*Journal of Hydrology*, 113 (1990) 147–162
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands



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# SALINITIES AND SEDIMENT TRANSPORT IN THE BOLIVIAN HIGHLANDS

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(Received February 21, 1989; accepted after revision April 15, 1989)

## ABSTRACT

Guyot, J.L., Roche, M.A., Noriega, L., Calle, H. and Quintanilla, J., 1990. Salinities and sediment transport in the Bolivian highlands. J. Hydrol., 113: 147–162.

Salinities and sediment loads of the rivers of the entire interior drainage basin of the Lake Titicaca, Rio Desaguadero, Lake Poopo and salars, as well as their evolution from upstream to downstream, have been characterized on the basis of the results of four samplings during runoff periods. On the other hand, the regimes of dissolved and suspended matter transport are characterized with periodic measurements and samplings at hydrometrical stations over several years. The junction of Lake Poopo and the Salar of Coipasa, since 1985 is noted, which recalls that an unique terminal lake of large area existed during some parts of the Quaternary. Mechanical and chemical erosion rates have been calculated for the basins that drain the Western (Rio Mauri) and Eastern (Rio Suches) Cordilleras of the Bolivian Andes. Most of the sediment comes from the Western Cordillera, with a mechanical erosion rate of 640 t $km^2$ $yr^{-1}$ for the basin of the Rio Mauri. On the other hand, Lake Titicaca is the main source of dissolved matter to Lake Poopo via the Rio Desaguadero.

## INTRODUCTION

The system comprised by Lake Titicaca and its inflowing tributaries, its outlet the Rio Desaguadero, which feeds Lake Poopo, the Rio Laca Jahuira, which exceptionally connects this lake and the Salar of Coipasa, and the Salar of Uyuni, constitute the main drainage of the interior drainage basin of the highlands in the heart of the high Andes. The climatological and hydrological Program of Bolivia (PHICAB)* undertook several field campaigns for the study of the salinities from upstream to downstream in the Bolivian highlands, in order to extend to the whole fluvio–lacustrine system the preliminary results reported by Ballivian and Risacher (1981) and Carmouze et al. (1981). Four

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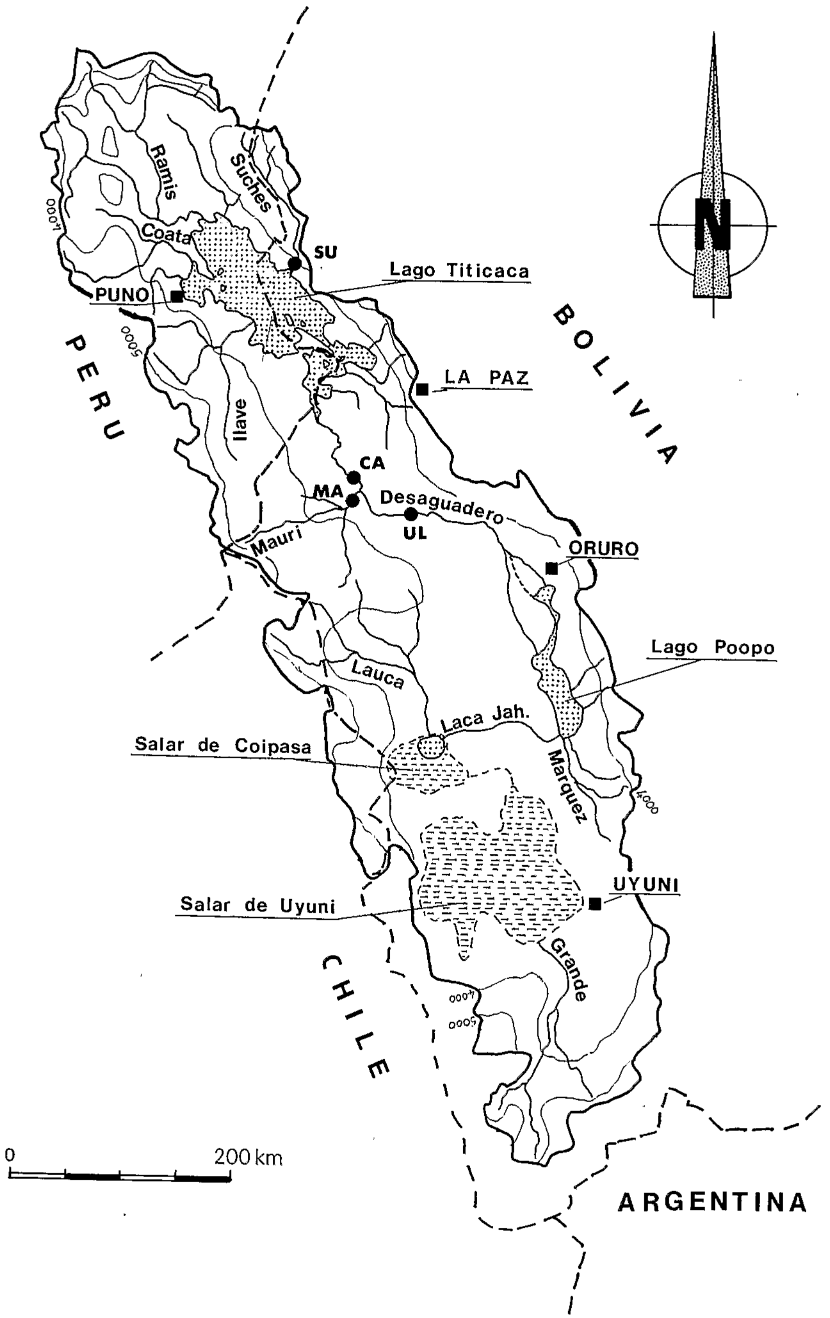


Fig. 1. Map of the interior drainage basin of the highlands showing position of measurement stations. See Table 1 for code to stations.

