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WATER RESOURCES, SALINITY AND SALT YIELDS OF THE RIVERS OF THE BOLIVIAN AMAZON

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ABSTRACT

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This is the first time that the water resources, the salinity and the yields of the upper basins of the Madera River have been reported. Formed by the confluence of the Beni and Mamore, the Madera is one of the world's largest rivers: 17,000 $m^3 s^{-1}$, approximately half the discharge of the Congo River. It has a dissolved discharge close to that of the Congo River: 1 t s^{-1} of ions. Likewise, the Beni and the Mamore Rivers, are also classified as large rivers, greater than the Volga River, the largest in Europe, and the Niger River, the second largest in Africa. The amounts of water involved are considerable. The average dissolved content of these rivers, 57–61 mg l^{-1} respectively, is relatively low to medium. Many types of water, classified according to their ionic compositions, have been characterized in the Andes, the Amazon Plain, and in the main drainage axis. The slightly mineralized black water of the plain seems the most unique type. Recycling of water vapor in the Amazon Basin is confirmed by the low chloride and sodium contents of the water in the plain. Thus the importance of this phenomenon in the genesis of rainfall throughout the basin is emphasized. The contribution of the Upper Madera River to the Amazon River is 9.7% of the water and 10.9% of ionic load.

INTRODUCTION

The Bolivian Amazon region lies in the upper middle part of the Madera River basin (Fig. 1), a portion of which also lies in Peru and Brazil. The basin extends through the Eastern Cordillera of the Andes, the adjoining Amazon Plain, and the Brazilian Shield. Consequently, the water flows through varied zones of relief, lithology, climate, and vegetation, which determine its diverse characteristics.

The Madera River is formed by the confluence of four large rivers: the Madre de Dios and the Beni Rivers, which join to continue as the Beni River; the Mamore and the Itenez which join to continue as the Mamore River. Finally the Beni and the Mamore join to become the Madera River.

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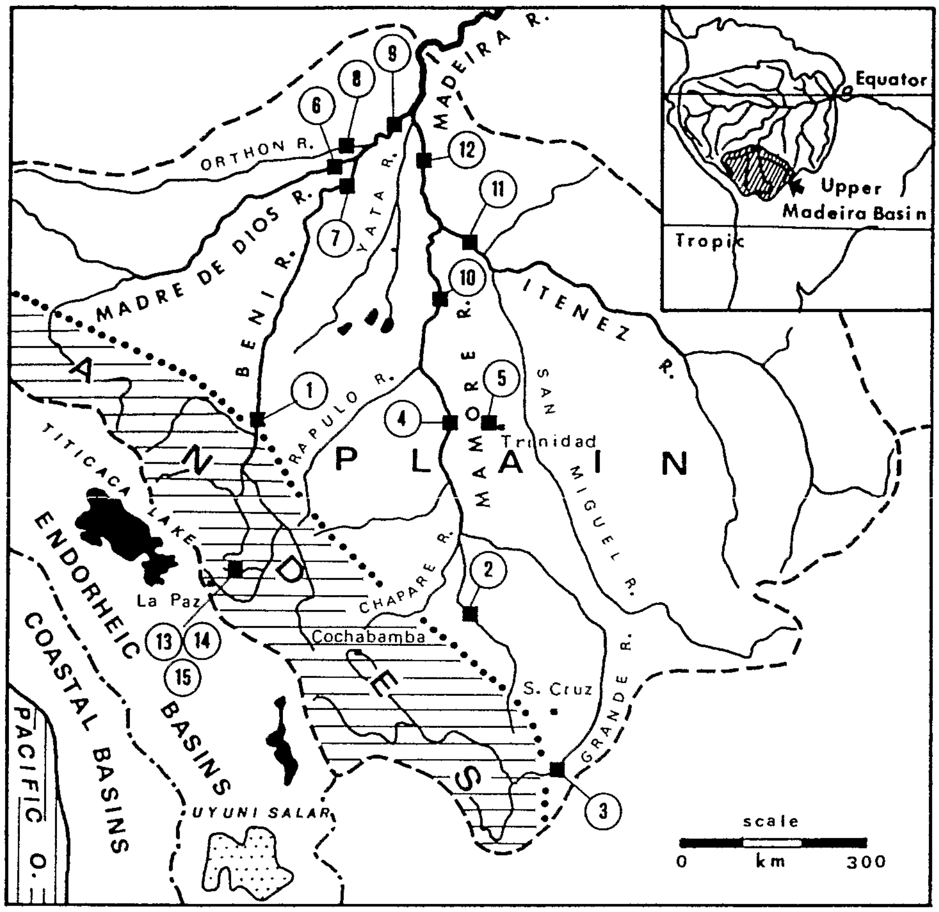


