VII.2. HYDROLOGICAL POTENTIAL
VII.2a. The water resources

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Lake Titicaca, with its 8500 km^2 of mirror-like waters during the season of mean water level is one of the largest and highest of the so-called "great lakes" in the world. The water resources of this immense natural reservoir of Lake Titicaca, situated at an altitude of over 3800 m, has aroused the interest of many researchers. No fewer than nine publications have been written on the hydrological balance of its catchment, in addition to numerous projects dealing with the exploitation of its "white gold."

Unfortunately, some of the projects dealing with this natural reservoir, shared between Peru and Bolivia, have been based on incomplete data, very often not supported by verified information, giving rise to an inaccurate interpretation of the true balance, or to theories not in accordance with reality. Moreover, it must be pointed out that these have generally not taken into consideration the impact of this exploitation on the environment as a whole.

In the light of a recent study of the water balance of the lake (Roche and Bourges, 1991), based on up-to-date information, it seems unrealistic to think of taking a discharge of 100 $m^3 s^{-1}$ from the basin and transferring it to another basin, without seriously damaging the environmental balance; this despite the fact that the potential energy that could be generated by taking advantage of a difference of level of 3000 m may be an idea to delight planners, engineers and hydrologists. The practicality of such projects depends not only on technical factors but also on geopolitical factors, since the lake is shared between two countries, and on multi-purpose factors of the applicability of its resources.

The aim of this study is not to propose an alternative project for the exploitation of the resources of Lake Titicaca, but to evaluate the water resources available, in the light of accurate up-to-date information.

C. Dejoux and A. Iltis (eds.), Lake Titicaca, 523–538.

Inventory of resources

The surface water resources of the catchment area

Since Lake Titicaca is a reservoir of water derived from an extensive basin, it is essential to take into account the potential of its catchment area, in order to determine the potential of the lake itself. Studies carried out in recent years have identified favoured areas in terms of availability of water resources:

- To the west of the lake where the main basin is that of the Rio Coata, possessing an exceptional water potential, and to a lesser extent the Rio Ilave. The mean annual specific discharge recorded over a period of 32 years is 7 l s^{-1} km^{-2} for the Coata and 5 l s^{-1} km^{-2} for the latter.
- To the north of the lake are the basins of the Rio Huancane and Rio Ramis. The mean annual input from these basins is greater than 5 l s^{-1} km^{-2} for the former but scarcely reaches 4.6 l s^{-1} km^{-2} for the Rio Ramis basin due to its larger area.
- The south and east, mostly in the Bolivian part of the catchment, the specific discharges are lower, at around 4 l s^{-1} km^{-2}, with the exception of small catchments such as that of the Sehuenca (Fig. 1), which benefit from a more favourable situation due to their steep gradients.

It should be pointed out that these mean values for specific discharge do not provide an assessment of the potential inputs from the basins, which are in any case very heterogeneous, but indicate the magnitude of the resources available in the piedmont zone around the lake, and therefore in the zone that is more suitable for agriculture.

In reality, the availabilty of water in this area depends mainly on two factors:

- firstly the orography, which is related to the influence of air of Amazonian origin descending from the Cordillera;
- secondly the proximity to the lake which provokes heavy precipitation due to nocturnal evaporation (Boulangé, 1981; Roche and Bourges, 1991).

The heaviest and most prolonged rainfall occurs over the lake itself or in its immediate proximity, and on the summits, particularly of some of the mountains in the Western Cordillera.

The estimated available surface water resources in relation to the altitude or the geographical area in question, and the type of environment or time of year, are given in Table 1.

For the zones lying above an altitude of 4500 m, it is useful to divide the basins according to the altitude of their highest point, which can determine whether or not glaciers are present, and therefore whether a different annual flow regime exists. When glaciers are present, a typical catchment would have a dry season discharge from melting snows around 4 to 8 l s^{-1} km^{-2}, but in the absence of a glacier this would be reduced to about 1 l s^{-1} km^{-2}.