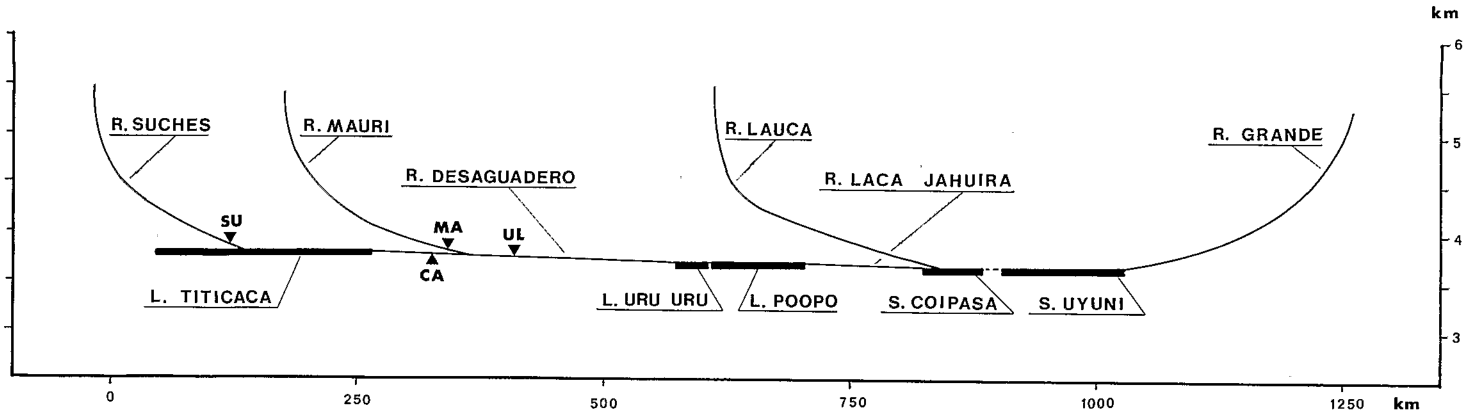


Fig. 2. Longitudinal profiles of the fluvio–lacustrine system of the Bolivian highlands. See Table 1 for code to stations.

samplings and flow measurements took place in 1987 and 1988 to characterize the salinity of many tributaries of the lakes.

Sediment yields have been evaluated for the 1976–1982 period on the Andean basins that supply Lake Titicaca and the Rio Desaguadero upstream Lake Poopo, using available data from three hydrometrical stations of the SENAMHI. Amounts of dissolved matters transported from Lake Titicaca, from the Western Cordillera and to Lake Poopo through the Rio Desaguadero have been calculated, using physicochemical data acquired by the PHICAB since 1983 at three hydrometrical stations. The spatio–temporal distributions of the sediment and dissolved loads, as well as the yields, have been characterized in relation to water yields, for which observations are available over a maximum period of about twenty years, depending on the stations.

## DESCRIPTION OF THE CLOSED BASIN

The closed basin of the highlands covers an area of 191,000 km$^2$, 27% of which is in Peru, 4% in Chile and 69% in Bolivia (Fig. 1). It is a large and narrow depression, about 200 km wide and 1000 km long, between the divides of the Eastern and Western Cordilleras of the Andes. Various subbasins can be identified: the basin of Lake Titicaca at its outlet of the Rio Desaguadero (57,100 km$^2$, 80% of which lies in Peru); the basin of Lake Poopo at Pampa Aullagas (57,200 km$^2$, 10% of which lies in Peru and 3% in Chile); the basin of the Salar of Coipasa (30,200 km$^2$, 20% of which lies in Chile); and the basin of the Salar of Uyuni (46,600 km$^2$). With peaks culminating to 6500 m in the Western (Sajama) and Eastern (Illampu...) Cordilleras and a minimum altitude of 3650 m at the Salar of Uyuni, the highlands fluvio–lacustrine system shows an average slope of 0.02%. Two topographical domains can be distinguished: that of the Andean Rivers (Suches, Mauri, Lauca, Grande) with high gradients, and that of the system of the lakes and salars, which are connected by the Rios Desaguadero and Laca Jahuira (Fig. 2).

Rainfall decreases from upstream to downstream (Roche and Rocha, 1985), i.e. from North to South, with a 710 mm average rainfall for the basin of Lake Titicaca (Lozada, 1985), 390 mm for the basin of Lake Poopo, 240 mm for the basin of the Salar of Coipasa, and 190 mm for the basin of the Salar of Uyuni (Mariaca, 1985). On the other hand, the rainfall distribution is the same, with a well marked rainy season from December to March (Fig. 3). The three wettest months supply from 51% of the yearly rainfall volume in the Andes of the Eastern Cordillera (Ulla–Ulla) to 81% in the South of the highlands (Salinas de Garcia Mendoza). The three driest months (from May to July), account only for 4.2 and 0.4% of this volume respectively. Receiving less than 200 mm yearly rainfall, concentrated in a few months of the year, the South of the highlands suffers an arid climatic regime, dry and cold, with almost no vegetation. With mean temperatures ranging from 6 to 10°C and higher rainfall, the North of the highlands is covered with pasture, that quickly grades to short and sparse vegetation with increasing altitude.