Fig. 1. Map of Bolivian Amazon Basin showing the hydrometric and periodic sampling stations (PHICAB network): *1* Angosto del Bala; *2* Puerto Villarroel; *3* Abapo; *4* Puerto Ganadero; *5* Puerto Almacen; *6* Miraflores; *7* Portachuelo; *8* Caracoles; *9* Cachuela Esperanza; *10* Puerto Siles; *11* Campamento More–Vuelta Grande; *12* Guayaramerin; *13, 14, 15* Puente Villa.

The research conducted under agreement among ORSTOM, IHH, and SENAMHI, titled "Project on Hydrology and Climatology of Bolivia" (PHICAB), as part of the IHP of UNESCO-Rostlac, has made possible for the first time an evaluation of the water resources of this region. A map of the mean annual rainfall was compiled on the basis of pluviometric data collected at reliable stations throughout the country (Roche and Rocha, 1985), and gauge heights and water discharges were measured at fifteen hydrometric stations on the largest rivers of the system (Roche et al., 1986b).

Consequently, the physicochemical characteristics of the water were assessed and the dissolved transport was evaluated. The compilation relied heavily on measurements and analysis made at hydrometric stations, and during a campaign throughout the basin in April–May, 1982 (Roche et al., 1986a, b). In spite of gaps in data collection due to the lack of available staff in those remote areas, it was possible to estimate the mean monthly and annual values with satisfactory precision.

The measurements reported herein generally are for 1984 and 1985, but three hydrometric stations (Angosto del Bala on the Beni River, Abapo on the Rio Grande and Guayaramerin on the Mamore River) have been observed over a 15 yr period. Thus the values obtained over the whole basin could be adjusted to interannual periods (1968 or 1970–1982).

Tables 1 and 2 recapitulate the surface area and mean inter-annual water volumes available at the outlet from the large basins, as well as the salinity with corresponding ionic tonnage exports. These values are shown graphically in Figs. 5 and 9.

SURFACE, VEGETATION AND GEOLOGY OF THE BASINS

At its head, the Madera River drains a basin of 851,000 km^2, 33.3% of which represented by the Beni Basin and 66.7% by the Mamore Basin. The surface of the Andean part is 204,500 km^2, i.e. 24% (Tables 1 and 2, Fig. 5).

In the Andes, the basins extend from the toes of glaciers, the highest ranging from 5200 and 7000 m, to the tropical humid forest of the piedmont. Between these zones, southeast of La Paz, the basins traverse semi-arid areas of high altitude, particularly in the Rio Grande Basin. In the Amazon Plain, the forest is interrupted on the east by savanna with the forest gallery reappearing again in the Brazilian Shield. To the north, below the confluence of the Mamoere and Itenez Rivers, the forest resumes where it marks the margin of the great Amazon Forest.

The Andean rocks are Paleozoic, Mesozoic, Tertiary and locally Quaternary in age. They were affected by Pliocene folding, with locally upper Cretaceous and Eocene folding. The highest mountains are composed of intrusive granitoid rocks. The Permian or Cretaceous sections contain red, gypsiferous clays, which are being exploited. A sodium chloride deposit is marked in the Rio Grande Basin. The black Paleozoic schists and diverse other terranes in the semi-arid areas characteristically are covered by white exudations in the dry periods, which then are leached in the rainy periods.

BASIN PLUVIOMETRY

The map of mean annual rainfall (Fig. 2), which is a simplification of an offset colored print at 1:4,000,000 scale (Roche and Rocha, 1985), displays the spatial rainfall distribution over all of Bolivia and border areas. The Mamore River basin can be subdivided in three zones:

(1) The Rio Grande Basin, semi-arid in its upper part, with minimal precipitation of some 480 mm in the Cochabamba area. An area of heavy rainfall, with a maximum of 1700 mm on the first ranges of the Andes, is noted to the west of Abapo. The mean rainfall in the basin is estimated at 750 mm.

