V.3. Dissolved matter and suspended sediment loads in some inflow rivers and in the Rio Desaguadero

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The hydrology and hydrochemistry of Lake Titicaca and of its main inflows have been the subject of many studies and a preliminary balance for lake inputs has been drawn up from a series of ten sampling campaigns between 1976 and 1979 (Carmouze *et al.*, 1978, 1981). Although the present rate of sedimentation is known from sedimentological studies in the Lago Huiñaimarca (see Chapter II.3), the direct inputs of riverine sediments have only been studied qualitatively (Boulangé *et al.*, 1981), and the seasonal changes in these inputs (dissolved and suspended) are still poorly known.

A recent typological study on water courses in the La Paz region, based on a regional ecological approach (Wasson and Marin, 1988) provided a series of data on the hydrology, hydrochemistry and suspended matter concentrations on two small Bolivian inflows into Lake Titicaca, the Rios Tiwanaku and Jacha Jahuira (or Keka). These two streams have similar mean annual discharges of about 1 $m^3 s^{-1}$, but originate from very different catchment areas, since the former (TI) is situated entirely on the Altiplano, whereas the latter (JJ) flows down a glacial valley from the Eastern Cordillera. Each stream was sampled every ten days throughout an entire hydrological cycle. Chemical analyses of the major ions were carried out and the concentration of suspended matter was measured by filtering 1 l of water through a Whatman GF/C filter followed by drying at 105 °C for 2 hours.

These data provide new information on the spatio-temporal variation of dissolved and suspended matter inputs to Lake Titicaca, in relation to the nature of the catchment areas and the hydrological season. These data are supplemented by observations on the Rios Suchez and Desaguadero (Guyot *et al.*, 1990a), in order to determine the seasonal cycle and annual balances of matter entering the lake and then exported by the Rio Desaguadero (Fig. 1).

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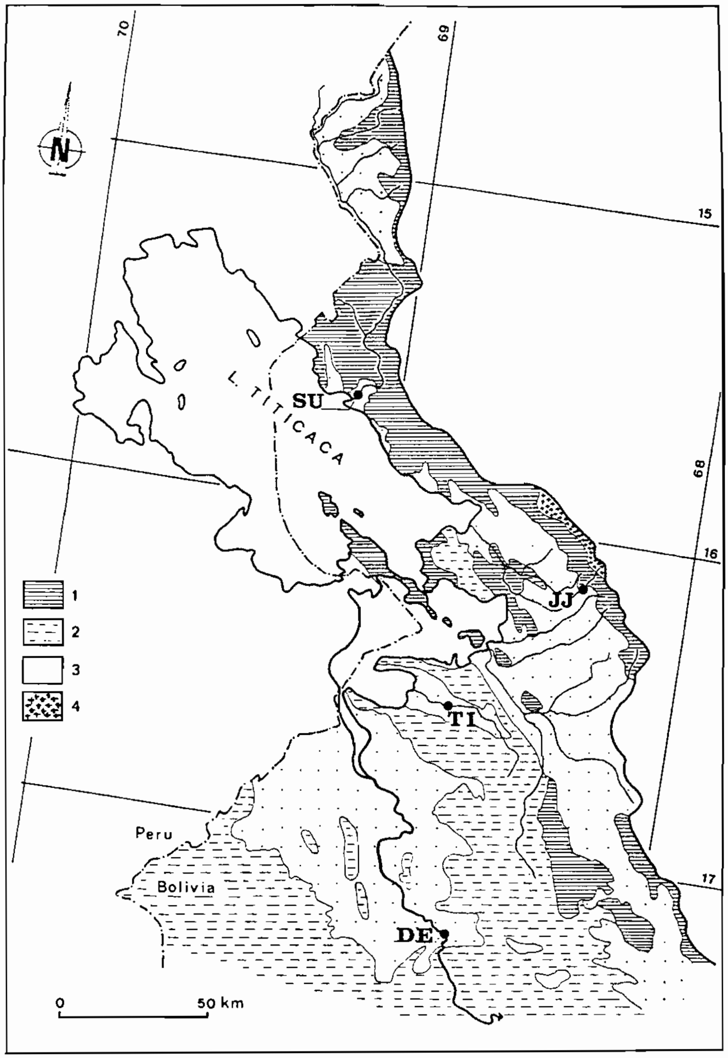