Quantitative variation in lake inputs over the year follows that of precipi-

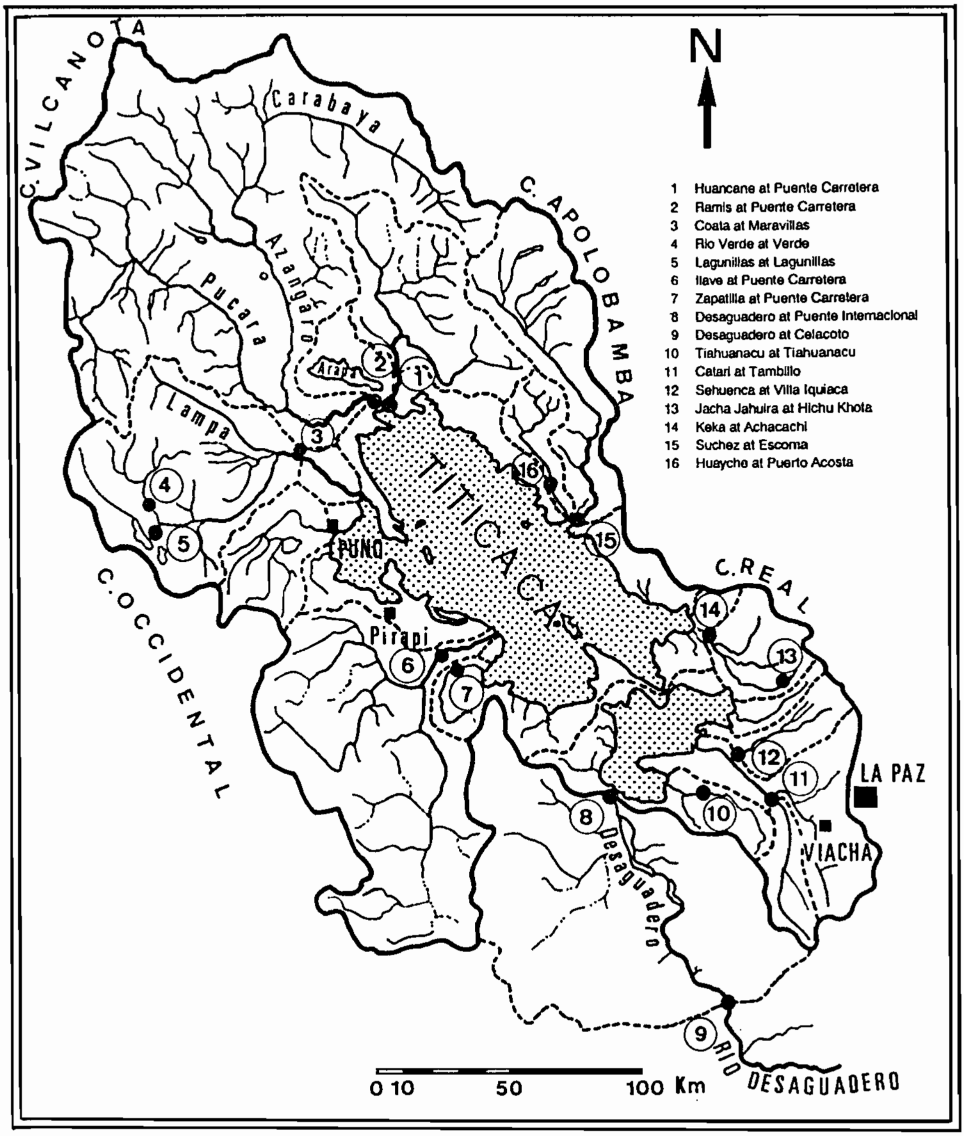

Figure 1. Hydrographic map of the Lake Titicaca catchment and location of gauging stations.

tation but with a delay. In general, there is a maximum in February and a minimum in August, but in reality nearly 80% of the annual input of water to the lake from the tributaries occurs between January and April. The dry season lasts for about six months from June to November (Lozada, 1985).

The variability between years in the resources originating from rivers is very great. Over the 20 years for which records are available, the total annual inputs from the network draining into the lake varied by ±70% around the

Table 1. Estimation of the water resources in each type of zone ($l\,s^{-1}\,km^{-2}$).