TABLE 1

Interannual salinity, water and ionic yields of the Upper Madera Basins, for the period 1968/70–82

Entire Madera River, Upper Basin		Surface (km^2)	Water						Salt						
			Rain mm	Runoff					Salinity		Exportation				
				$10^9 m^3$	%	%	$m^3 s^{-1}$	$l s^{-1} km^{-2}$	μS	$mg l^{-1}$	$10^6 t$	%	%	$kg s^{-1}$	$t km^2$
Beni	Andes	73670	980	72.2	13.5	25.7	2228	31.1	102	72	5.2	16.4	30.4	165	71
Beni	Plain	48710	626	30.5	5.7	10.9	966	19.8	79	53	1.6	5.0	9.4	52	33
Beni	subtotal	122380	839	102.9	19.2	36.7	3261	26.6	95	66	6.8	21.5	39.8	217	56
Madre de Dios	total	125000	1242	155.1	28.9	55.3	4915	39.6	68.8	45.5	7.1	22.3	41.3	224	57
Orthon	total	32360	482	15.6	2.9	5.6	494	15.3	41.2	23.4	0.37	1.2	2.2	11.6	11.3
Beni	total	283350	993	280.4	52.3	100	8885	31.5	88.1	60.9	17.1	53.9	100	542	60.3
Grande	Andes	59840	137	8.3	1.5	3.2	264	4.4	595	464	3.9	12.3	26.7	123	65
Eastern basins	Andes	29000	1767	51.0	9.5	19.9	1617	55.7	106	75	3.8	12.0	26.0	121	132
Andes	subtotal	88840	669	59.3	11.1	23.2	1880	21.2	175	130	7.7	24.3	52.7	244	87
Mamore	Plain	133230	747	99.6	18.6	39.0	3155	23.7	80	54.2	5.4	17.0	37.0	171	40
Mamore	subtotal	222070	716	158.9	29.6	62.1	5033	22.7	115	82.5	13.1	41.3	89.7	415	59
Itenez	total	303280	211	63.9	11.9	25.0	2021	6.7	34	17.6	1.1	3.5	7.5	35.3	2.8
Mamore	Guayaramerin	547060	455	248.7	46.5	97.4	7880	14.4	84.6	58.1	14.5	45.7	99.3	459	26.5
Yata + Brazil Basin		20770	340	7.0	1.3	2.7	222	10.7	37	20	0.14	0.4	0.9	4.4	6.7
Mamore	total	567830	450	255.7	47.7	100	8105	14.3	83.4	57.2	14.6	46.1	100	463	25.7
Madera	confluence	851180	631	536	100	-	17000	20	86	59	31.7	100	-	1005	37

TABLE 2

Interannual salinity, water and ionic yields of the Andean Upper Madera Basins in Bolivia, for the period 1968/70–82

Bolivian Amazon, Andes	Surface (km^2)	Water							Salt					
		Rainfall (mm)	Actual evapotr. (mm)	Runoff					Salinity		Exportation			
				mm	$10^9 m^3$	%	$m^3 s^{-1}$	$l s^{-1} km^{-2}$	μS	$mg l^{-1}$	$10^6 t$	%	$kg s^{-1}$	$t km^{-2}$
Rio Beni	73670	1719	781	980 938	72.2	54.9	2288	31.1	102	72	5.2	40.3	165	71
Eastern basins	28870	2984	1224	1767	51.0	38.8	1617	56.0	106	75	3.8	29.5	121	132
Rio Grande	59840	751	614	137	8.32	6.3	264	4.44	595	464	3.9	30.2	123	65
Total Amazon Andes in Bolivia	162380	1587	798	810	131.5	100	4169	25.7	135	98.1	12.9	100	409	80

