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Characterisation of river bed and suspended sediments in the Rio Madeira drainage basin (Bolivian Amazonia)

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Abstract

The grain size distribution of river bed sediments in the Rio Madeira drainage basin shows rapid deposition of the coarser material (> 10 mm) as the river flows out of the Andean range to enter the Amazon plain (Llanos). In the Andes, the suspended sediment grain size varies between 0.02 and 0.10 mm in diameter, while in the Llanos the suspended load is dominated by fine silts, between 7 and 13 μm in diameter. In the Llanos, neither the bed sediment nor the suspended sediment varied along a 800 km reach. © 1999 Elsevier Science Ltd. All rights reserved.

Resumen

La granulometría de los sedimentos transportados sobre et lecho de los cursos de agua (arrastre) demostró que el material más grueso (> 10 mm) se deposita rápidamente en la zona de pie-de-monte. En los Andes, et tamaño del material en suspensión varía de 0.02 a 0.10 mm, mientras que en los Llanos el sedimento transportado es limo fino, con una granulometría entre 7 y 13 μm. En los Llanos, no es perceptible cualquier evolución en el tamaño de los materiales en suspensión, o de los sedimentos de fundo, de aguas arriba hasta agtias abajo, sobre 800 km. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Knowledge about the grain size distribution of the river bed and suspended sediment is fundamental to the study of geomorphological process along a fluvial hydrosystem. Modelling sediment load by means of transport equations, estimating the major and trace element fluxes in the fine fraction transport, understanding sediment transfer processes, identifying sediment deposition areas, calculating sedimentation/suspension and water/sediment discharge ratios, all require good granulometric data. Moreover, the biological component of river ecosystems is strongly dependent on the structure and stability of the bed sediment, as well as water turbidity. Thus sediment dynamics are a key factor in understanding the ecological functioning of many rivers, especially in the Amazonian area (Sioli, 1984).

The Rio Madeira is the most important southern tributary of the Amazon with a mean annual discharge of 31,200 $m^3\ s^{-1}$ (Molinier et al., 1997), and is the river that drains the Andean range, the Brazilian shield and the Amazon plains (or "Llanos"). Despite the geographical importance of this tributary, data on grain size distribution are extremely limited for bottom sediment, and totally lacking for suspended sediment matter.

The present study aims (1) to provide the results of numerous granulometric observations carried out in the Bolivian part of the Rio Madeira drainage basin,

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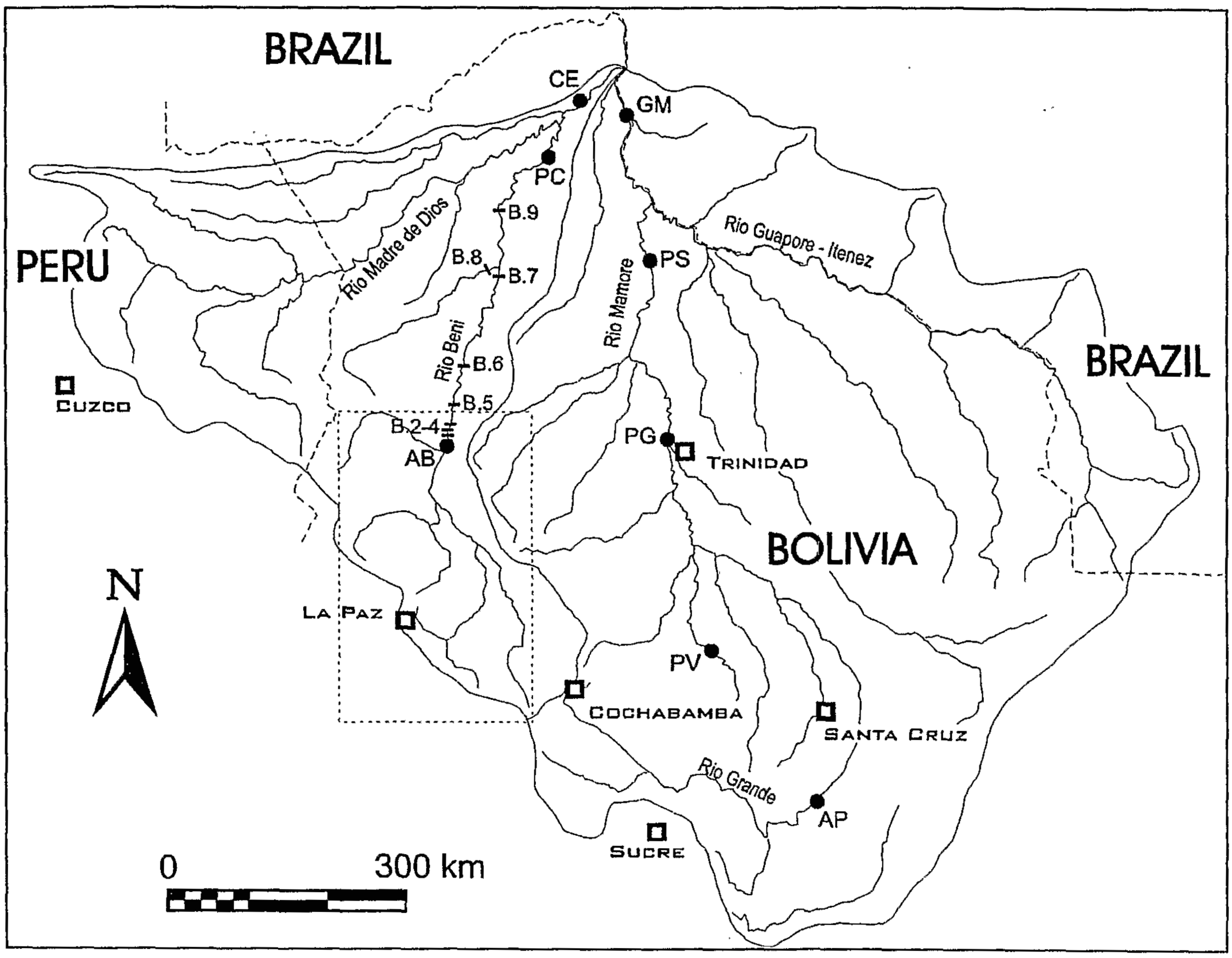

