Dissolved solids and suspended sediment yields in the Rio Madeira basin, from the Bolivian Andes to the Amazon

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Abstract The Rio Madeira is the main southern tributary of the Rio Amazonas, and the second Andean tributary of the Amazon drainage basin. Using Bolivian data from the PHICAB programme and Brazilian data from the DNAEE sediment measurement network, downstream trends in the dissolved solids and suspended sediment yields, from the Andes to the Rio Amazonas, have been investigated. The dissolved solids load (36 $\times$ 10^6 t year^{-1} at Villabella on the Bolivia-Brazil frontier) increases progressively from upstream to downstream, in line with the discharge. Sediment loads decrease from the piedmont to Villabella (250-300 $\times$ 10^6 t year^{-1}) because substantial deposition occurs on the flood plain. The significant differences observed in Brazil are probably linked with the sediment load sampling technique and calculation method.

INTRODUCTION

With a basin covering over 6 million km^2 and a mean discharge of 209 000 m^3 s^{-1} (Molinier *et al.*, 1994), the Amazon is the largest river on Earth. The Amazon's yield to the Atlantic Ocean is estimated at 270 $\times$ 10^6 t year^{-1} for dissolved matter (Martinelli *et al.*, 1989) and from 1100 to 1300 $\times$ 10^6 t year^{-1} for suspended sediment (Meade *et al.*, 1985; Richey *et al.*, 1986; Meade, 1994).

Beginning its course in the eastern Andean Range in Peru and Bolivia, the Rio Madeira drains a basin of 1.4 $\times$ 10^6 km^2 and has a mean discharge of 31 200 m^3 s^{-1} (Molinier *et al.*, 1993). The pioneering work of Gibbs (1967) reported dissolved solids and suspended sediment yields of 59 $\times$ 10^6 t year^{-1} and 217 $\times$ 10^6 t year^{-1}, respectively, at the mouth of the Rio Madeira on the Amazon. Subsequent work from the ALPHA-HELIX, and the later CAMREX studies in the Brazilian Amazon region, showed that Gibbs' results greatly underestimated the suspended sediment load. The yield of the Rio Madeira to the Amazon has more recently been estimated at 37-45 $\times$ 10^6 t year^{-1} for dissolved matter and 550 $\times$ 10^6 t year^{-1} for suspended sediment (Ferreira *et al.*, 1988;

Martinelli *et al.*, 1989; 1993). In Bolivia, the results obtained by the Climatological and Hydrological Programme of the Bolivian Amazon basin (PHICAB) for the upper Rio Madeira basin at Villabella, from 1983 to 1990, show that the Rio Madeira transports a dissolved load of 35-40 $\times$ 10^6 t $year^{-1}$ and a suspended sediment yield of 223 $\times$ 10^6 t $year^{-1}$ (Roche & Fernandez, 1988; Guyot, 1993).

The dissolved solids results are consistent in all studies, but the same is not true for suspended sediment: the sediment load observed downstream (near the confluence with the Amazon) is twice that observed at Villabella. In order to address this apparent discrepancy, a critical study of the PHICAB data was carried out by updating the information from Bolivia (gauging station rating curves, 1990 data) and using DNAEE data for the Brazilian basin of the Rio Madeira.