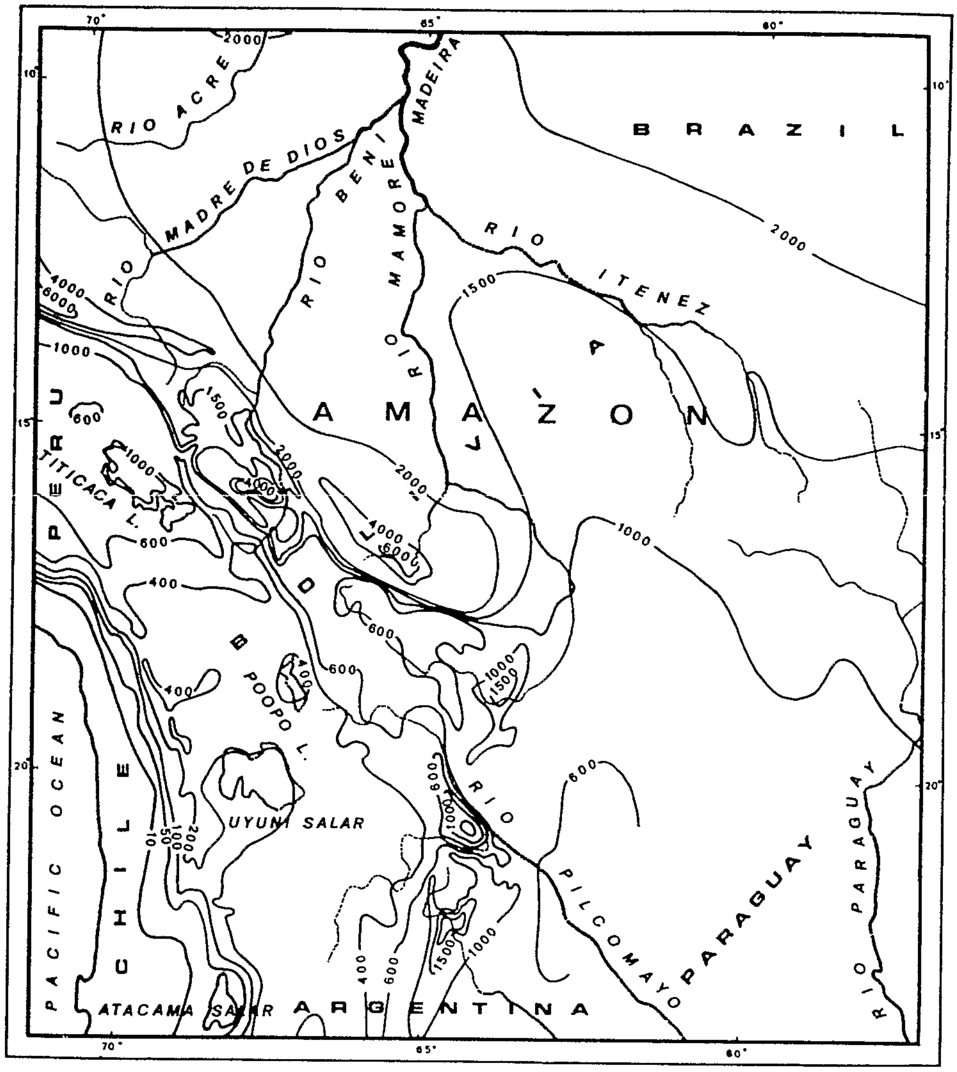


Fig. 2. Annual precipitations in Bolivia and border regions (mm) during 1951–1982 (maximum). Simplification of a colored map at 1:4,000,000 (Roche and Rocha, 1985).

(2) The Andean basins of the tributaries of the Mamore River, located between those of the Rio Grande and Upper Beni River are the most rainy in Bolivia, with rainfall ranging from 2000 to 6000 mm; the maximum occurs in two tributaries of the Chapare River (the Espiritu Santo and San Mateo Rivers), the Upper Secure River, on the Chimore and Sacta Rivers. The mean rainfall here is estimated at 3000 mm.

(3) The Amazon Plain, has rainfall between 800 mm in the Rio Grande, 3000 mm in the Ichilo and 1900 mm at the head of the Madera River. The

increase in rainfall is remarkable toward the north (800–1900 mm) and to the west (1000–1900 mm to 2000–4000 mm). The mean rainfall on the basin is estimated at 1850 mm, and 1524 mm over the entire Mamore Basin.

The Itenez River basin receives rainfall as follows: 900 mm in the south, 1800 mm in the east and 1900 mm in the northeast, with a mean value estimated at 1375 mm.