Type of area	Dry season (August)	Rainy season (February)	Annual mean
Altitude > 4.500 m Basin with a surface < 100 km² (presence of glaciers)	3 - 8	30 - 50	8 - 20
Altitude > 4.200 m Basins : 500 < S < 1.000 km²	0.5 - 1.5	20 - 50	6 - 15
Piedmount area	0.15 - 0.30	6 - 12	2 - 3
Lake shore	0.3 - 0.7	12 - 25	4 - 6

mean, and in only 10 years out of 20 was it within 20% of the mean value. This irregularity is accentuated by the occurrence of "runs" of years; for example the inflows close to the mean all occurred between 1970 and 1982, whereas during the period 1984–86 the values were all more than 30% greater than the mean.

The utilisation of these resources therefore implies not only rigorous management of the quantities of water taken, but also, depending on the scale of the project, a regulation of discharge at least on an annual basis or even over several years.

The water resources of the lake

Assessment of the resources

The water resources of the lake, as a reservoir, depend directly on those of the catchment. Even though its great volume has the effect of regulating lake levels in the face of variations in input, it is nevertheless very sensitive to meteorological variations.

The overall study of the potential water resources of the lake-catchment system therefore implies the creation of a model taking into account all the variables in the hydrological balance of the reservoir (Roche and Bourges, *op. cit.*), plus a study of the impact of any change in one of the variables on the lake level.

Under a natural regime without any human influence, the lake absorbs any fluctuations in inputs due to weather, by changes in its water volume. In order to manage these resources more efficiently, it is nevertheless possible to control certain of the variables, such as the quantity of water flowing out by the Desaguadero, and therefore influence the lake level.

The theoretical utilisable water resources, available for any given period, can be considered as the algebraic sum of the volume flowing out via the Desaguadero and the change in lake volume compared to its initial volume.

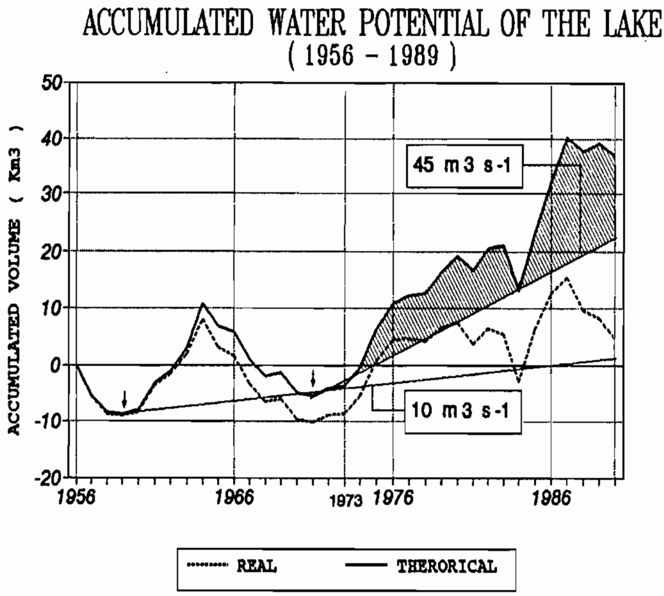

Figure 2. Changes in the theoretical annual cumulative potential water resources from 1956 to 1989 and comparison with the true potential (in billions of m^3). A zero potential was arbitrarily chosen for the level on 1 January 1956, i.e. 3809.65 m altitude. Striped area = available reserve in the case of 43 $m^3 s^{-1}$ option.

To calculate this balance, the outflow discharge needs to be known with an acceptable accuracy that has required a preliminary re-examination of the raw data (Bourges *et al.*, 1991). The real potential only takes into account the lake level.

If the theoretical water resources of the lake are accumulated for each hydrological year running from January to December, over the best documented period (1956–1989), it can be seen that this potential at first fluctuates and then increases greatly from 1973 onwards (Fig. 2).

Because a period of deficit existed between 1956 and 1958, no offtake of water could be envisaged for these years, without leading to an additional lowering of lake level. For the purposes of a simulation, it was therefore necessary to wait until 1959 before starting.

The total offtake of water is the sum of the quantities removed from the tributaries/lake system, whether continuously or discontinuously, and by whatever means: pumping from the lake, evacuation by the Desaguadero or withdrawal from the tributaries.