Fig. 1. PHICAB gauging stations (●) in the Amazonian drainage basin of Bolivia, and sediment sampling points along the Rio Beni (see Tables 1 and 2 for station codes).

and (2) to point out salient features of sediment structure characteristics and dynamics along this poorly known hydrosystem.

Most of the data were collected between 1983 and 1992 within the scope of the Hydrological and Climatological Program of the Bolivian Amazon Drainage Basin-PHICAB; ORSTOM: Institut Français de Recherche Scientifique pour le Développement en Coopération; SENAMHI: Servicio Nacional de Meteorología e Hidrología de Bolivia; UMSA: Universidad Mayor de San Andrés, La Paz, Bolivia (Guyot, 1993), and during hydrobiological studies (Wasson and Marin, 1992).

2. Study area

The Bolivian part of the Rio Madeira drainage basin (Fig. 1) covers 903,500 km^2, extending over the Andes (25%), the Brazilian shield (27%), and the Llanos (48%). At the Brazilian frontier (Villabella), mean annual discharge of the Rio Madeira is 18,000 m^3 s^{-1}, with a minimum low value of 2000 m^3 s^{-1} and a flood maximum of 52,000 m^3 s^{-1} (Bourges and Hoorelbecke, 1995). At Villabella, the sediment load is estimated at 230 × 10^6 t yr^{-1}; 72% of the sediment load is supplied by the Rio Beni and 28% by the Rio Mamore, the two main Andean tributaries of the Rio Madeira, originating in the eastern Peruvian and Bolivian mountain ranges. The regional sediment budget of the Madeira river basin shows that more than 50% of the suspended yield exported by the Andes will sediment in the Amazonian floodplain (Guyot et al. 1988, 1989).

This large and relatively pristine basin presents a wide range of climatic and geomorphological features. Altitude varies from 6500 to 120 m, and rainfall ranges from 200 to more than 6000 mm yr^{-1}. In the Andes, individual watersheds are heavily contrasted; they range from semi-arid, highly erodible basins incised in the Altiplano Tertiary–Quaternary sedimentary series (such as the Rio La Paz watershed), to densely vegetated hyper-humid basins on Palaeozoic rocks (such as the "Yungas" valleys), or Tertiary sedimentary series