Figure 1. Simplified hydrographic and geological map of the Bolivian catchment area of Lake Titicaca, from the geological map of Bolivia at 1: 1000,000 (YPFB-GEOBOL, 1978).
1: Palaeozoic, 2: Cenozoic, 3: Quaternary, 4: Granite massifs. See station codes in Table 1.

The seasonal cycle

Hydrology

Under the influence of the same pattern of precipitation, typified by a marked rainy season from December to March, the lake inflows generally have a period of high water levels lasting from January to March (Fig. 2A). In

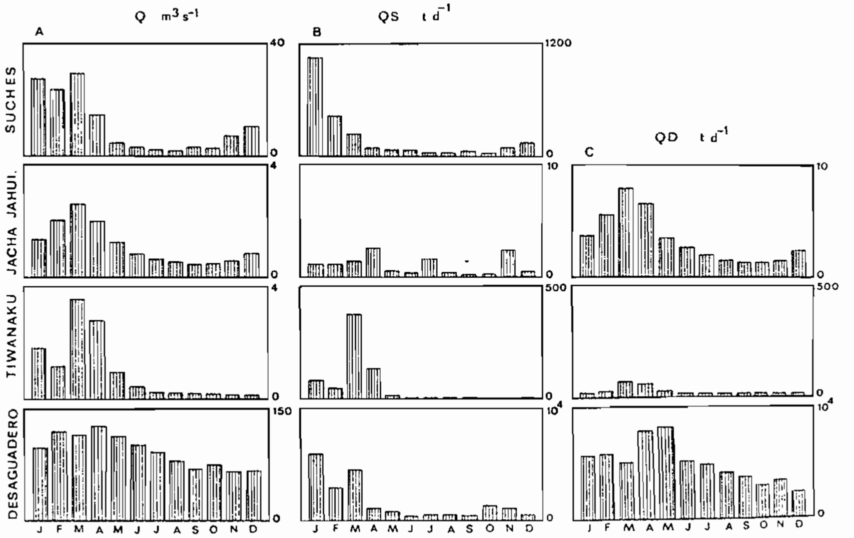

Figure 2. Seasonal cycle from January to December of suspended and dissolved matter. 2A: mean monthly discharges (Q, in $m^3 s^{-1}$). 2B: mean monthly flux of suspended matter (QS, in $t d^{-1}$). 2C: mean monthly flux of dissolved matter (QD, in $t d^{-1}$).

contrast, in the Rio Desaguadero, whose discharge is directly influenced by the level of water in Lake Titicaca, the period of high water levels extends until May because of the inertia related to the volume of water in the lake (Guyot *et al.*, 1990a).

Concentrations

The concentrations of total dissolved solids (TDS) and total suspended sediments (TSS) have very different seasonal cycles in the Rios Tiwanaku and Jacha Jahuira. In the former, changes in river discharge lead to great variations in the concentrations of suspended and dissolved matter, whereas in the latter the concentrations remain very low and remarkably stable throughout the seasonal cycle.

These differences are related to the geological and geomorphological characteristics of the catchment areas. In the case of the Rio Jacha Jahuira, only Palaeozoic rocks occur, dominated by the granite massifs of the Cordillera, which explains the very low concentrations of TDS. The profile in the form of a series of terraces, leading to the presence of a series of lakes upstream of the sampling station, contributes to decreasing the concentration of TSS carried. In contrast, the Rio Tiwanaku drains the Quaternary sedi-