If, for example, the total annual offtake was fixed, as from 1959, at $315 \times 10^6 m^3$, or a discharge of $10 m^3 s^{-1}$, it appears that such a quantity could be removed from the lake until 1989, without any effect on the lake's resources. It should be noted, however, that by the end of 1970, the lake would have returned to its initial state of 1 January 1959, with a level of

3808.60 m above sea level (Fig. 2). This is in fact what actually was observed, since the lake was 12 cm below this level and the mean discharge of 11 $m^3 s^{-1}$ evacuated by the Desaguadero was very similar to the chosen hypothetical value for offtake. The extreme levels reached between 1959 and 1977 would have been 3808.55 m in December 1970 and 3811.20 in April 1963.

It is evident that after 1970, the total withdrawals, by offtake or by outflow, would have been much greater; if not, the increase in the lake's volume, which was greater than 40×10^9 m^3 at the time of the maximum in April 1986, would have led to levels much higher than those recorded during the floods.

If instead of taking 10 $m^3 s^{-1}$, the volume taken as from 1971 was 45 $m^3 s^{-1}$ (equivalent to a volume of 1420×10^6 m^3), with the exception of a slight drop in lake level in 1972, the initial level would have been reached at the end of 1983 (Fig. 2). Under this hypothesis, the lake level from 1971 to 1985 would have fluctuated at between 3808.30 and 3809.90 m altitude and the available resources would have been maintained at about 10×10^9 m^3 for eight years between 1975 and 1982.

Under the same hypothesis, the level reached in April 1986 would have been slightly less than 3812 m, or 60 cm below the maximum recorded, but still excessive in relation to the risks faced.

For the period 1956–1989, it would therefore appear that it would have been possible to ensure an annual volume for withdrawals of 315×10^6 m^3, while maintaining a minimum lake level of 3808.55 m, in 31 years out of 34. If this volume were to be increased to 1420×10^6 m^3 $year^{-1}$, it could only have been ensured for 19 years, between 1971 and 1989, and even this would have implied accepting a drop in level to 3808.30 m. In both cases these offtakes would have required additional outflows in 1985 and 1986, to maintain the lake level below the alert threshold.

The hypothetical discharges (10 and 45 $m^3 s^{-1}$) correspond to offtake values, which actually could be spread over the year according to real requirements.

Determination of the management criteria

If it were possible to control the discharge evacuated by the Río Desaguadero (creation of artificial spillways, dredging of a channel in the river), it would be possible to fix as objective the maintenance of a minimum lake level of 3808.30 m and a maximum level of 3811.00 m.

Between these two limits, it would be possible in a wet year to use the water resources as from the month of April – which usually corresponds to the peak level – so as to reach at the period of low water level the level of 3809.50 which is the lake's mean level between 1915 and 1989. This would provide two advantages:

– The available reserve above the minimum threshold would represent

10×10^9 m^3 which could either provide additional supplies during several successive average years, or lessen the effects of two successive years of deficit (4×10^9 m^3) or one exceptionally dry year such as 1983 (8×10^9 m^3).
- The lake level could be maintained below the fixed maximum in wet years. Since the annual range in lake level over the 34 years has varied from extremes of 169 cm (in 1984) and 55 cm, with a mean of about a metre, there is a sufficient safety margin.

In contrast in an average or dry year, it is necessary to withdraw from the available reserves and manage the resources so as to try and get back to the level of 3809.50 m.

Simulation of management with upper and lower thresholds. Application to the period 1915–1989

Once the extreme limits of variation in lake level were adopted, a simulation of management was carried out, using the two options already proposed (10 and 45 m^3 s^{-1}), and the following results were obtained:
- from 1959 to 1978 inclusive, by taking a hypothetical discharge of 10 m^3 s^{-1}, the lake would have fluctuated between 3810.85 m and 3807.35 m. It would have been necessary to release additional discharges in only two years out of twenty, in 1962 and especially 1963 (240 m^3 s^{-1}). These volumes of water would not have been available in the dry years from 1967 to 1973 when the lake level would have dropped below the fixed limit of 3808.30 m
- from 1971 to 1989 inclusive, the lake level would have been maintained at between 3811.15 m and 3808.30 m, by taking a hypothetical discharge of 45 m^3 s^{-1}. It would have neen necessary to evacuate additional disharges in six years out of nineteen, in particular in 1986 (210 m^3 s^{-1}). The levels fixed would have been complied with, except that the maximum limit would have been slightly exceeded. It should be noted, however, that if the discharge that should have been released in 1986 had been evacuated starting in January, the maximum level would not have exceeded 3811.05 m, or approximately the fixed limit.