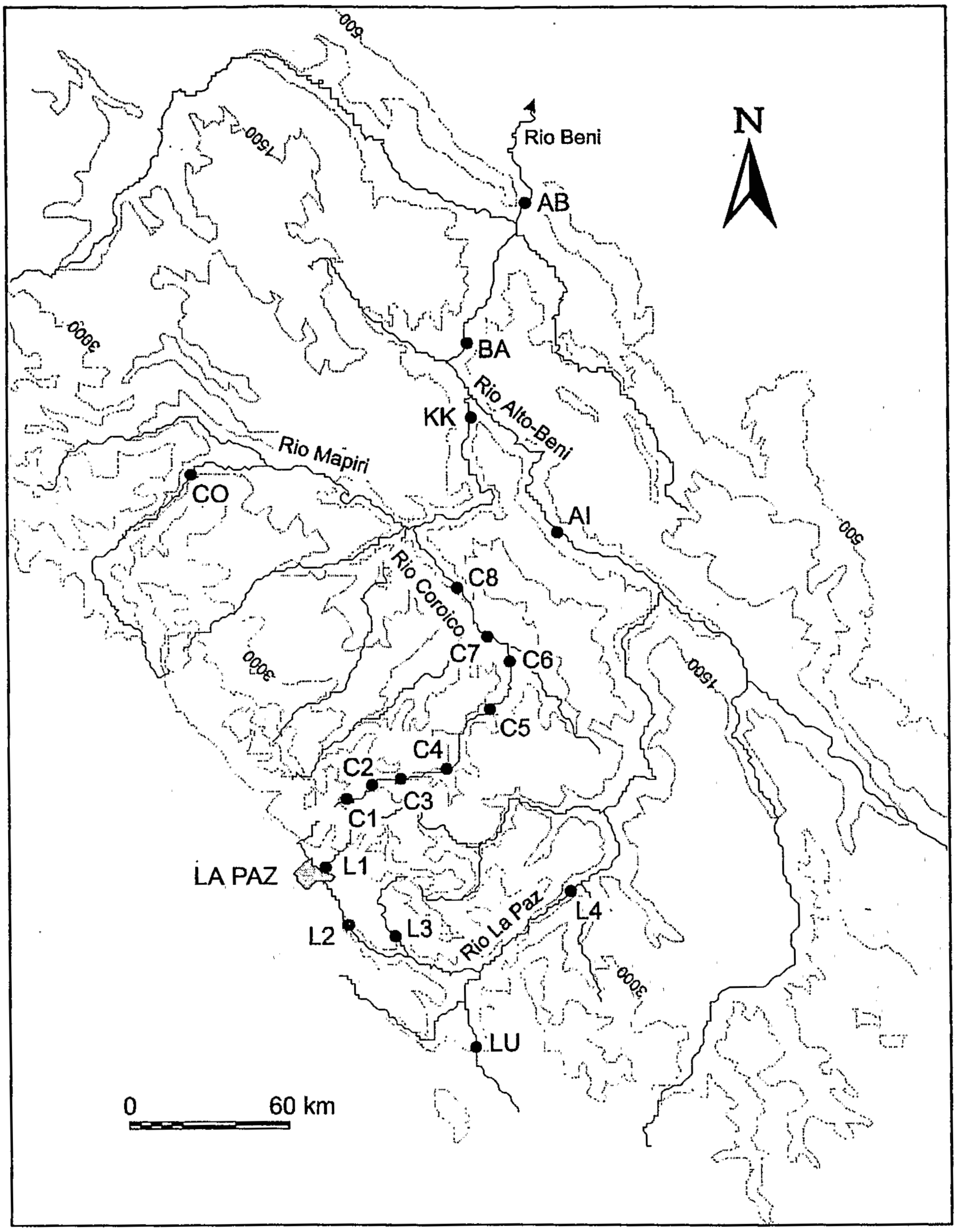

Fig. 2. Sediment sampling points localisation in the Andean Rio Alto-Beni drainage basin (see Tables 1 and 2 for station codes).

in the Alto-Beni foothills. The Bolivian Llanos is a flat plain of recent alluvial sediments, whose level is controlled by the Precambrian Brazilian Shield outcrops upstream of Villabella. About 150,000 km^2 are flooded annually in this region (Roche and Fernandez, 1988).

Sediments have been sampled in these three main valley types, and will be referred to in the following text as (1) "semi-arid" for the Rio La Paz and tributaries, and (2) "Yungas" for the Rio Huarinilla–Coroico–Kaka stem; the Rio Alto-Beni drains both types and (3) "Llanos" for the Amazonian floodplain rivers (see Fig. 2). All the rivers sampled originate in the Andean range, which is the main source of the sediment yield.

3. Methodology

3.1. Bed sediments

The granulometry of coarse bed sediment in the Andes was determined in situ by a "rope" method derived from Wolman (1954). A graduated rope is placed randomly within (if possible) or nearby the stream bed

Table 1
River station characteristics and river bed sediment median diameter (d_{50})

Code	River station	Altitude (m)	Distance from Villabella (km)	d_{50} (mm)
C1	Rio Huarinilla near the Cumbre	4000	1115	193
C2	Rio Huarinilla at the Inca bridge	2900	1110	226
C3	Rio Huarinilla at Choro	2000	1100	130
C4	Rio Huarinilla at Chairo	1300	1085	187
C5	Rio Coroico at San Pedro	650	1050	144
C6	Rio Coroico at IBTA Station	600	1035	84
C7	Rio Coroico at Santa Fe	500	1020	72
C8	Rio Coroico at Alcoche	450	1010	63
KK	Rio Kaka at Puerto Pando	380	920	58
L1	Rio Achumani at La Paz	3550	1200	28
L2	Rio La Paz at Puente Lipari	2950	1240	27
L3	Rio Palca at Tahuapalca	2400	1225	64
L4	Rio La Paz at La Plazuela	800	1135	25
BA	Rio Alto-Beni at Chepite	300	850	32
AB	Rio Beni at Angosto del Bala	280	810	35
B2	Rio Beni	260	805	57
B3	Rio Beni	240	796	26
B4	Rio Beni	220	785	0.13
B5	Rio Beni	200	710	0.10
B6	Rio Beni	190	570	0.15
B7	Rio Beni	180	445	0.09
B8	Rio Madidi	180	427	0.10
B9	Rio Beni	160	340	0.11
PC	Rio Beni at Portachuelo	150	200	0.09

at low flow. Space between rope graduations is about twice the diameter of the largest elements of the sediment. Each element found under a graduation is measured by passing it through a granulometer, which is analogous to a sieve series in geometric progression according to the Phi scale (with half-Phi graduation). The grain size of the finest elements is referred to as fine gravel (2–8 mm), coarse sand (0.5–2 mm), fine sand (0.5–0.062 mm), or silt (<0.062 mm) by a visual comparison with sieved sediment. 50 elements are measured by sample (Kellerhals and Bray, 1971) and sampling is replicated 2–5 times according to the apparent heterogeneity of the substrate. In the larger Llanos rivers with sandy substrate, the grain size was obtained by the classical method of sieving and weighing of a river bed sediment sample, in the SENAMHI Laboratory (El Alto, Bolivia).

In situ granulometric measures and river bed sediment samples were collected from the Rio Beni drainage basin during the 1988 and 1989 low flow periods.

3.2. Suspended matter

At the PHICAB stations in the Llanos (Fig. 1), suspended sediment samples were collected near the surface, in the middle of the river. Measurements made with depth integrating samplers at gauging stations exhibited good homogeneity of suspended sediments over the whole cross-section (Guyot, 1993). The sediments collected on filters were extracted by passing through an ultrasound tank. Particle-size distribution analyses were then performed on the suspension, using a laser grain-size measuring device (3600E Malvern model) in the Bordeaux University Laboratory (France).

The suspended sediment samples of Beni and Mamore rivers in the Llanos were provided by the PHICAB Network during the 1986–87 period. For the Andean rivers, suspended sediments were collected during the March 1988 flood period.