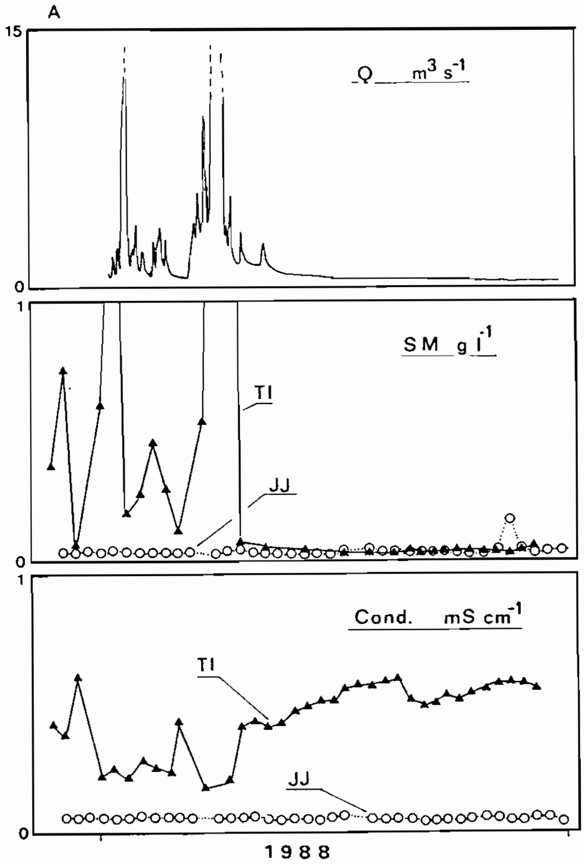

Figure 3. Seasonal changes over the period 1987–1988 in discharge at Tiwanaku (Q, in m^3 s^{-1}), suspended sediments (SM, in g l^{-1}) and electrical conductivity (Cond., in mS cm^{-1} at 25 °C) at Tiwanaku (TI) and Hichu Kkota (JJ).

ments of the Altiplano, which are very easily transported during floods (Fig. 3).

Flux

As a consequence, the cycles of the flux of dissolved and particulate matter are very different in these two water courses. In the Rio Jacha Jahuira, fluctuations in the TSS load are barely significant and the TDS load are directly related to river discharge. In contrast, in the Rio Tiwanaku, the TSS load is very high in the four months of high water level and practically zero in the dry season. Variations in the TDS load are much lower, because of a degree of dilution during the floods (Fig. 3).

The seasonal cycle of TSS in the Rios Suchez (at Escoma) and Desaguad-

Table 1. Characteristics of the sampling stations and quantities of matter transported.

Sites characteristics					Hydrology		
Codes	Rivers	Sites	Altitude of the sites (m)	Basin areas (km²)	Observation poriods	Mean annual discharges (m^{-3} s^{-1})	Specific discharges ($l.s^{-1}$ km^{-2})
SU	Suchez	Escoma	3.850	3.100	1976–1982	10	3.4
JJ	Jacha Jahuira	Hichu Kkota	4.320	63	1945–1975	1.1	17
TI	Tiwanaku	Tiwanaku	3.850	320	1987–1988	1.2	3.8
DE	Dosaguadero	Calacoto	3.790	9 800 + SL*	1976–1982	52	-

SL* = Lake Titicaca basin (57.100 km²))

Suspended sediments						Dissolved sediments				
Codes	Observation periods	N° sample	Contents (mg l^{-1})	Solid discharges (10^3 t yr^{-1})	Erosion rates (t km^{-2} yr^{-1})	Observation periods	N° sample	Contents (mg l^{-1})	Dissolved discharges (10^3 t yr^{-1})	Erosion rates (t km^{-2} yr^{-1})
SU	1976-82	52	180	65	21	1983-88	5	60	30	9
JJ	1987-88	39	9	0.3	5	1987-88	39	34	1.2	9
TI	1987-88	40	330	34	110	1987-88	40	280	6.6	10
DE	1976-82	100	250	580	59	1983-88	788	670	1800	-

ero (at Calacoto) have one characteristic in common with the Rio Tiwanaku: most of the transport of suspended matter takes place during the period of high water levels (Fig. 2B). This is not surprising in the case of the Rio Desaguadero where the TSS come from tributaries situated between Lake Titicaca and the sampling station and which drain catchments on the Altiplano of the same type as that of the Rio Tiwanaku. In the case of the Rio Suchez, this indicates that the Cenozoic and Quaternary sedimentary deposits traversed by the water course after leaving the Palaeozoic formation must have a significant influence on the TSS dynamics.