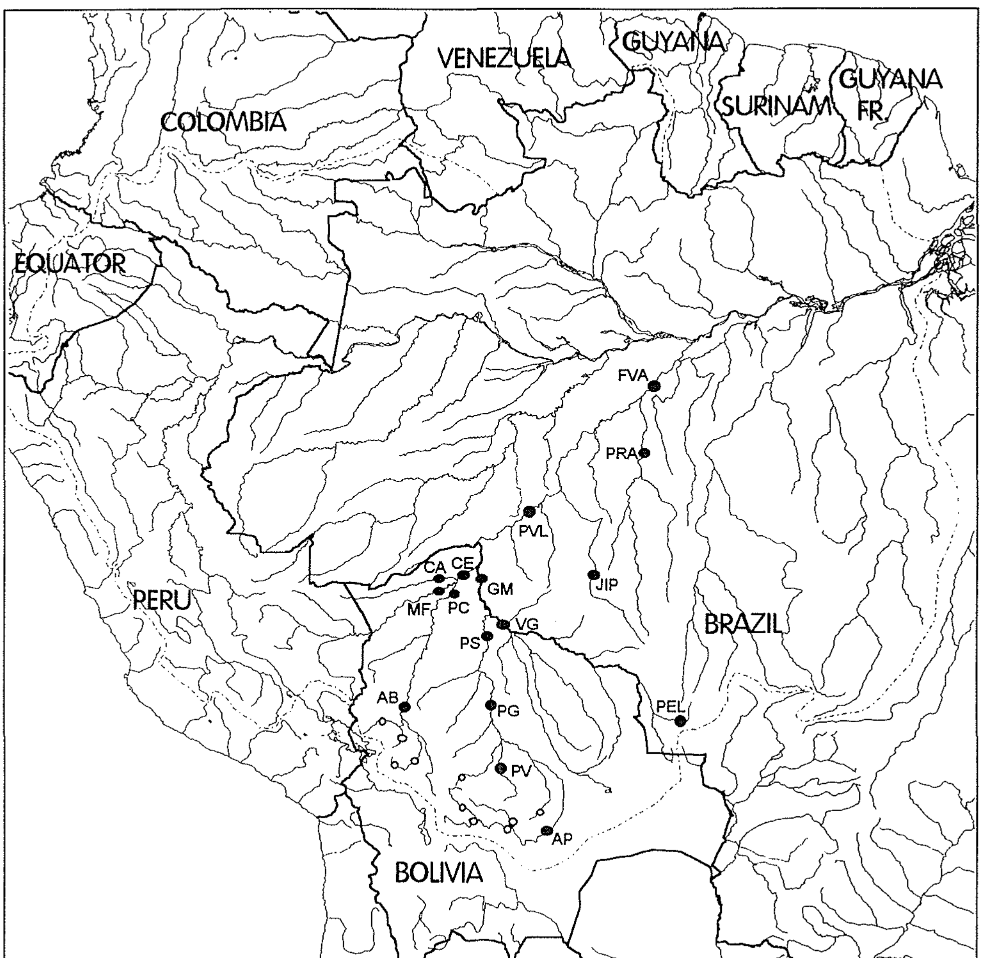

Fig. 1 The Amazon drainage basin (● PHICAB gauging stations in Bolivia, DNAEE sediment stations in Brazil; ○ some sediment stations in the Bolivian Andes).

THE RIO MADEIRA DRAINAGE BASIN

The Rio Madeira Basin extends over three countries (Bolivia, Brazil and Peru). It represents 23% of the overall Amazon basin, and 29% of the Amazon basin at Óbidos, and drains 35% of the Andean range within the Amazon basin (Fig. 1). The three large morpho-structural units observed in the Amazon region are present, but the Brazilian shield divides the Amazon plain into two different parts: the upstream plain and the downstream plain. While the downstream plain is an integral part of the vast Amazon lowlands, the upstream plain is isolated by the Precambrian outcrops of the Brazilian basal complex that act as a hydraulic threshold for the Andean tributaries of the Rio Madeira. One of the consequenres is the existence of vast flooded areas at altitudes under 100 m, upstream from this threshold. From Guayaramerin (GM, Rio Mamore) or Cachuela Esperanza (CE, Rio Beni) to Porto Velho (PVL), the Rio Madeira crosses the Brazilian shield for a distance of more than 350 km, where it shoots over a dozen rapids (Cachuelas or Cachoeiras) for a 50 m drop.