4. Results and discussion

4.1. Bed sediments

A noticeable difference appears between the bed sediments of the two main valley types (Table 1). In the Yungas, along the Huarinilla–Coroica–Kaka river transect (from 4000 to 380 m — C1 to C8, KK — Fig. 2), d_{50} values decrease normally from 200 to 60 mm (Fig. 3), indicating the progressive settling of largest particles. In the semi-arid valley, along the La Paz–Palca–Alto Beni river stem (from 3550 to 300 m – - L1 to L4, LU, AI — Fig. 2), no significant d_{50} variation is observed downstream, suggesting a mass transport of unsorted sediment. This is due to the particular granulometric composition of the sediments in these basins. Some samples (L3 and L4) showed two main modes, one of which corresponds to a stock

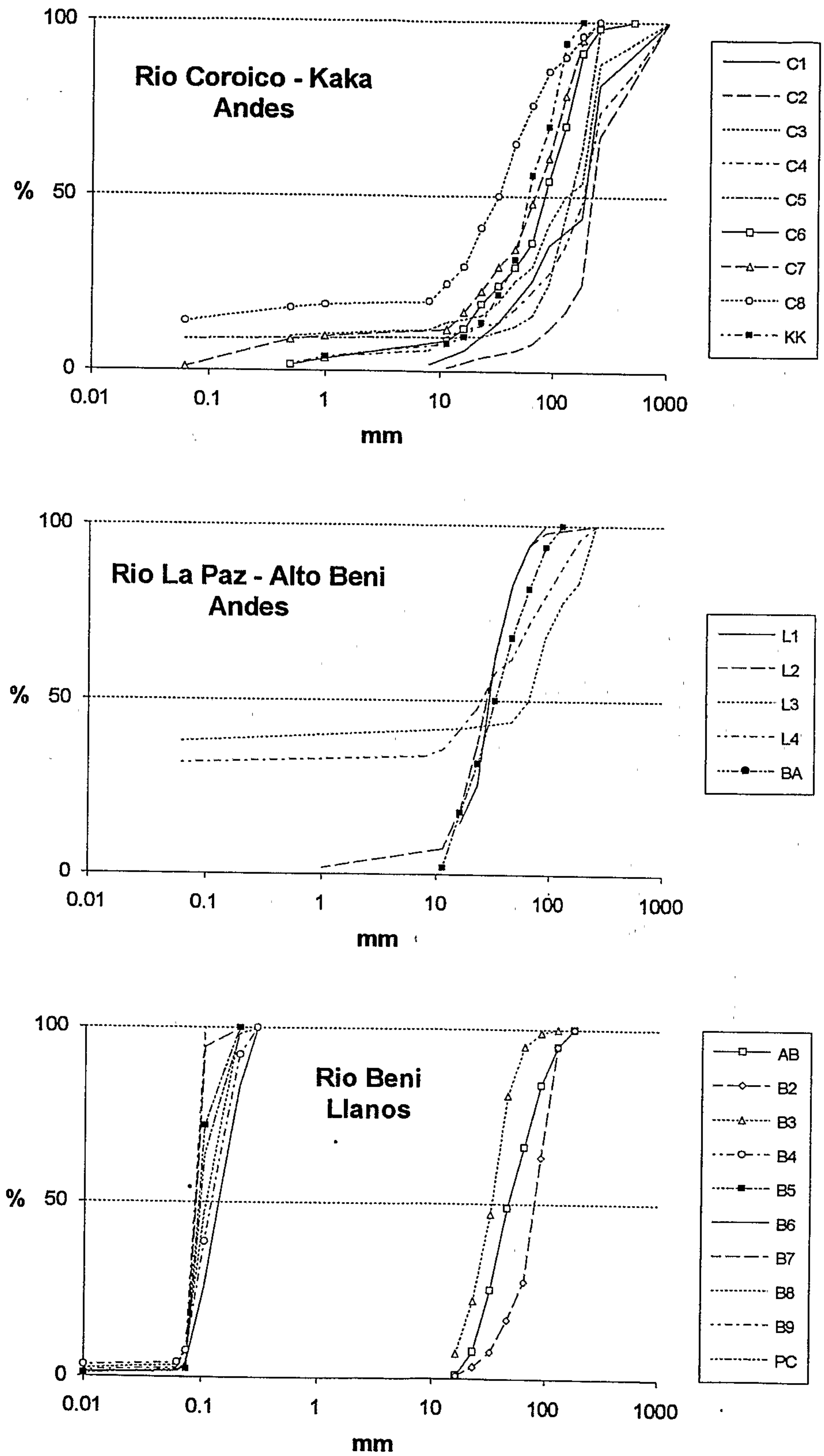

Fig. 3. River bed sedimentary granulatory of the Rio Beni drainage basin (see Table 1 for station codes).