It is clearly evident that the period 1959–1989 was a rather wet one compared to the entire period of records (1915–1989), especially after 1973 (Figs 3 and 4) and that care should be taken in extrapolating these results. For example if the overall slope of the curve of cumulative potential resources since 1915 is estimated (Fig. 5), the mean volume of offtake is around 380×10^6 m^3, whereas during the period 1945–1989, this volume would have been 850×10^6 m^3 year^{-1}, i.e. 27 m^3 s^{-1}.

A simulation covering the latter period, with an annual adjustment of the dry season level to 3809.50 m, if the level was higher, and an offtake of 315×10^6 m^3 year^{-1}, would have made the lake level drop to 3805.30 m in 1943, and the minimum annual level would have been below the limit in 34

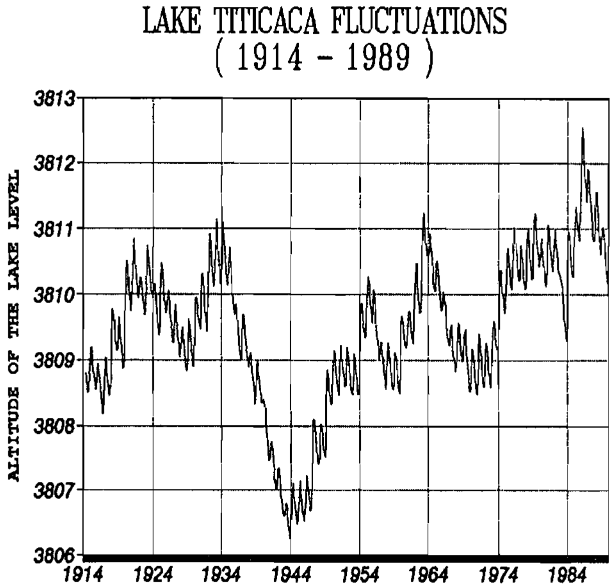

Figure 3. Changes in the level of Lake Titicaca from 1914 to 1989. Altitude in metres a.s.l.

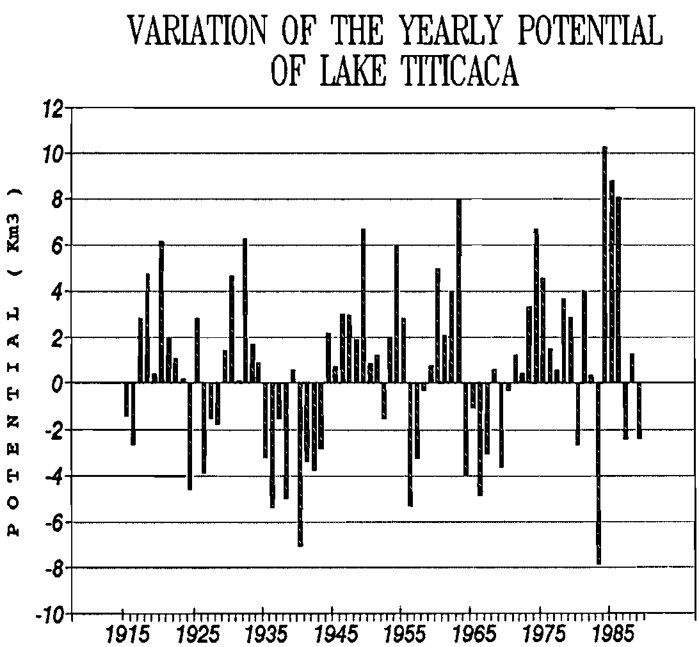

Figure 4. Value of the theoretical water potential of Lake Titicaca on the 31 December of each year, compared to its value on the previous 1 January.