In the Bolivian Andes, the basins studied present great contrasts. Their characteristics vary from semi-arid zone basins developed on the Quaternary sediments of the Altiplano (Rio La Paz valley) to the tropical forest hyper-humid basins on the Paleozoic rocks of the Cordillera Real. Rainfall varies from 500 to 5000 mm year^{-1} depending on the basin. In the lowlands, the rainfall distribution is more regular, and the mean annual rainfall values are 1800 mm in Bolivia (Roche *et al.*, 1992) and 1950 mm on the Brazilian side (DNAEE-ORSTOM, 1994).

Over the area that makes up the Rio Madeira basin at Villabella, the southern tropical rainfall regime prevails. It is characterized by a marked alternation of cold-weather drought periods and excess rainfall during the hot season. In the Andes and its foothills, the multiple-flood hydrographs come together downstream to form a large annual tropical flood, preceded or followed by small, well differentiated floods. The annual flood is much more regular and flattened on the Rio Mamore and Rio Itenez, because of the longer course and, particularly, the size of the extensive flood plain areas of the two basins (Bourges *et al.*, 1993).

SUSPENDED SEDIMENT YIELD

The data assembled for the 41 constituent basins (Table 1) were derived from several hydrometric networks, relate to various periods, and are based on different sampling methods. Thus, the comparison of such data is a delicate matter. The data for the Andean basins in Bolivia come from the ENDE, SENAMHI and SEARPI networks. They are based on sampling at several verticals in the measuring section, carried out using different integrating samplers according to the size of the rivers. The samples from the Rio Achumani basin (small, high-altitude Andean streams) were taken from the surface in the middle of the section, but also included some measurements of bottom transport. The sampling executed by the PHICAB programme was based on daily turbidity measurements and 10-day TSS determinations by surface sampling carried out by observers recruited for that purpose. The values obtained were corrected by means of a ($[TSS]_{section} = f([TSS]_{surface})$ relationship. After having examined the distribution of

Table 1 Suspended sediment (TSS) and dissolved solids (TDS) load results in the Rio Madeira drainage basin (Bolivia-Brazil).