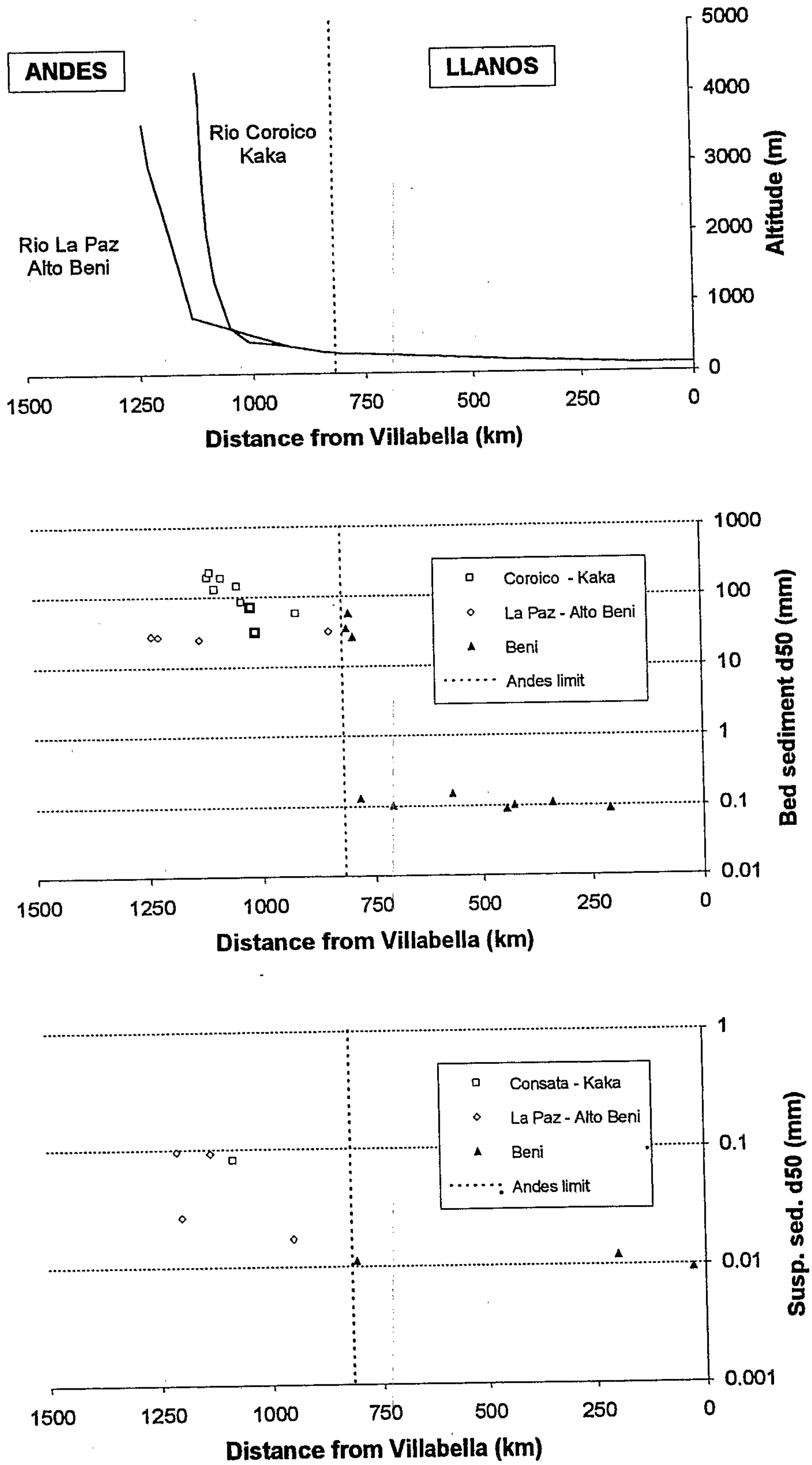

Fig. 4. Longitudinal section, river bed and suspended sediment median diameter (d_{50}) of the Rio Beni drainage basin.

Table 2
River station characteristics and suspended sediment median diameter (d_{50})

Code[a]	River station	Altitude (m)	Distance from Villabella (km)	Number of samples	d_{50} (μm)	d_{90} (μm)	d_{10} (μm)
L1	Rio Achumani at La Paz	3550	1200	1	26		
L4	Rio La Paz at La Plazuela	800	1135	1	92		
LU	Rio Luribay at Luribay	2550	1210	1	95		
CO	Rio Consata at Consata	900	1085	1	81		
AI	Rio Alto-Beni at Angosto Inicua	390	950	1	17		
AB	Rio Beni at Rurrenabaque	280	810	4	11.0	3.4	39.8
PC	Rio Beni at Portachuelo	130	200	4	12.0	3.4	41.2
CE	Rio Beni at Cachuela Esperanza	120	30	4	9.4	3.1	37.0
AP	Rio Grande at Abapo	450	1725	4	7.1	2.9	20.5
PV	Rio Ichilo at Puerto Villarroel	170	1487	4	12.7	4.0	36.5
PG	Rio Mamore at Puerto Ganadero	140	920	39	9.0	3.0	33.9
PS	Rio Mamore at Puerto Siles	130	436	36	8.1	2.9	28.0
GM	Rio Mamore at Guayaramerin	120	55	3	9.4	3.1	32.0

[a] L1, L4, LU, CO and AI data from Barragan, 1990.

of fine sand (<0.1 mm) and the other, to a coarse stock (>10 mm). Such bed sediments are highly unstable, and scoured very frequently due to the energy of these high gradient streams (slope >3%), as evidenced by the scarcity of the benthic fauna (Wasson and Marin, 1992). This particularity is due to the fine sediment load of the Andean rivers (rios La Paz, Sapahaqui and Luribay) which drain the highland quaternary basin of the Altiplano.

Other data obtained from bed load sampling in the same region seems to corroborate these findings. In the Yungas valley, the d_{50} of the material transported is 26 mm for the Rio Unduavi at Sirupaya (alt. 1600 m — ENDE, 1980), lower than the bed sediment d_{50} values for the same altitudinal range in our data (Table 1). Conversely, bed load sampling on the Archumani and Huayllani rivers, two tributaries of the Rio La Paz, resulted in d_{50} values ranging from 3 to 80 mm during flood events, with an average of 25 mm (Bourges et al., 1995), very close to the bed sediment d_{50}.

The most abrupt discontinuity in the bed sediment composition occurs at the transition between the Andes and the Llanos. Sites located before the outflow of the Andes (BA and AB — Fig. 2) have a bed sediment made of gravel and pebbles with d_{50} near 30 mm. As the Rio Beni enters the Llanos, the same granulometric composition of the bed sediment is observed on the first 20 km (B2 and B3), but then the median diameter decreases drastically over 10 km (Fig. 4), to remain remarkably stable thereafter along the next 800 km with a d_{50} ranging from 0.09 to 0.15 mm.