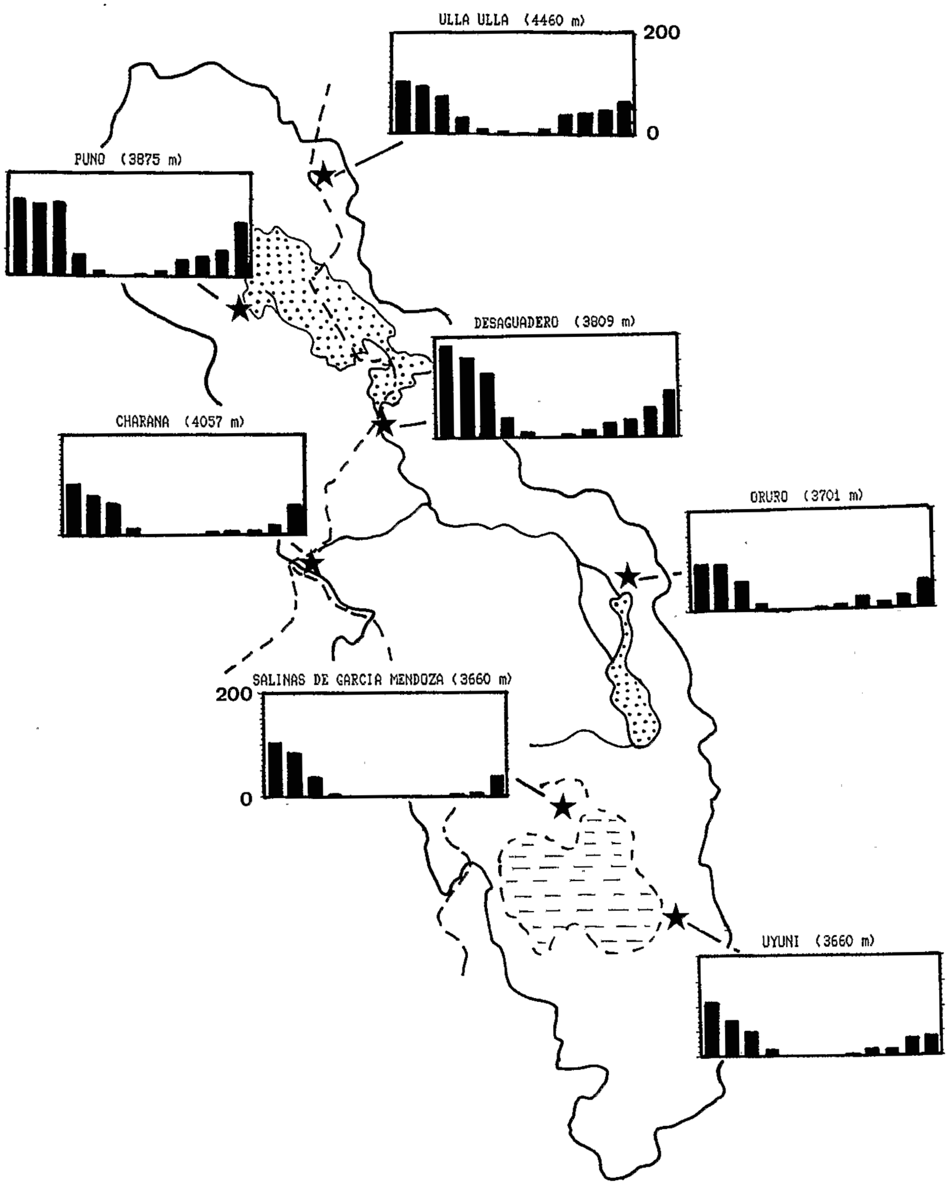


Fig. 3. Rainfall regime of the highlands (1968–1982) in mm, from Lozada (1985) and Mariaca (1985).

The Bolivian highland is mostly underlain by Tertiary or Quaternary sediments. The slopes of the Western Cordillera consist of eruptive series of the same age (Sajama volcano). The Eastern Cordillera, consisting mostly of Primary detrital series, shows some intrusive blocks that form the highest summits (Illampu . . .).

## HYDROLOGY

The hydrology of the basin of Lake Titicaca has been studied at length. The water balance of this system showed that meteoric yields are of the same order as the yields from the tributaries, and that more than 80% of the total yield is accounted for evaporation. The Rio Desaguadero accounts for less than 5% of the loss of the lake (Carmouze et al., 1978; Carmouze and Aquize, 1981; Lozada, 1985). The hydrology of the South of the highlands is much less known. Two budgets of the basin of Lake Poopo have been reported, one of them by a hydrochemical method (Carmouze et al., 1978), the other by a climatic balance (Mariaca, 1985). These two studies have shown that it is a closed environment, without a surface outlet and whose yield is mainly due to the tributaries, including the Rio Desaguadero. All of the hydrometrical stations used to study the transport of sediments (Table 1) are located in the Northern half of the drainage basin, because the South of the highlands is a scarcely populated zone of difficult access.

The station Calacoto on the Rio Desaguadero allows the characterization of the outflow of Lake Titicaca, in spite of the influence of a 9800 $km^2$ residual drainage basin. The stations of Escoma on the Rio Suches and Calacoto on the Rio Mauri give indications on the regime of the yields of the Eastern and Western Cordilleras of the Andes. Finally, the station of Ulloma provides an estimate of the yield of the Rio Desaguadero to Lake Poopo and the adjacent flood plain.

As measurements of sediments have been made from 1976 to 1982, the hydrological regimes of the studied rivers are described for this period. The average discharges are different from ones that had been previously published. For example, the Rio Ramis, a Peruvian tributary of Lake Titicaca has the following discharges: 71 $m^3 s^{-1}$ for the 1956–1973 period (Carmouze et al., 1978), 75 $m^3 s^{-1}$ for the 1956–1978 period (Carmouze and Aquize, 1981), 66 $m^3 s^{-1}$ for the 1968–1982 period (Lozada, 1985) and 73 $m^3 s^{-1}$ for the 1976–1982 period.

On the other hand, the evolution of mineralization at the stations of Calacoto (Rio Mauri and Rio Desaguadero) and Ulloma (Rio Desaguadero) has been investigated by the PHICAB since 1983. For this recent period, time records of the discharges are incomplete or lacking, except for the station of

TABLE 1

Characteristics of the hydrometric stations

| Code | Station | River | Altitude (m) | Area ($km^2$) |
|---|---|---|---|---|
| SU | Escoma | Suches | 3850 | 3100 |
| CA | Calacoto | Desaguadero | 3790 | 9800 + 57100* |
| MA | Calacoto | Mauri | 3790 | 9400 |
| UL | Ulloma | Desaguadero | 3775 | 22800 + 57100* |

* Lake Titicaca drainage basin area.