Code	River	Altitude (m)	Area (km^2)	Period	Organization	Discharge ($m^3\ s^{-1}$)	Number of samples: *TSS*	Number of samples: Turbidity	*TSS* (mg l^{-1})	*QS* ($\times 10^3$ t $year^{-1}$)	*Ts* (t km^{-2} $year^{-1}$)	Number of samples: *TDS*	Number of samples: Conductivity	*TDS* (mg l^{-1})	*QD* ($\times 10^3$ t $year^{-1}$)	*Td* (t km^{-2} $year^{-1}$)
AQM	Mapiri at Angosto Quercano	500	9400	75-79	SENAMHI	420	351		2960	36800	3920					
SRC	Coroico at Santa Rita	440	4700	76-77	SENAMHI	260	49		870	7100	1510					
ACM	Acero Marca at Unduavi	2960	61	87-88	ORSTOM	2.8	36		11	1	16	36		39	3.4	22
UNV	Unduavi at Unduavi	2940	66	87-88	ORSTOM	3.0	38		21	2	30	38		33	3.1	21
SIR	Unduavi at Sirupaya	1640	270	80-86	SENAMHI/ENDE	12	194		5990	2120	7850					
TAM	Tamampaya at Puente Villa	1185	950	75-85	SENAMHI/PHICAB	52	320		1270	2480	2610	8	986	39	64	35
VBA	Tamampaya at Villa Barrientos	1050	1900	75-84	SENAMHI	67	353		3160	7820	4120					
HUL	Huayllani at Achumani	3620	17	88-92	HAM/PHICAB	0.11	554	1039	18460	61	3590	9	807	91	0.3	12
ACH	Achumani at Achumani	3580	38	90-92	HAM/PHICAB	0.19	130		22490	140	3680					
LUR	Luribay at Luribay	2550	810	87-88	ORSTOM	10	39		20300	6400	7900	39		920	290	270
POR	Porvenir at Porvenir	2500	240	87-88	ORSTOM	3	36		8400	790	3300	36		420	40	90
CAJ	La Paz at Cajetillas	760	6500	73-75	SENAMHI	99	332		36340	118600	18250					
AIN	Alto Beni at Angosto Inicua	400	29900	75-83	SENAMHI	840	157		4800	115200	3850					
AB	Beni at Angosto del Bala	280	67500	69-90	SENAMHI/PHICAB	1990	456	541	3380	211700	3140	60	1077	83	5210	41
PC	Beni at Portachuelo	130	119000	83-90	PHICAB	3070	91	745	1260	121600	1020	48	916	84	8150	34
MF	Madre de Dios at Miraflores	130	124200	83-90	PHICAB	5210	226	1085	430	70900	570	71	1850	66	10900	40
CA	Orthon at Caracoles	125	32300	83-90	PHICAB	470	112	483	120	1770	55	35	1062	57	850	15
CE	Beni at Cachuela Esperanza	120	282500	83-90	PHICAB	8810	174	1043	690	190600	680	63	1937	71	19700	34
LOC	Santa Isabel at Locotal	1700	200	71-75	ENDE	15	1000		1430	670	3340					
PPA	Esperitu Santos at Palmar	600	160	71-74	ENDE	22	970		15450	10700	66600					
PV	Ichilo at Puerto Villarroel	170	7600	83-90	PHICAB	750	118	857	370	8710	1150	83	1211	52	1220	110
BER	Bermejo at Bermejo	900	480	77-83	SEARPI	4.2	2220		4530	600	1250					
ANG	Piray at Angostura	650	1420	76-85	SEARPI	10	3027		9360	2950	2080					
TAR	Piray at Taruma	600	1590	76-83	SEARPI	7.6	2264		5600	1340	840					
ELV	Elvira at Elvira	650	64	77-83	SEARPI	0.5	2162		1880	30	460					
EPS	Espejos at Espejos	550	203	77-83	SEARPI	2.6	2186		5070	420	2070					
LBE	Piray at La Belgica	350	2880	77-82	SEARPI	13	1684		5560	2280	790					
PEI	Piray at Puente Eisenhover	280	4160	77-82	SEARPI	20	1519		1690	1070	260					
AMO	Caine at Angosto Molineros	1850	9200	71-74	SENAMHI	66	580		51390	106300	11560					
HUR	Chayanta at Huayrapata	1600	11200	76-82	SENAMHI	112	282		6680	23600	2110					
ARC	Grande at Puente Arce	1500	23700	69-74	SENAMHI	127	868		33840	135700	5730					
PNA	Grande at Puesto Nava	950	31200	71-75	SENAMHI	250	938		25680	203400	6520					
MIZ	Mizque at Puesto Nava	950	10800	71-75	SENAMHI	70	897		11970	26300	2440					
PAZ	Azero at Puente Azero	1080	4360	75-82	SENAMHI	33	557		2020	2080	480					
AP	Grande at Abapo	450	59800	76-90	SENAMHI/PHICAB	330	851	876	12910	138200	2310	58	1549	458	4830	48
SAN	Parapeti at San Antonio	550	7500	76-83	SENAMHI	91	642		6770	19400	2590					
PG	Mamore at Puerto Varador	140	159100	83-90	PHICAB	2970	120	643	680	63600	400	72	1059	95	8940	28
PS	Mamore at Puerto Siles	130	216200	83-90	PHICAB	5080	148	883	290	47100	220	101	1141	87	13900	31
PEL	Guapore at Pontes e Lacerda	300	2500	79-93	DNAEE	54	30		23	39	16					
VG	Itenez at Vuelta Grande	130	354300	83-90	PHICAB	2320	241	696	23	1700	5	116	1357	37	2740	4
GM	Mamore at Guayaramerin	120	599400	83-90	PHICAB	7550	219	1236	280	66200	110	54	2103	69	16500	13
VB	Madeira at Villabella (CE+GM)	115	881900	83-90	PHICAB	16360			500	256800	290			70	36200	15
PVL	Madeira at Porto Velho		954300	78-93	DNAEE	20100	23		483	306100	320					
JIP	Jiparana at Jiparana		33000	81-93	DNAEE	690	33		55	1190	36					
PRA	Aripuana at Prainha		108600	84-94	DNAEE	3460	29		27	2930	27					
FVA	Madeira at Fazenda Vista Alegre		1324700	84-94	DNAEE	26400	35		181	150800	110					