The same stability over long distances has been observed in other large tropical rivers, such as the Amazon and the Orinoco (Nordin et al., 1980; Mertes and Meade, 1985). In fact, particle-size distribution of sediments varies from one site to another on a given stream, but there does not seem to be an overall trend of downstream fining. The mean value of the median grain size of the Rio Beni bed sediments in the Llanos is 0.11 mm; this value is consistent with Taborga's data (1964) for the Beni river. The samples of the Rio Mamore and its tributaries, from the Andean piedmont to Guayaramerin, show a more regular decrease of particle sizes. The d_{50} of the Mamore sediments in the Llanos range from 0.02 to 0.08 mm, with an average of 0.04 mm (Taborga, 1963). The d_{50} of the Rio Mamore bed sediments is three times smaller than that of the Rio Beni. Such sediment characteristics are explained by the difference in gradient between the two streams, as well as the extent of their flood plains, which are seven times larger in the case of the Rio Mamore basin (Roche and Fernandez, 1988).

The median diameter of bed sediment particles in the Bolivian Llanos rivers flowing out from the Andes (around 0.1 mm) appears to be lower than in other rivers in the Amazonian range: 0.25 mm for the Amazon, 0.4 mm for the Orinoco, and 0.34 mm for the Rio Guapore–Itenez (Taborga, 1967), a tributary of the Rio Mamore which drains the Brazilian shield. The coarser sediments of the Rio Itenez may be explained by ancient hydraulic conditions, since present day current suspended matter concentrations are always very low (an average 30 mg/l, which made grain-size analysis very difficult).

4.2. Suspended matter

In the Andes, the grain size distribution of suspended sediment has been determined by means of samples taken from some tributaries of the Rio Beni during the March 1988 flood period (Barragan, 1990; Guyot et al., 1993). Suspended sediments seem to be made up of fine sands and silts, although the clay fraction always exceeds 10%. The median grain size in such suspensions varies between 0.02 and 0.10 mm

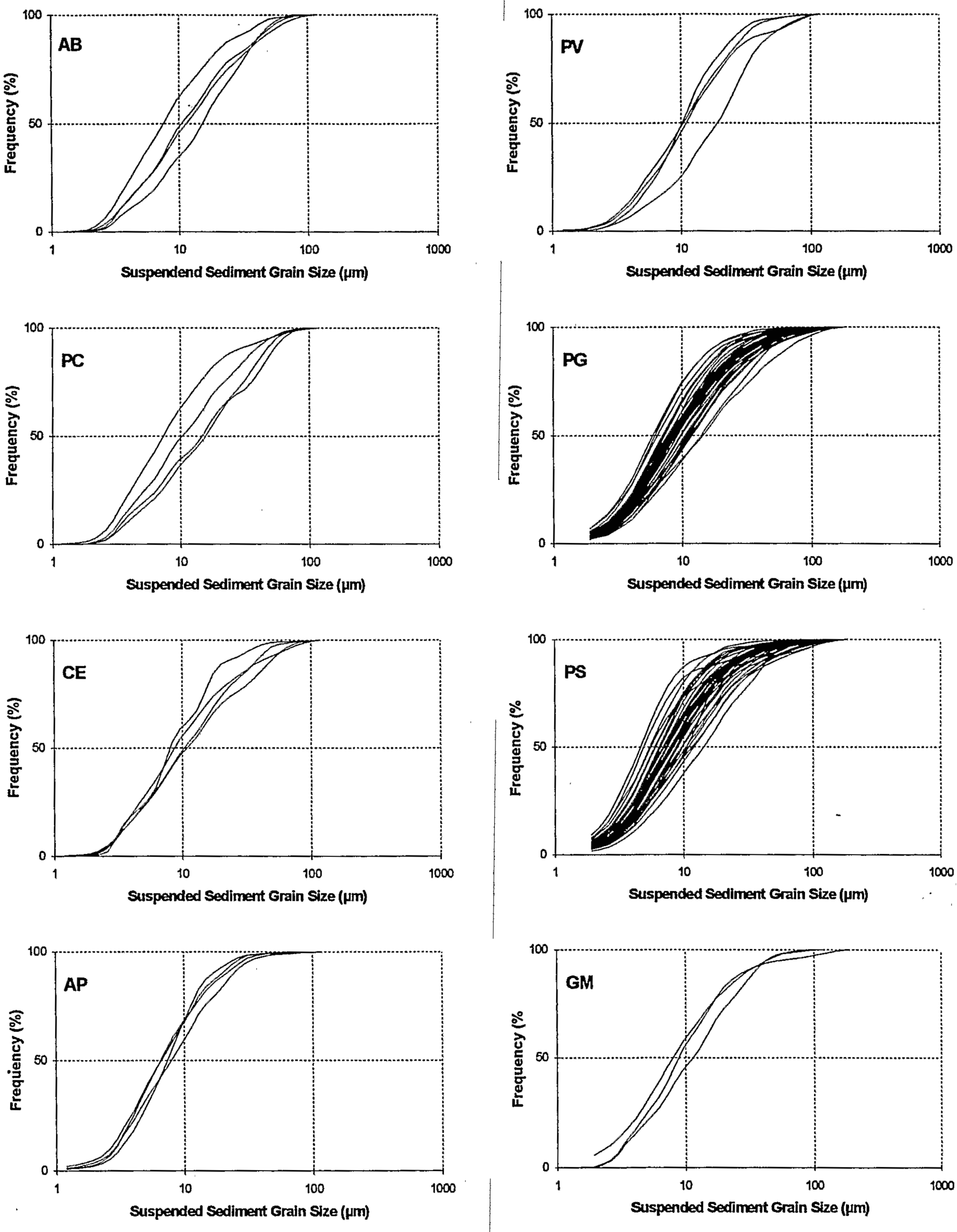

Fig. 5. Suspended sediment granulometric curves of the PHICAB gauging stations in the Llanos (see Table 2 for station codes).