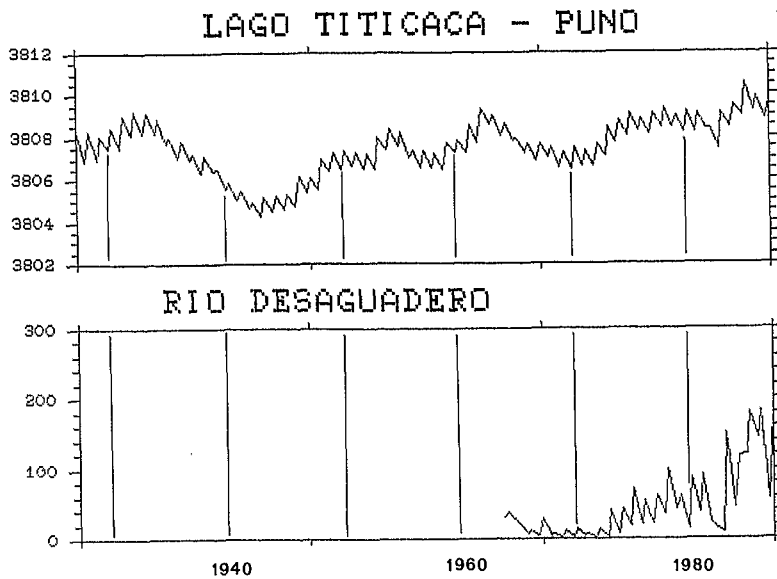


Fig. 4. Gauge heights of Lake Titicaca at Puno (1928–1988) in m.a.s.l. and discharge of the Rio Desaguadero at Calacoto (1964–1988) in $m^3 s^{-1}$ from data of the SENAMHI of Peru and Bolivia.

Calacoto on the Rio Desaguadero. The discharge of this river is $94 m^3 s^{-1}$ for 1983–1988 and only $52 m^3 s^{-1}$ for the 1976–1982 period. The mean yearly discharge for the whole 1964–1988 period is $46 m^3 s^{-1}$. The high variability of the discharge of the Rio Desaguadero is related to the gauge height of Lake Titicaca (Fig. 4). The studied periods (1976–1982 and 1983–1988) are periods of higher inflow compared to the average for 1928–1988. The rainfall excess is ever more important for the second period, whose consequences are the dramatic floodings around the Lake Titicaca, in the region of Oruro, and finally of Lake Poopo. The rising waters of Lake Poopo allowed the Rio Laca Jahuira to flow again, draining the waters of Lake Poopo to the Salar of Coipasa, since 1985. This exceptional connection recalls that a single terminal lake of large area existed during parts of the Quaternary (Servant et al., 1978). As there is no gauging station on this river, a few discharge measurements have been made by the PHICAB, giving values from $4 m^3 s^{-1}$ (February 1988) to $120 m^3 s^{-1}$ (April 1988). The hydrological regimes of the Andean tributaries (Rios Ramis, Suches and Mauri) are close and show a distribution of average monthly discharges similar to the distribution of rainfall (Fig. 5). The high water, from January to March, is responsible for 55% (Rio Suches) to 66% (Rio Ramis) of the average yearly discharge. The regime of the Rio Desaguadero at Calacoto is identical to the distribution of the average monthly gauge heights of Lake Titicaca at Huatajata, which indicates that the Rio Desaguadero at Calacoto is mostly supplied by the outflow of Lake Titicaca. On the other hand, at the station of Ulloma, the influence of the Rio Mauri of Andean origin is marked, and the regime of the Rio Desaguadero is mixed with a maximum of high water from

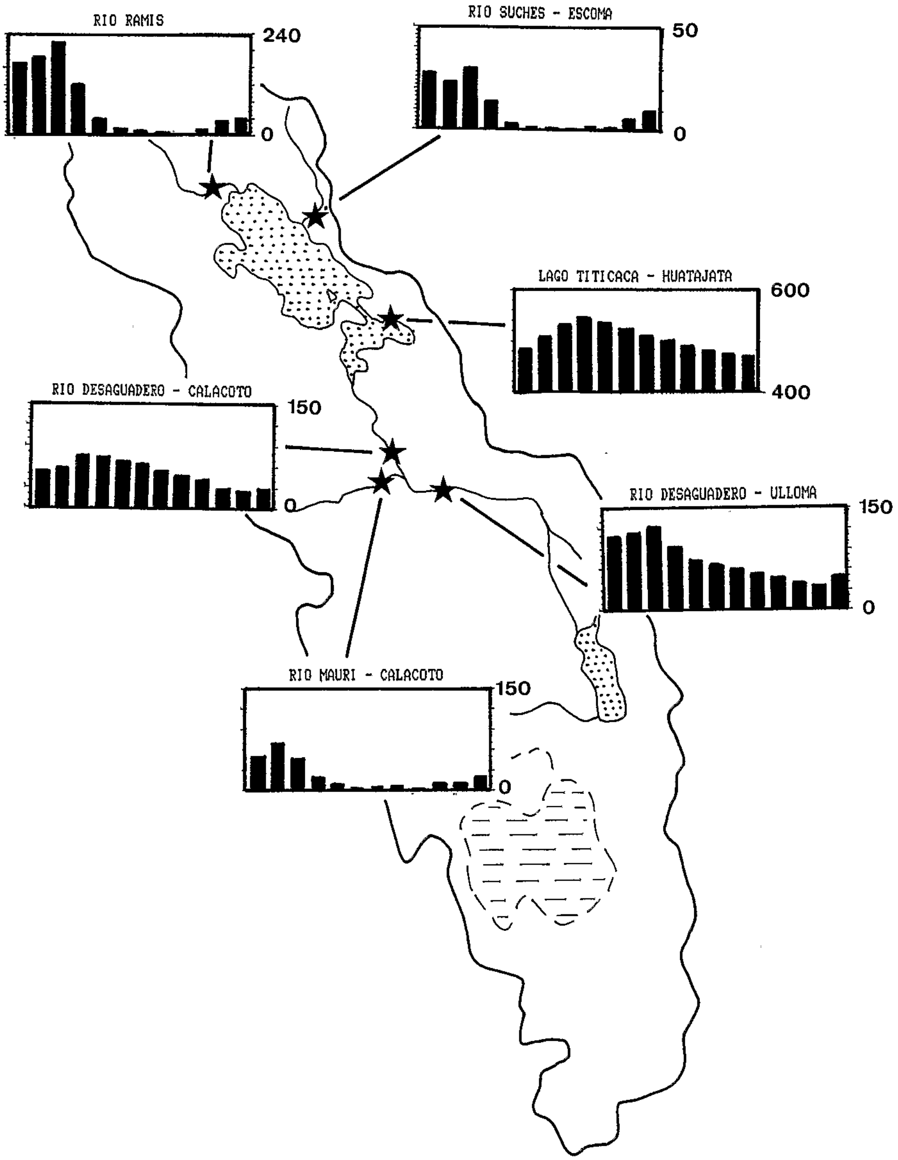


Fig. 5. Discharge of the rivers of the highlands (1976–1982) in $m^3s^{-1}$, and gauge heights of Lake Titicaca at Huatajata (1976–1982) in cm, from data of the SENAMHI of Peru and Bolivia.