the TSS contents in the section on the basis of 61 gaugings undertaken from 1986 to 1988, this equation became $[TSS]_{section} = 1.10 * [TSS]_{surface}$. The data from the Brazilian basin (DNAEE network) comprise the samples collected by Brazilian companies (CPRM and/or HIDROLOGIA/SA) using integrating USD-49 samplers.

For the Bolivian rivers, the suspended sediment yield (*QS*) was calculated as follows:

(a) (for month *i*)

$$QS_{mi} = 1/k * \Sigma Q_j * [TSS]_j$$

where k = number of daily measurements (j) in month i;

(b) $$QS_{monthly} = 1/n * \Sigma QS_{mi}$$

where n = number of years with QS_{mi} values; and

(c) $$QS_{mean} = 1/12 * \Sigma QS_{monthly}$$

This simple method was applied to the Brazilian set of data (Bordas *et al.*, 1988) using the data from the DNAEE stations with enough samples. It is better than the $QS = f(Q)$ curves because of the strong scatter of the points in this relationship (Fig. 2). Nevertheless, use of such rating curves was necessary in order to calculate the sediment loads for the DNAEE stations on the Rio Madeira in Brazil (PVL, JIP, PRA, FVA), taking into account the small number (<40) of samples (Fig. 3). This method was also used by Martinelli *et al.* (1993) with the CAMREX data. In the case of the PHICAB network stations in Bolivia, the turbidity data enabled researchers to extend the TSS observations after having established the relationship $[TSS] = f(Turbidity)$ for each hydrometric station. The TSS concentration indicated in Table 1 corresponds to a mean value weighted by the discharge: $[TSS] = QS/Q$.

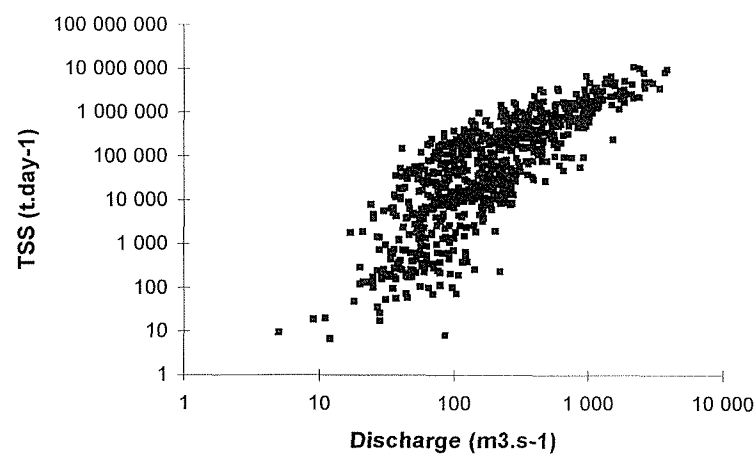

Fig. 2 The relationship between suspended sediment load and discharge for the Rio Grande at Abapo, Bolivia.