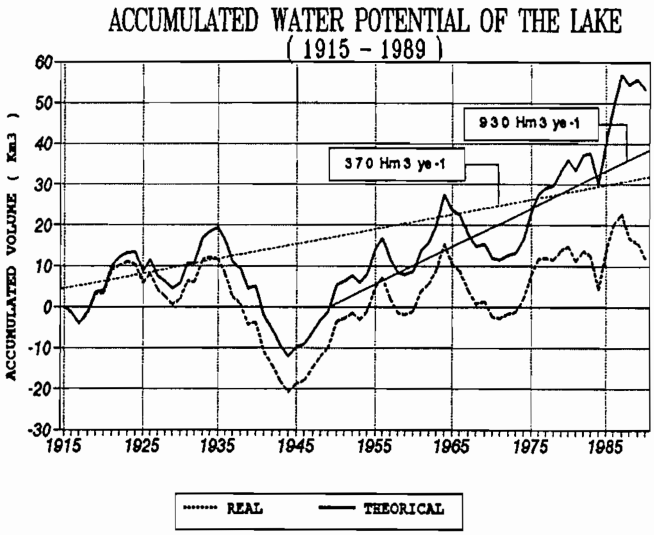

Figure 5. Changes in the theoretical annual cumulative potential water resources from 1915 to 1989 and comparison with the true potential. The zero potential corresponds arbitrarily to the level on 1 January 1915, i.e. 3808.81 m altitude., i.e. about $7 \times 10^9\,m^3$ below the previous reference (Fig. 2).

years out of 75. The maximum of 3911.15 m would have been reached in this case in 1986.

Therefore, over the entire period of observations, from 1915 to 1989,it would appear that it would have been possible to take a hypothetical discharge of $10\,m^3\,s^{-1}$ from 1915 to 1936 and then from 1949 to 1972, and from 1973 onwards this could have been increased to $45\,m^3\,s^{-1}$, while only just reaching the permissible limits for lake level.

Recommendations

It is evident that the Rio Desaguadero, the natural outflow of the lake and which irrigates all the Bolivian Altiplano, should be accorded a minimum discharge, to prevent salinisation of the water course by its tributaries downstream in the event of drying up of flows coming from the lake.

For a rational management, it should be agreed that the catchment be equipped with a network of remote transmitting rain gauges and river gauging stations, connected to a forecasting model. This arrangement would provide advance information on the quantity of the resources and would warn of natural hazards due to excessive inputs of the catchment and of their consequences on the lake level. For example, the mean monthly input from inflow rivers for February 1971 reached $1700\,m^3\,s^{-1}$. By adding the input of direct rainfall on the lake, a total input of $2100\,m^3\,s^{-1}$ is reached. More recently in March 1986, the mean discharge that it would have been necessary to evacuate in order to avoid a rise in lake level would have been 2000 $m^3 s^{-1}$.

Since the hydraulic properties of the Río Desaguadero limit the discharges that can be evacuated to much lower values, additional outflows have to be looked for. If such a solution is not possible the storage capacity of the lake is incapable of absorbing such inputs and there is no other alternative but to face flooding.

In addition, as Lake Titicaca is part of an endorheic system, account must be taken of the consequences that management of the lake, and the injection or retention of very large volumes of water, could have downstream in Lake Poopo or possibly in the Salar de Coïpasa.

Subterranean water resources

Although quantitatively small the subterranean water resources participate in the hydrological balance of the lake. It is very probable in fact that the lake is fed laterally by the water tables situtated around its margins (Gumiel, 1988), and that removal of water from these water tables would decrease inputs to the lake.

Despite the absence of any complete estimate of these subterranean water resources, it is nevertheless on record that on the Peuvian side there are about 12,000 wells or boreholes around the lake (Ministerio de Agricultura, 1986). These are mainly on the plain, near low-lying coastlines and below 4000 m altitude. In this zone the water table is very near the surface, at about 1 to 3 m depth, and therefore always with a positive head with respect to the lake, which supports the hypothesis of subterranean inflows into the lake. Trial pumpings carried out in Peru give average outputs of 20 to 25 $l\,s^{-1}$.

According to a United Nations study (1973) carried out over only two years, the total recharge available for the Bolivian catchments situated to the south-east of the lake would be around 160×10^6 m^3 per year, mainly concentrated in the Catari catchment (Fig. 1).

Water quality

With a few exceptions (Pallina, Huancané) the surface waters are relatively lightly mineralised. In their lower reaches most of the tributaries have mean concentrations of dissolved salts of between 200 and 300 $mg\,l^{-1}$, with the exception of the Río Suches and the rivers running off the Cordillera Real, where they are around 50 $mg\,l^{-1}$ (Carmouze *et al.*, 1981; Guyot *et al.*, 1990, and see also Chapter V.3).