January to March, followed by a slow decrease of the discharges and no marked low water periods.

## SEDIMENTS

The sediment samplings of the SENAMHI from 1976 to 1982 at the stations

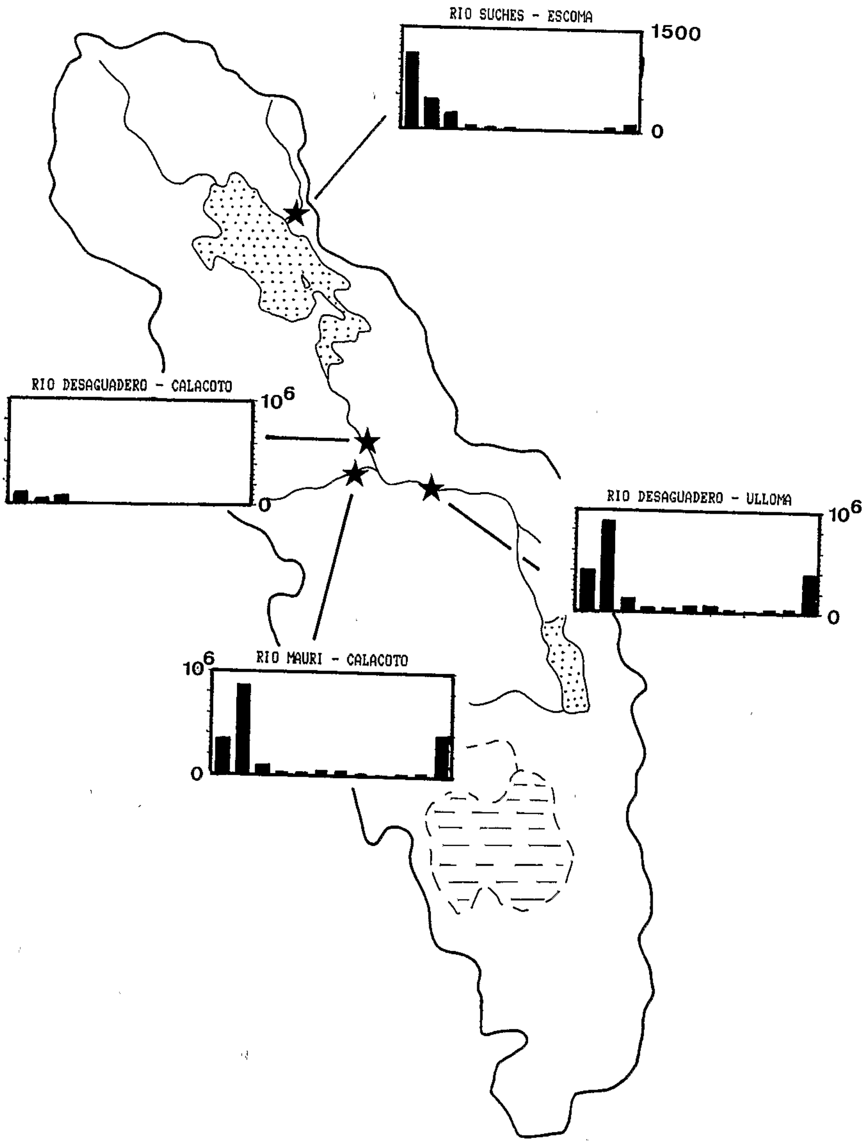


Fig. 6. Sediment transport from the Bolivian highlands (1976–1982) in ton $d^{-1}$.

of Escoma, Calacoto, and Ulloma allowed the estimation of sediment transport on this fluvio–lacustrine system of the highlands. It is clear at once that most of the sediment transport, for all the stations occurs from December to March and is coincidental to the pluviometrical regime, i.e. to the high flows of the Andean rivers (Fig. 6). The three months of high yield represent from 71% (Rio Desaguadero at Calacoto) to 81% (Rio Suches and Rio Mauri) of the yearly

TABLE 2

Sediment transport (1976–1982)

| Code | Discharge ($m^3 s^{-1}$) | TSS ($mg l^{-1}$) | Sediment discharge ($10^6 t yr^{-1}$) | Erosion rate ($t km^{-2} yr^{-1}$) |
|---|---|---|---|---|
| SU | 10 | 180 | 0.07 | 21 |
| CA | 52 | 250 | 0.58 | 59 |
| MA | 22 | – | 6.0* | 640 |
| UL | 73 | 1800 | 6.6 | 290 |

* Obtained by difference between UL and CA.

sediment volume. The Rio Desaguadero at Calacoto shows the same distribution as the Rio Mauri, but the values are ten times lower (Table 2).

As Lake Titicaca does not yield sediments to the Rio Desaguadero, the erosion rates upstream from the stations of Calacoto and Ulloma have been calculated without taking into account the area of the tributary drainage basin of Lake Titicaca.

Most of the sediment yield seems to come from the rivers of the Western Cordillera. The Rio Suches and Rio Mauri, which are fed by the Eastern and Western Cordilleras, respectively, with a similar longitudinal profile, show very different sediment yields, related to the geological characteristics of their drainage basin. The Rio Suches drains the Cordillera of Apolobamba, which is underlain by the Primary detrital series, whereas the Rio Mauri traverses Tertiary volcano–sedimentary rocks. The contribution of the Rio Desaguadero upstream is low, because the sediments come from the sedimentary rocks of the highlands, where the slopes are gentle.