The Beni River basin, in its Andean part, receives between some 800 and 1000 mm on the summits, and more than 4000 mm in the upper part of the hot valleys (Yungas). The rainfall on the more protected zones of these valleys is about 1500 mm. The most protected zones due to its western situation below the summits of the Cordillera, such as the valley of the La Paz and the Luribay Rivers, have rainfall in the range from 300 to 500 mm, the mean rainfall in the Andean basins is estimated at 1720 mm.

Rainfall in the Alto Beni ranges from 1500 to more than 2000 mm, while that of the Plain ranges from 1650 to 2000 mm. The mean precipitation in the Plain Basin is evaluated at 1810 mm, and in the entire Beni Basin, at the confluence with the Madre de Dios River, at 1755 mm.

The Madre de Dios River basin receives heavy rainfall from 2500 to 7000 mm on the Andean flank, and from 1800 to 2500 mm on the Plain, with a mean of about 2380 mm. The mean in the Beni and the Madre de Dios Basin, as a whole, is 2060 mm. The mean precipitation on the Upper Madera Basin is 1705 mm.

The spatial distribution of the rainfall differs greatly according to the regions, while the monthly rainfall distribution in the course of the year presents a similar pattern over the entire Amazon Basin.

The seasonal variation of the climate is determined by the movements of the Intertropical Convergence Zone (ITCZ) and the movements of the Atlantic and Pacific anticyclones between which a low-pressure valley frequently remains over Bolivia.

During the austral winter, the ITCZ reaches the Antilles and the tropical anticylones remain in more septentrional latitudes, near the Bolivian Amazon Basin. This is the dry season, characterized by greater air stability, but nevertheless with rainfall due to diurnal convection. Sometimes southern air intrusions, of polar origin, occur (Surazos), with the presence of a cold front which meets at this time a slightly humid air mass.

During the austral summer, the convergence zone returns toward Bolivia, and then oscillates over the country, where it marks a strong inflection toward the south. This is the rainy season, which finally determines the spatial distribution of precipitation. The trade winds from the northeast or from the north, as well as the turbulences of the ITCZ (vaguadas), maintain over the Amazon Basin an air mass, the humidity of which is recycled from the Amazon Plain and which meets the Andes, thus being diverted toward the southeast. In these regions it meets drier masses of air coming from the south. This mass is made up on one hand of some Pacific air, which seems to have lost a large part of its humidity over the Andes in the southern part of Chile. It then moves over the semi-arid zone of Argentina, and on the other hand, merges with Atlantic air

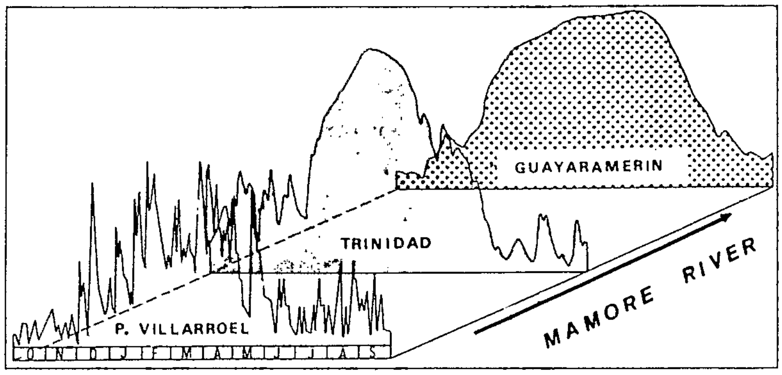


Fig. 3. Shape of hydrographs proceeding down stream on Mamore River from the foot of the Andes to the head of the Madera River.