TDS and TSS budgets

An assessment of the flux of matter transported has been calculated from the available data (Table 1). For the Hichu Kkota station (JJ) for which the hydrological data come from an old series of observations (S.N.D.C. – G.T.Z., 1981), calculations were carried out from monthly averages corresponding to various periods, because of the absence of regular discharge records. In this particular case, this method does not present any major inconvenience because of the stability of the measured concentrations. On the other hand, in the case of a water course such as the Rio Tiwanaku, where major variations in concentrations are recorded over the seasonal cycle, calculation of the quantity transported from annual means (discharge and concentration) would result in an underestimate of the flux of suspended matter and an overestimate of the flux of dissolved matter.

The results given in Table 1 demonstrate the apparent uniformity of the rates of chemical erosion (dissolution), calculated after allowance for atmospheric inputs (bicarbonates in solution). These rates are of the order of 10 t km^{-2} yr^{-1} in all three inflows to the lake studied, despite the dissimilarities in their geographical situations.

Conversely, the rates of mechanical erosion are very variable depending on whether the catchments are situated on the Altiplano or in the Cordillera. In the Rio Jacha Jahuira, for example, the flux of dissolved matter is about twice as high as the flux of suspended matter and the rate of mechanical erosion (5 t km^{-2} yr^{-1}) is one of the lowest ever recorded in the Bolivian Andes. In the Rio Suchez, this rate although four times higher is still rather low for an Andean water course (Guyot *et al.*, 1988, 1989, 1990a, 1990b). In contrast, in the Rio Tiwanaku, although the mean concentrations of TSS are of the same order as those of TDS, the flux of TSS is five times higher because of the great temporal variation in concentrations. The rate of mechanical erosion in this water course is 110 t km^{-2} yr^{-1} and that recorded in the Rio Desaguadero is about half this value.

This area of the Altiplano would therefore seem to be characterised by a total erosion rate (solution + suspension) of the order of 60 to 120 t km^{-2} yr^{-1}, whereas the data obtained for the Rios Suchez and Jacha Jahuira give results that are four times lower for the western slopes of the Eastern Cordillera.

Consequences for Lake Titicaca

These data provide the first indication of the spatio-temporal variations in the regimes of dissolved and suspended materials entering and leaving Lake Titicaca.

As far as the export of material via the Rio Desaguadero is concerned, analyses carried out along this water course have shown that the dissolved content at Calacoto is the same as that of Lake Titicaca (Guyot *et al.*, 1990a); it is therefore valid to use this gauging station in drawing up the lake balance. Obviously, only the flux of dissolved matter (1800×10^3 t yr^{-1}, which is directly related to discharge, can be taken into consideration. In addition, a flux of total organic carbon (mainly in the dissolved form) of 18×10^3 t yr^{-1} leaving the lake has been estimated for the period 1976–1982 (Wasson *et al.*, 1991).

Estimating the flux entering the lake is a much more complex problem, because it is essential that the variability demonstrated be taken into account in drawing up the total quantities of matter. The rivers draining the Tertiary and Quaternary sedimentary deposits show great variations in their concentrations of dissolved salts and particularly in TSS during the seasonal cycle.

A regional approach by type of catchment basin, and from a sufficiently long series of measurements would appear to be essential to produce precise estimates, particularly for the suspended matter flux. At this time, the absence of data on the TSS in other inflows into Lake Titicaca prevents the drawing up of a total figure (TDS + TSS) for the flux of matter entering the lake. The results given here are a start in this direction and are of value in studies of present-day sedimentation in Lake Titicaca. They also form part of a wider study on the transport of matter and of erosion in the Bolivian Andes.

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