The underground waters are slightly more mineralised than the surface waters and have salinities around 400 $mg\,l^{-1}$ (United Nations, 1973).

Because of evaporation, the waters of the lake are more mineralised, their concentration of dissolved salts averaging around 700 mg l^{-1} (Chapter V.1).

The quality of these waters is therefore suitable for all types of usage, although, in the case of the lake water, good drainage is often required if it is to be used for agricultural purposes. For example, Lake Titicaca water has been used for 30 years in the Pirapi irrigation district, situated near Puno (Fig. 1), without any observable soil salinisation.

Use of the water resources

Principles of use

Before dealing with the many possibilities for exploiting these resources, it seems useful to put forward some principles which should govern its use:

- The water used should be exploited as a priority within the catchment area of the lake or of the Desaguadero. Any transfer towards another catchment should only be envisaged as a last resort and be subject to a detailed impact study.
- Priority for use should be given to the areas around the shoreline.
- Since the lake lies in two countries, the use of the resources should benefit both countries in the same manner.

As for the actual use of Lake Titicaca's water, this covers several essential applications such as energy production, agriculture and human requirements.

Energy production

If all transfer outside the catchment is excluded, the only projects that can be envisaged are dams on the tributaries.

In this case the quantities of water lost are rather low since the majority of the water is returned to the water course downstream from the dam. Five moderate-sized projects are planned for the Peruvian side (ElectroPerú, 1981) and a larger project is under study for the Bolivian side on the Río Suches.

Given the very low gradient on the Río Desaguadero, any project for using the outflow from the lake in this water course would seem to be excluded, unless very expensive schemes are carried out.

Agricultural use

Simple forms of irrigation have been practised around the lake for a long time, for crops or more frequently pastures. The non-quantified resulting water consumption is implicitly taken into account in the estimation of resources and is not therefore included in the present requirements.

As far as irrigation schemes are concerned, the following developments can be noted:

- 18,600 ha in Peru are in the course of being supplied with water, of which 6500 ha already function in an irregular fashion (Ministerio Agricultura Perú, 1986).
- on the Bolivian side, 5000 ha are already functioning near Huarina, irrigated by surface water, and 8800 ha are planned using underground water.

The irrigation period mainly concerns the five or six months of the year from October to March, depending on the crops (cereals, root crops, vegetable gardening). It lasts almost all the year for pasture land.

If the efficiency is assumed to be 50%, the gross water requirements can be evaluated at about 1500 to 2000 $m^3 ha^{-1}$ per month, depending on rainfall. Under this hypothesis, if only surface water is used, the irrigation schemes in the process of being created or already in operation will use the entire resources available under the minimum option envisaged above ($315 \times 10^6 m^3 year^{-1}$). A small proportion will be returned to the network in the form of drainage. Even if underground resources are also used, it is probable that the inputs into the lake in October of 35 $m^3 s^{-1}$ for the entire catchment, would not guarantee these requirements every year.

Using the same bases for calculation, the entire irrigated area (around 200 000 ha) would require $2 \times 10^9 m^3$ in a dry year, of which a part would be returned, but nearly one billion m^3 would be used by the plants. In some years this volume would represent a very large withdrawal compared to the inflows to the lake from rivers.

Domestic and industrial water supply

At present these sectors of consumption only involve a negligible proportion of the quantitative balance, especially as in this case the water is usually restored to the network. All the offtake points are situated on the tributaries upstream from the lake.

On the Peruvian side, the industrial requirements include cement works, power stations and food processing. They are probably more of a threat due to possible pollution caused by their effluents than to their water consumption.

On the Bolivian side, in addition to the rural consumption and a few industries (Viacha cement works), mention must be made of the water supply to the city of La Paz, 70% of whose requirements come from the lake's catchment ($32 \times 10^6 m^3 year^{-1}$), as well as the great quantities pumped from the water table within the catchment ($11 \times 10^6 m^3 year^{-1}$).