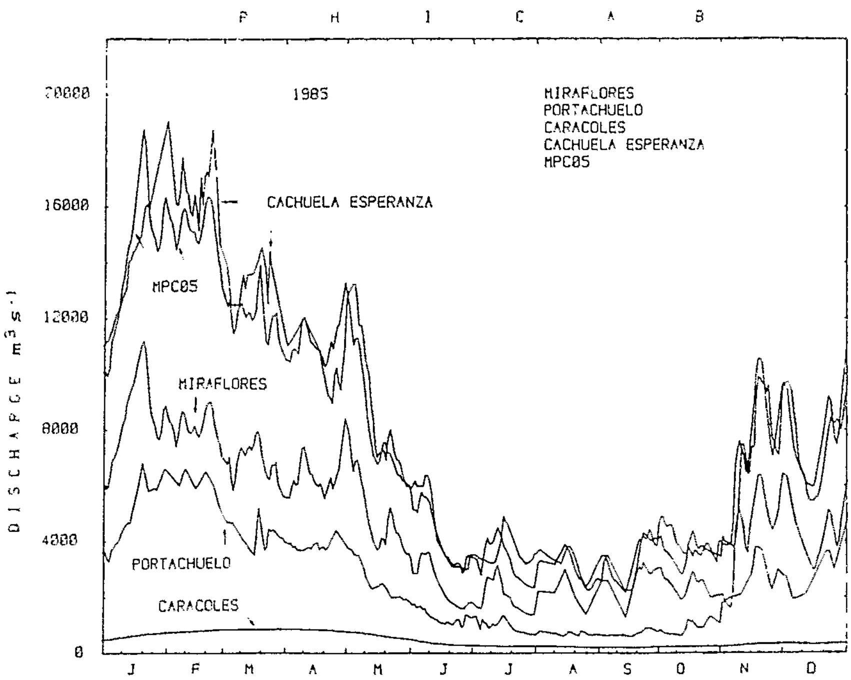


Fig. 4. Comparison of hydrographs of the Beni, Madre de Dios and Orthon Rivers, in 1985. The discharge at the simulated MPC05 station is the sum of that at Miraflores, Portachuelo and Caracoles stations, corresponding to the observed record at Cachuela Esperanza station.

coming from the southeast while leaving a part of its humidity south of Brazil and Paraguay. This southern air moves into the Amazon Plain, between the Andes and the highlands of the Brazilian Shield.

The influence of this mass of air, which is very pronounced in the south of Bolivia, with rainfall less than 600 mm, gradually decreases toward the north part of the Amazon Plain, where the rainfall reaches more than 2000 mm. The deviation of the humid air along the Andes and its blockage in the "bays" of the relief meeting the first spur, cause heavy rainfall in regions such as the Chapare or the Upper Madre de Dios in Peru where rainfall exceeds 6000 and 7000 mm. On the other hand, the blockage of humid air over the summits of the Cordillera protects other regions of the Andes, such as Cochabamba or Luribay, and most of the basin of the Rio Grande. When this humid air passes over the summits, it descends over lowlands, where it becomes warmer, this being also unfavourable for precipitations. The thickness of the Amazon air flow and its raising by the meriodional air determine the maximum altitude of intervention on the Andean flank, and its possible overflow on the Altiplano.

FUNCTIONING OF THE HYDROLOGICAL SYSTEM

The annual rain distribution, conditioned by the alternation of a rainy season and a dry season, determines in the Andes and its piedmont, hydrographs of multi-peaked floods which fuse downstream to originate the large annual flood of tropical type, preceded or followed by small well-differentiated floods (Figs. 3, 4 and 7). The annual flood seems more and more defined from upstream to downstream of the large drainage axis. It is more regulated and flattened in the Mamore and Itenez Rivers because of longer courses and above all because of the lateral extension of broad flooded areas. This also explains the delay of the floods of the Mamore and Itenez Rivers versus those of the Beni and Madre de Dios Rivers. This can represent a two-month difference of phase.

These floods, of a remarkable magnitude, extend over surfaces on the order of 100,000–150,000 km^2, particularly in the Mamore and Itenez River basins. These are mainly produced starting at the confluence of the Chapare, Ichilo and Grande Rivers, and extending up to the Mamore and Itenez Rivers.

During the flooding period, it appears that the whitish and turbid water of the upstream tributaries is sufficient to fill the bed of the Mamore River which, having very slight slope, does not allow the prompt discharge of water from the lateral plain. Floods on the plains, originating from local rains and the overflow of the tributaries, the upstream parts of which, can be situated on the western flank of the Andes, are transparent and reddish-black. The mixture of "white" and "black" water seems to take place gradually but the color difference makes it possible to distinguish lateral trails, which indicate a longitudinal component of the drainage of the flood water. The Itenez River, which does not descend from high mountains, also drains large flooded areas carrying clear water. These floods take place from January to May/June, their decay toward the main axis being delayed downstream.