(Table 2), which is the same order of magnitude of the bed sediments in the Amazon plains. From upstream to downstream, suspended sediment d_{50}, progressively decreases (Fig. 4), except for the Rio Achumani (L1 — Fig. 2), which has a low d_{50} value at 3550 m. This particularity is due to the fine fraction of the Altiplano quaternary sediments.

In the Llanos, the results obtained during the 1986–87 hydrological year indicate that, over the whole basin, suspended matter is essentially silt and the per-

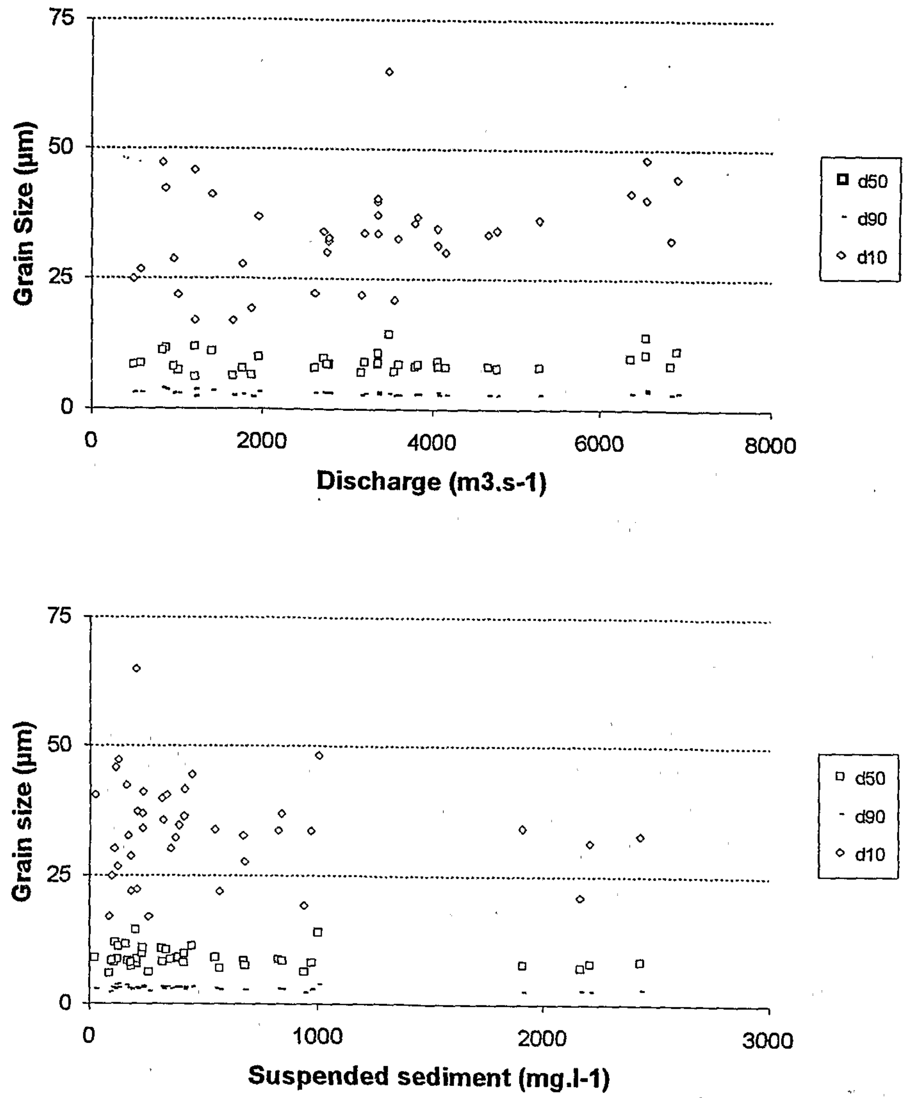

Fig. 6. Suspended sediment grain size vs discharge and suspended sediment load, Rio Mamore et Puerto Ganadero (PG).

centage of fine sands is always low. The suspended sediment d_{50} value in the Amazonian plain presents no significative variation from upstream to downstream. The transition from the Andes to the Llanos is not as marked as for the bed sediments (Fig. 4).

Systematic grain-size analyses of suspended sediment for the complete 1986–87 hydrologic year have been carried out using samples taken at 10-day intervals at two stations on the Rio Màmore (PG and PS — Fig. 1). Results show little variation throughout the year (Fig. 5) and no relation between distribution of grain-size fractions and discharge or suspended sediment load (Fig. 6).

The mean median grain size of suspended sediment was similar at all stations in the Llanos, and varied from 7 to 13 µm (fine silts). The median grain size of suspended matter varied from 2 to 20 µm in the Amazon (Meade, 1985) and from 6 to 16 µm in the Rio Paraná (Drago and Amsler, 1988), whereas, in the Congo, it varied from 9 to 14 µm (Jouanneau et al., 1990). Like river bed sediments, suspended sediment particle size does not vary much from upstream to downstream. The suspended sediment's diameter in the two large rivers (Rio Beni at Cachuela Esperanza and Rio Mamore at Guayaramerin — CE and GM — Fig. 1) is similar (d_{50}=9 µm), equivalent to approximately one-tenth of the bed sediments diameter.