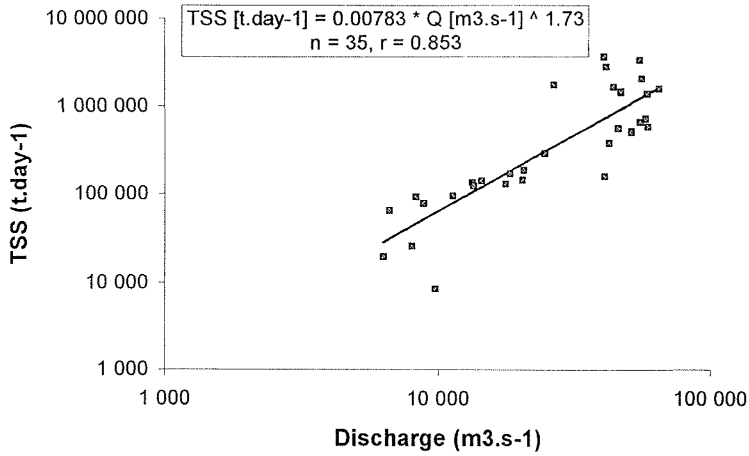

Fig. 3 Use of the relationship $QS = f(Q)$ to calculate sediment yield in Brazil (Rio Madeira at Vista Alegre, Brazil).

The results for the 41 stations in the basin are shown in Table 1. The results are provisional for the Brazilian part of the basin, since the DNAEE database is being restructured and some information has not yet been compiled (Filizola & Guyot, 1994). The data for the Andean basins in Bolivia may differ from those of earlier publications, because the rating curves for those streams were recently reviewed. The data from the PHICAB network in the Amazonian plain have been updated (addition of 1990 data) and the discharges corrected. In the Bolivian Andes, the suspended sediment yields (*Ts*) vary considerably from one basin to another, from less than 50 t km^{-2} $year^{-1}$ in the high altitude basins of the Real Cordillera (ACM, UNV) to 50 000 t km^{-2} $year^{-1}$ in the hyper-humid region of Chapare (PPA). Such variability is linked to the bio-geographical characteristics of these mountainous basins. Despite the variations in observation period and methodology, the results are consistent throughout the basin (from upstream to downstream). Comparison of the SENAMHI (1969-1982) and PHICAB (1983-1990) data for the two Andean foothill stations shows similar results for Abapo, while for Angosto del Bala the PHICAB values are clearly lower. The sampling technique, or the reliability of the observer, may account for this difference. There is evidence of sedimentation along the valleys, as well as on the Rio Grande between PNA and AP (Guyot *et al.*, 1994). The total TSS flow exported by the Andean basins in Bolivia has been estimated at 500-600 $\times 10^6$ t $year^{-1}$, which corresponds to a mean sediment yield for the Andean chain close to 3200 t km^2 $year^{-1}$. During the crossing of the Amazon lowlands in Bolivia (Llanos) suspended sediment yields tend to progressively decrease (43% in the Rio Beni between AB and PC, 54% in the Rio Mamore between AP and PG), reflecting substantial sedimentation on the flood plain (Guyot *et al.*, 1988). In the Llanos, the data on the contribution of the various tributaries are consistent with the downstream observations (PC + MF + CA $\approx$ CE, PG + VG $\approx$ GM). Nevertheless, an anomalous situation was observed on the Rio Mamore between PG and PS. The data for the Rio Orthon at CA provide an estimate of the sediment yield (55 t km^{-2} $year^{-1}$) that reflect the Tertiary sedimentary series in the Amazon plain. For the Brazilian shield, such rates vary from 16 to 36 t km^{-2} $year^{-1}$ depending on the station (PEL, JIP, PRA), and are similar to earlier observations (Bordas *et al.*, 1988; Mortatti *et al.*, 1989, 1992). The very low value measured at the outlet (VG) of the Rio Itenez-Guapore (5 t km^{-2} $year^{-1}$) reflects major depositional losses of the material exported from the shield throughout the course of the main river. This phenomenon is clearly visible along the lower courses of the Negro, Tapajós and Xingu rivers in the Brazilian Amazon (Sioli, 1984). According to the PHICAB data, the suspended sediment yield for the Rio Madeira at Villabella (VB = CE + GM) is about 250-300 $\times$ 10^6 t $year^{-1}$. This value is consistent with the observation made slightly downstream at Porto Velho (PVL, DNAEE), although they involve different periods, sampling techniques and methods of calculation. Close to the confluence with the Amazon, the suspended sediment load of the Rio Madeira at FVA is estimated to be half that value. This raises the question as to whether this difference is due to sedimentation phenomena in the lower course of the Rio Madeira, or whether it simply reflects estimation errors associated with the small number of samples. Finally, the results obtained for the Brazilian side using DNAEE data are significantly lower than those published by CAMREX (Ferreira *et al.*, 1988; Martinelli *et al.*, 1993). The reason for this discrepancy is uncertain. It could reflect differences in the techniques used for sampling or calculating the sediment discharge.