## DISSOLVED MATTER

The regime of dissolved matter, which has been studied at the stations of Calacoto and Ulloma by the PHICAB since 1983, shows a monthly distribution close to the distribution of discharges at these stations (Fig. 7), with a maximum in April–May for the Rio Desaguadero at Calacoto, and from December to March for the Rio Mauri. The Rio Desaguadero at Ulloma exhibits a mixed regime. The interannual variation of the dissolved matter discharge is much lower for the sediment discharge. The three months of heavy transport of dissolved matter is responsible for only 34% (Rio Desaguadero at Ulloma) to 46% (Rio Desaguadero at Calacoto) of the annual total of dissolved matter. The yield of the Rio Suches, which drains Paleozoic rocks, to Lake Titicaca is of low concentration (Carmouze et al., 1981). Most of the dissolved matters (70%) is supplied by the Rio Desaguadero, i.e. comes from Lake Titicaca (Table 3).

The evolution of the mineralization of the Rio Desaguadero at Calacoto, during the 1983/84/85 hydrological cycles (Fig. 8), shows a classic inverse relation between the discharge and mineralization curves. The high water due

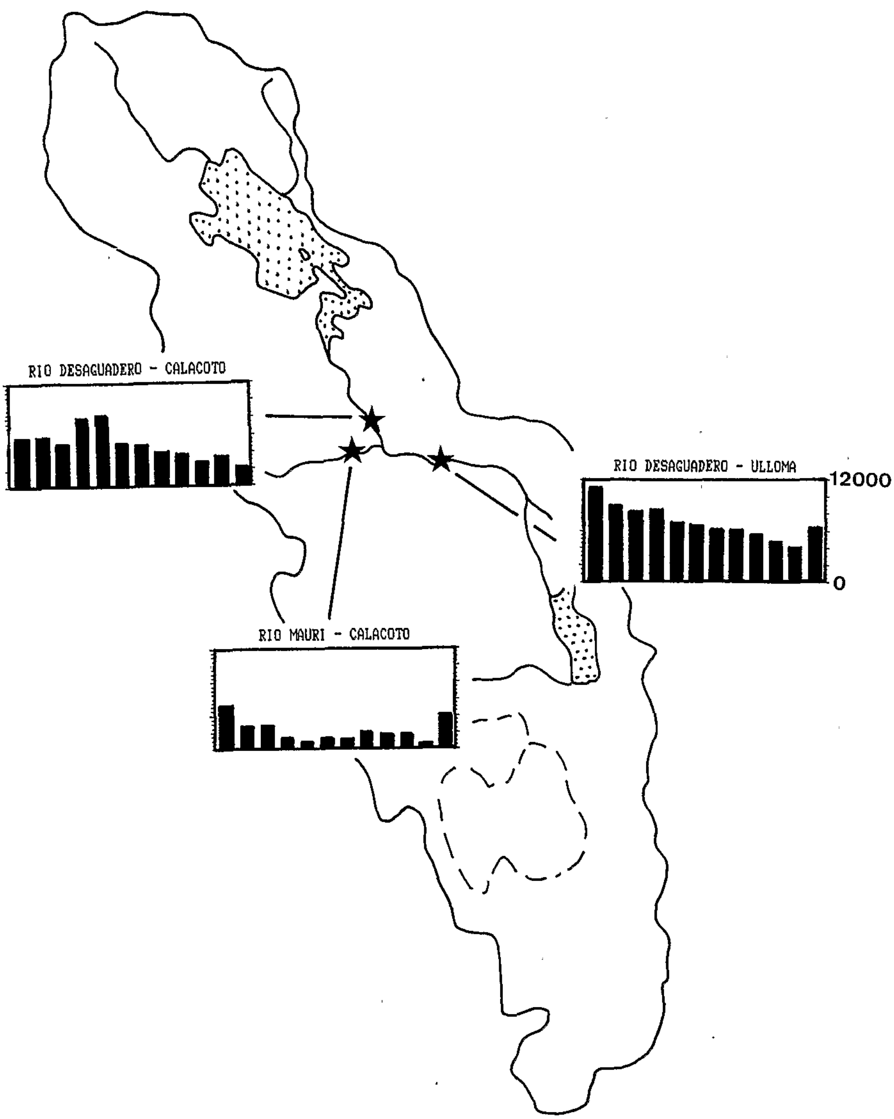


Fig. 7. Dissolved matter transport from the Bolivian highlands (1983–1988) in ton $d^{-1}$.

to the rainfall on the drainage basin between the station and Lake Titicaca provokes a drop in mineralization. At the end of the low–water period, dissolved matter tends to increase, probably in relation to the supply of the Rio Desaguadero by alluvial aquifers. After the high water, mineralization increases quickly up to a stable level, which agrees with the salinity of Lake Titicaca. This level seemed to decrease slowly during the time of the study, because of the increasing surface runoff of the system.

TABLE 3

Transport of dissolved matter (1983–1988)

| Code | Discharge ($m^3 s^{-1}$) | TDS ($mg l^{-1}$) | Dissolved discharge ($10^6 t yr^{-1}$) | Erosion rate ($t km^{-2} yr^{-1}$) |
|---|---|---|---|---|
| SU | 15* | 60 | 0.03* | 9* |
| CA | 94 | 670 | 1.8 | – |
| MA | 36* | 540 | 0.8* | 87* |
| UL | 130* | 660 | 2.6* | – |

* Estimated values.

## PHYSICO–CHEMICAL CHARACTERIZATION OF THE RIVERS

Under the PHICAB project, four sampling collections have been accomplished on the whole interior drainage basin of the Bolivian highlands, including discharge measurements on the main rivers. They were made in September and December 1987, and February and April 1988. The physico–chemical analyses were carried out in the laboratory of the IIQ–UMSA.

