *Arch. Hydrobiol.*, 32: 239–254.

VINCENT (W.F.), WURTSBAUGH (W.A.), VINCENT (C.L.), RICHERSON (P.J.), 1984. Seasonal dynamics of nutrient limitation in a tropical high-altitude lake (Lake Titicaca, Peru-Bolivia): application of physiological bioassays. *Limnol. Oceanogr.*, 29: 540–552.

VINCENT (W.F.), VINCENT (C.L.), DOWNES (M.T.), RICHERSON (P.J.), 1985. Nitrate cycling in Lake Titicaca (Peru-Bolivia): the effects of high-altitude and tropicality. *Freshw. Biol.*, 15: 31–42.

VINCENT (W.F.), WURTSBAUGH (W.A.), NEALE (P.J.), RICHERSON (P.J.), 1986. Polymixis and algal production: latitudinal effects on the seasonality of photosynthesis. *Freshw. Biol.*, 16: 781–803.

VOLLENWEIDER (R.A.), 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *Mem. Ist. Ital. Idrobiol.*, 33: 53–83.

WASSON (J.G.), GUYOT (J.L.), SANEJOUAND (H.), 1991. Premières données concernant le carbone organique transporté par le Rio Desaguadero (Altiplano bolivien). *Rev. Fr. Sci. Eau* (in press).

WASSON (J.G.), MARIN (R.), 1988. Tipología y potencialidades biológicas de los ríos de altura en la región de La Paz (Bolivia). Congreso Iberoamericano y del Caribe sobre la Pesca y la Acuicultura, Isla Margarita, Venezuela, 8–14 Mayo 1988: p. 120, multigr.

WETZEL (R.G.), 1983. Limnology. Saunders College Publishing, Philadelphia, 767 p.

WIDMER (C.), KITTEL (T.), RICHERSON (P.J.), 1975. A survey of the biological limnology of Lake Titicaca. *Verh. Internat. Verein. Limnol.*, 19: 1501–1510.

WURTSBAUGH (W.A.), HORNE (A.J.), 1983. Iron in eutrophic Clear Lake, California: its importance for algal nitrogen fixation and growth. *Can. J. Fish. Aquat. Sci.*, 40: 1419–1429.

WURTSBAUGH (W.A.), VINCENT (W.F.), ALFARO TAPIA (R.), VINCENT (C.L.), RICHERSON (P.J.), 1985. Nutrient limitation of algal growth and nitrogen fixation in a tropical alpine lake, Lake Titicaca (Peru/Bolivia). *Freshwat. Biol.*, 15: 185–195.

C. DEJOUX and A. ILTIS / Editors

Lake Titicaca

A Synthesis of Limnological Knowledge

Kluwer Academic Publishers

Lake Titicaca

A Synthesis of Limnological Knowledge

Edited by

C. DEJOUX and A. ILTIS

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