DISSOLVED SOLIDS YIELD

In the case of dissolved solids yield, data are only available for six Andean stations in Bolivia (ACM, UNV, TAM, HUL, LUR, POR) and 11 stations in the PHICAB network on the Amazon plain (Table 1). All samples were taken from the surface, since the distribution of dissolved material in the measurement section was very homogeneous.

The calculation of the dissolved solids yields was carried out following the same methodology used for suspended sediment (see previous section). The relationship *Salinity* = *f*(*Conductivity*) was established for each of the 11 stations on the Amazon plain, and the resulting formula was used for the calculation of the dissolved loads. The concentration of dissolved matter (*TDS*) indicated in Table 1 corresponds to the mean value weighted by the discharge: $[TDS] = QD/Q$. The dissolved solids yield (*Td*), or "chemical erosion", has been calculated taking into account atmospheric contributions.

The results presented in Table 1 again differ from those in earlier publications because of changes in the discharge data and also the fact that the TDS concentration corresponds to the discharge-weighted mean. In the Bolivian Andes, the dissolved solids yield (*Td*) documented in the Alto-Beni basin varies from 12 to 270 t km^{-2} $year^{-1}$ (HUL, LUR) as a function of the lithology of the basins. The two main Andean streams, the Rio Alto-Beni at Angosto del Bala (AB) and the Rio Grande at Abapo (AP) export the same amount of TDS (5 $\times$ 10^6 t $year^{-1}$) from the Andes, but the concentrations are much higher in the Rio Grande. The lower rainfall observed in this basin is compensated by the higher solubility of the rocks. The TDS load exported from the Bolivian Andes was estimated at 14 $\times$ 10^6 t $year^{-1}$ using the results from these two stations (AB and AP), which drain 74% of the Andean area of the basin. After correction for the atmospheric contribution, this dissolved load corresponds to a mean dissolved solids yield (*Td*) of 40 t km^{-2} $year^{-1}$, which is 80 times smaller than the suspended sediment yield (Guyot, 1993). The Rio Itenez-Guapore (VG) data suggest that the dissolved solids yield from the Brazilian shield is about 4 t km^{-2} $year^{-1}$, which is slightly lower than the results obtained for the small basins in Rondonia, namely, 10 t km^{-2} $year^{-1}$ for the Rio Jiparana and 8 t km^{-2} $year^{-1}$ for the Rio Jamari (Mortatti *et al.*, 1992). The results obtained in Bolivia are consistent throughout the length of the basin (PC + MF + CA $\approx$ CE, PS + VG $\approx$ GM). The dissolved solids yield calculated for the Rio Madeira at Villabella (36×10^6 t $year^{-1}$) is compatible with the observations made in Brazil, close to the confluence of the Rio Madeira with the Amazon (Martinelli *et al.*, 1989).

CONCLUSION

The results obtained from the Bolivian Andes demonstrate the existence of a strong regional heterogeneity as regards the production of both suspended sediment and dissolved load. Along the two main transects (Beni and Mamore rivers), the dissolved load is conservative, with a progressive increase from upstream to downstream, which is linked to the increasing discharge. However, consideration of the same upstream-downstream trend for the suspended sediment load demonstrates the existence of deposition in the downstream part of the Andean valleys, and particularly in the Llanos. While the dissolved loads observed in Bolivia and Brazil are in agreement, the same is not true for the suspended sediment load. The two-fold decrease can easily be explained by the sampling methods and frequency, or by the method of load calculation. A common methodology would allow researchers to compare results and be able to determine the upstream-downstream sediment yield variability.

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