The waters of the fluvio–lacustrine system Titicaca–Desaguadero–Poopo–Laca Jahuira–Coipasa–Uyuni are of sodium chloride type with a progressive increase of mineralization from upstream to downstream. The concentration range from about 0.5 $g l^{-1}$ in Lake Titicaca up to 300 $g l^{-1}$ for the salt brines of the salars of Coipasa and Uyuni (Ballivian and Risacher, 1981). The tributaries of the system, which come from the Western Cordillera or from the

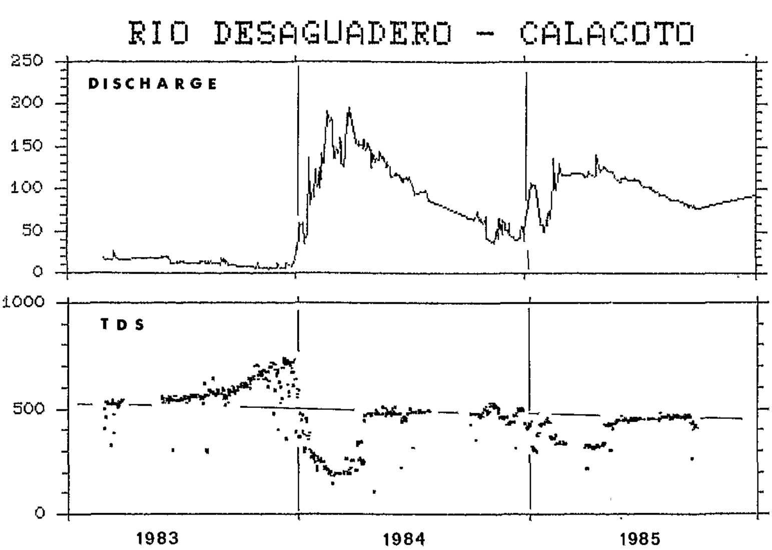


Fig. 8. Daily discharge in $m^3 s^{-1}$ and mineralization in $mg l^{-1}$ of the Rio Desaguadero at Calacoto station (1983–1985).

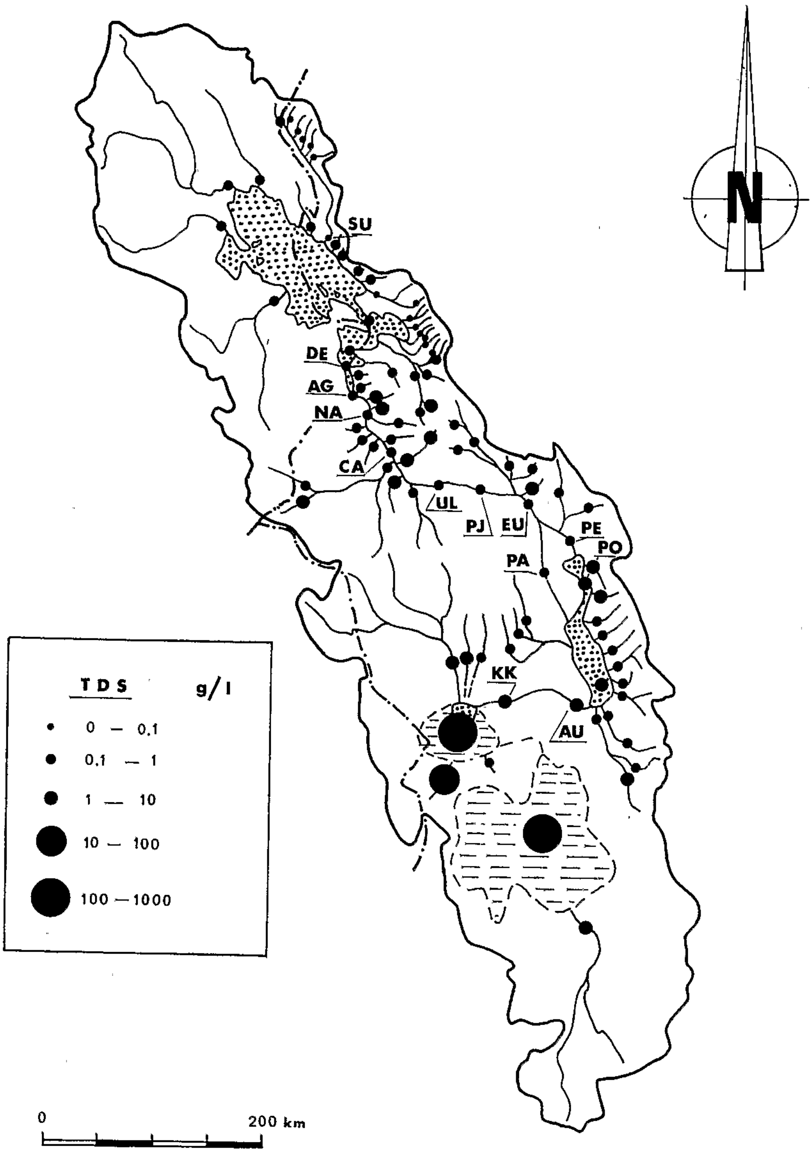


Fig. 9. Map of mineralization of rivers and lakes of the Bolivian highlands. *SU* = Rio Suches at Escoma; *DE* = Rio Desaguadero at Desaguadero; *AG* = Rio Desaguadero at Aguallamaya; *NA* = Rio Desaguadero at Nazacara; *CA* = Rio Desaguadero at Calacoto; *UL* = Rio Desaguadero at Ulloma; *PJ* = Rio Desaguadero at Puente Japones; *EU* = Rio Desaguadero at Eucaliptus; *PA* = Rio Desaguadero at Puente Aroma; *PE* = Rio Desaguadero at Puente Español; *PO* = Rio Desaguadero at Poopo; *AU* = Rio Laca Jahuira at Pampa Aullagas; *KK* = Rio Laca Jahuira at Khala Khala.