Conclusions

It would appear to be difficult to reconcile an optimal utilisation of the lake's water resources using a regulation between years, with minimal variation in lake level, without creating reservoirs capable of storing the excess volumes of water present in some years, upstream from the lake, on the tributaries. With a total storage capacity of 3 billion m^3, discharges would have had to be released (i.e. waste resources) in only two years out of 75, whatever the option chosen from among the two hypotheses presented above. However, other than the fact that the creation and use of reservoirs would lead to an increase in losses, mainly through evaporation, it should be stressed that the volumes to be stored would require the construction of very large engineering schemes, requiring major investment. At present only natural lakes exist, especially in Peru, or artificial reservoirs with a capacity of less than 30 million m^3.

Among the potential uses of Lake Titicaca's water resources, it would appear that energy production should not be a priority, since more suitable sites exist in the two countries bordering the lake, in the Amazonian basin. Nevertheless, the construction of hydroelectric reservoirs on the inflows would have the advantage of regulating their discharge without significantly decreasing the resources.

In the hypothesis of a transfer of water out of the catchment area, the maximum discharge could not exceed 30 to 35 $m^3 s^{-1}$, corresponding to an available discharge in the case of the simulated maximum option (45 $m^3 s^{-1}$) and assuming that no other project arrives to create new requirements. Despite the large amount of energy produced (700 MW) because of the considerable head of water that can be used, this discharge would not seem sufficient justification for the investment, which could be very heavy. Even a combined irrigation-hydroelectric scheme, which would be more economically justifiable, could not justify the consequences of transferring these resources out of the basin, unless external inputs could be envisaged, that would at least partially compensate for this removal.

Well-planned agriculture adapted to the existing potential resources would be more beneficial in terms of economic and human benefits for the inhabitants living around the lake or along the Río Desaguadero (maintenance of the rural population). In this case, if the offtakes were limited to a few $m^3 s^{-1}$, the hypothesis of a transfer of water out of the catchment could be envisaged in a different manner.

In any case, if the uses of the lake's water resources are to be planned and coordinated, it is essential above all to draw up a model based on data from an adequate measuring network, which would provide real-time information on the surface and underground resources available. Once the resources are known, optimal use should be made of them by using a management model capable of simulating the various hypotheses complying with the chosen options.

It is difficult to envisage the extraction of 500 or 1000 $m^3 s^{-1}$ by the only exit from the lake, the Río Desaguadero, since the maximum discharge occurring at the lake outlet with a hundred years recurrence is around 300 and 350 $m^3 s^{-1}$ (Bourges *et al.*, 1991). With the aid of flood forecasting, it would be possible to regulate the volume of the lake's reserves so as to absorb exceptional inputs over 2000 $m^3 s^{-1}$, during one month, with a discharge of only 300 $m^3 s^{-1}$.

Although, *a priori*, a moderate drop in lake level would appear to favour a decrease in evaporative losses and therefore an increase in the potential water resources, a detailed study would be needed to determine the impact of this measure on the hydrological balance, and particularly on the cycle of evaporation and precipitation.

Finally, an overexploitation of the lake's water resources should be avoided as this could lead to an excessive drop in lake level with ecological and human consequences, likely to be negative rather than positive:

- destruction of ecosystems in shallow areas (Puno Bay, Lago Pequeño, etc.) which could lead to a decrease in the fishing potential.
- difficulties in navigation in certain areas.
- progressive decrease in the discharge of the Río Desaguadero, and perhaps drying out of its upper reaches.
- reclaiming of land, with possible, but unproven, agricultural potential.
- lowering of the water tables around the lake and probably of certain parts of the Bolivian Altiplano.
- progressive decrease in evaporation from the lake and therefore of rainfall in the immediate surroundings of the lake and on the lake itself.

Lake Titicaca represents an as yet untouched hydrological system in comparison to many others. In order that man can benefit from its resources he must be able to preserve it from overexploitation. This is the objective that has been fixed by Lake Titicaca Study Project (PELT), financed by the European Community, and at present in the stage of being set up.

Its aim is to draw up an overall binational Management Plan, for controlling, conserving and using the resources of the entire endorheic system as far as the Salars, and especially the water and fishing resources.

To achieve these aims it will particularly involve itself with:

- studying the problems of draught and flooding
- analysing the various alternatives for regulation using simulation on models
- determining the volumes of water that can be used without inflicting environmental damage
- developing the best solutions by defining the regulatory engineering works and by setting up a binational organisation
- developing a methodology for updating the Management Plan by integrating new data as they become available.[1]

[1] According to the terms of reference of the PELT study project.

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