5. Conclusion

This first insight into the granulometric composition of river bed and suspended sediments in the Bolivian Rio Madeira drainage basin has shown a clear distinction and a very sudden transition between the Andes and the Llanos.

Emphasis must be given to the transition zone at the Andean piedmont; a strongly subsident area, which is the preferential accumulation zone for the coarse material of Andean origin. Only the fine particles are transported towards the Amazon, with the flood plains playing a regulating role in the transfer. This explains the homogeneity of bed and suspended sediment grain size over several hundreds of kilometers, in both the Beni and the Mamore rivers, and the lack of relationship between river discharge and grain size distribution in the lower part of these rivers.

Within the Andean range, the two main geomorphological valley types referred to as "semi-arid" and "Yungas" sampled in our study also exhibited distinct granulometric characteristics, corresponding to different sediment structure and transport processes. Such differences are reflected in substratum stability and water quality, and have important biological implications. Thus geomorphological valley type appears to be a relevant descriptor of river functional types in aquatic ecology.

Acknowledgements

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References

Barragan, M.C. 1990 Estudio sedimentológico de la cuenca andina del Rio Beni. Tesis de grado, Univ. La Paz, Bolivia, 267 pp.

Bourges, J., Hoorelbecke, R., 1995. Variation du régime des écoulements dans le système ando-amazonien de Bolivie. In: Servat, E., LeBarbe, L. (Eds.), Régionalisation en hydrologie. ORSTOM, Paris, pp. 471–487.

Bourges, J., Ribstein, P., Dietze, C., Guyot, J.L., Hoorelbecke, R., 1995. Flux et crues singulières d'un petit cours d'eau andin ou les effets pervers de l'urbanisation. Revue de Géographie Alpine 1995 (1), 111–126.

Drago, E.C., Amsler, M.L., 1988. Suspended sediment at a cross section of the middle Paraná river: concentration, granulometry and influence of the main tributaries. In: Bordas, P., Walling, D.E. (Eds.), Sediment budgets. IAHS, Wallingford, UK, pp. 381–396 174.

ENDE, Empresa Nacional de Electricidad SA, 1980. Proyecto hidroeléctrico Sakhahuaya, Hdrología y sedimentología. ENDE, Cochabamba, Bolivia, 121 pp.

Guyot, J.L. 1993 Hydrogéochimie des fleuves de l'Amazonie bolivienne. Coll. Etudes et Thèses, ORSTOM, Paris, France, 262 pp.

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. In: Bordas, P., Walling, D.E. (Eds.), Sediment budgets. IAHS, Wallingford, UK, pp. 443–451 174.

Guyot, J.L., Bourges, J., Calle, H., Cortes, J., Hoorelbecke, R., Roche, M.A., 1989. Transport of suspended sediments to the Amazon by an Andean river: the River Mamore, Bolivia. In: River Sedimentation. IRTCES, Beijing, China, pp. 106–113.

Guyot, J.L., Jouanneau, J.M., Quintanilla, J., Wasson, J.G., 1993. Les flux de matières dissoutes et particulaires exportés des Andes par le Rio Béni (Amazonie Bolivienne), en période de crue. Geodinamica Acta 6 (4), 233–241.

Jouanneau, J.M., Lapaquellerie, Y., Latouche, C., Tastet, J.P., 1990. Résultats préliminaires de la campagne Oubangui-Congo de Novembre 1988. Bull. des Sciences Géologiques 43 (1), 3–14.

Kellerhals, R., Bray, D.I., 1971. Sampling procedures for coarse fluvial sediments. American Society of Civil Engineers 97, 1165–1179.

Meade, R.H., 1985. Suspended Sediment in the Amazon River and its Tributaries in Brazil during 1982–1984, US Geological Survey Open File Report 85-492, Denver, USA, 39 pp.

Mertes, L.A.K., Meade, R.H., 1985. Particle sizes of sands collected from the bed of the Amazon River and its tributaries in Brazil during 1982–84, US Geological Survey Open File Report 85-333, Denver, USA, 16 pp.

Molinier, M., Guyot, J.L., Callède, J., Guimarães, V., Oliveira E, Filizola, N., 1997. Hydrologie du bassin amazonien. In: Théry, H. (Ed.), Environnement et développement en Amazonie brésilienne. Belin, Paris, pp. 24–41.

Nordin, C.F., Meade, R.H., Curtis, W.F., Bósio, N.J., Landim, P.M.B., 1980. Size distribution of Amazon River bed sediment. Nature 286, 52–53.

Roche, M.A., Fernandez, C., 1988. Water resources, salinity and salt yields of the rivers of the Bolivian Amazon. Journal of Hydrology 101, 305–331.

Sioli, H., 1984. The Amazon. W. Junk, The Hague, 763 pp.

Taborga, J., 1963. El transporte fluvial en Bolivia. Tomo I: Cuenca de los rios Ichilo y Mamore. Fuerza Naval Boliviana, La Paz, Bolivia, 169 pp.

Taborga, J., 1964. El transporte fluvial en Bolivia. Tomo II: Cuenca de los rios Beni, Madre de Dios y Orton. Fuerza Naval Bolivinia, La Paz, Bolivia, 169 pp.

Taborga, J., 1967. El transporte fluvial en Bolivia. Tomo III: Cuenca des Río Itenez. Fuerza Naval Boliviana, La Paz, Bolivia, 77 pp.

Wasson, J.G., Marin, R., 1992. Tipología y potencialidades biológicas de los rios de altura en la región de La Paz (Bolivia). Memoria de la Sociedad de Ciencias Naturales La Salle 48, 97–122.

Wolman, G., 1954. A method of sampling coarse river bed material. Trans. Amer. Geoph. Union 35 (6), 951–956.