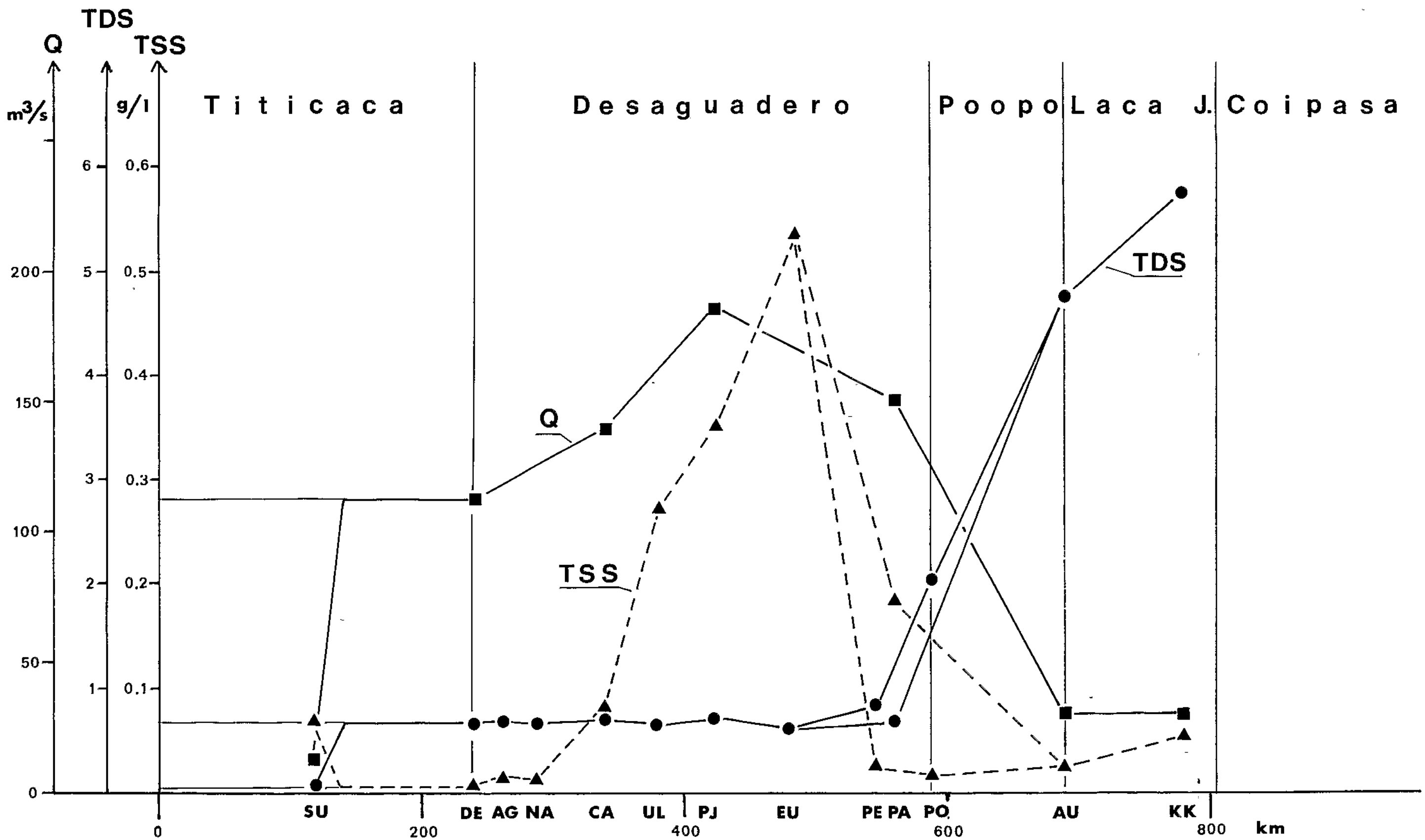


Fig. 10. Discharge in $m^3 s^{-1}$ and average content of sediment and dissolved matter in $g\,l^{-1}$, along the system Lake Titicaca–Rio Desaguadero–Lake Poopo–Rio Laca Jahuira (September 1987–April 1988). For legend see Fig. 9.

highlands, generally exhibit the same sodium chloride regime, although sometimes sodium sulfate predominates. On the other hand, the rivers that flow from the Eastern Cordillera, are weakly mineralized and essentially of calcium bicarbonate type, although sometimes magnesium contributes significantly and locally, calcium sulfate predominates in thermal springs area (Fig. 9).

The upstream to downstream evolution of sediment and dissolved mineral concentrations on the whole fluvio–lacustrine system, estimated from the mean values of the four samplings (Fig. 10) shows a progressive increase of the flow of the Rio Desaguadero down to Puente Japones, i.e. down to the flood plains. The flow decreases considerably through Lake Poopo, testifying to strong evaporation. The sediment load (TSS) decreases greatly in Lake Titicaca, all suspended material being deposited in the lake. Downstream of Lake Titicaca, the concentrations increase progressively along the Rio Desaguadero, together with the discharge, and drop as soon as the river enters the flood zone of the Uru–Uru Poopo system. The suspended sediment is deposited in this lacustrine environment, and is negligible at the exit of Lake Poopo. The dissolved matter concentration (TDS) is relatively stable along the Rio Desaguadero, from the exit of Lake Titicaca to Lake Poopo. Then, mineralization increases strongly, contrary to the discharge, because of evaporation.

## CONCLUSIONS

The samplings on the whole interior drainage basin of the Bolivian highlands have allowed the hydrochemical characterization of the different tributaries of this system. Waters coming from the Eastern Cordillera are weakly mineralized, generally of calcium–bicarbonate type, and show quite low suspended sediment contents. The rivers from the highlands and from the Western Cordillera are generally quite mineralized and of sodium–chloride type. Upstream to downstream evolution shows an increase of mineralization through flood plains or lakes, due to evaporation; on the contrary, suspended sediment coming mostly from the Western Cordillera, is deposited in this fluvio–lacustrine system. A transported matter budget has been calculated from results of regular samplings at several stations. The mechanical erosion rates range from 21 $t\,km^{-2}yr^{-1}$ for the Rio Suches basin, which drains a small massif of the Eastern Cordillera, to 640 $t\,km^{-2}yr^{-1}$ for the Rio Mauri basin, which is underlain by volcano–sedimentary rocks of the Western Cordillera. The budget of dissolved matter shows that about 70% comes from Lake Titicaca. The chemical erosion rates for the basins of the Rio Suches and Rio Mauri are respectively 9 and 87 $t\,km^{-2}yr^{-1}$, i.e. 2 and 7 times less than the mechanical erosion.

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