WATER RESOURCES AND COMPARISON WITH THE WORLD'S LARGEST RIVERS

The mean interannual volume (1968 or 70–1982) flowing in the Madera River at its head has been estimated as $536 \times 10^9 m^3$, i.e. a mean of $17{,}000 m^3 s^{-1}$, of which 53.2% is contributed by the Beni River and 47.7% by the Mamore River

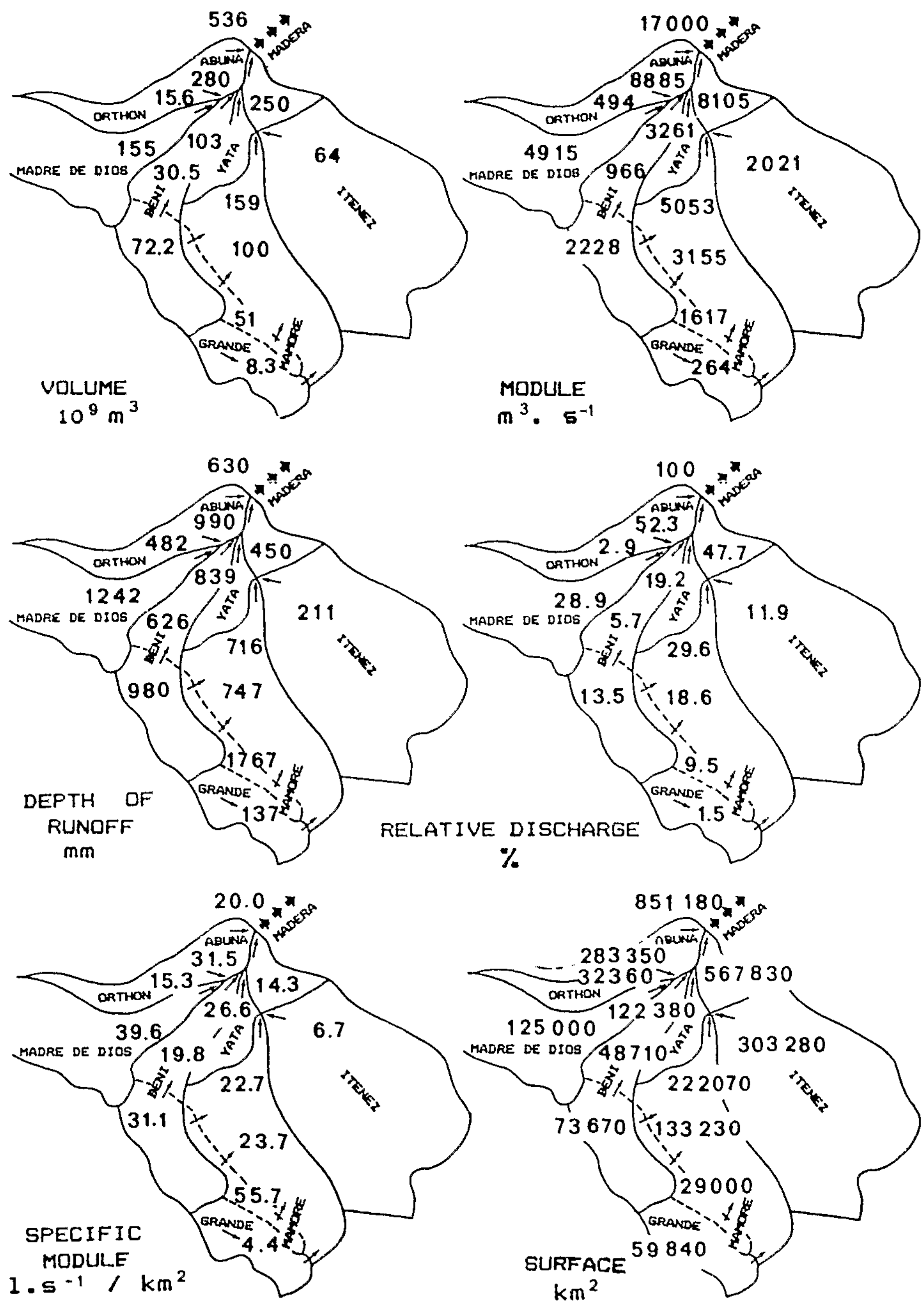


Fig. 5. Annual water yields of the Upper Madera Basin rivers.

(Table 1, Fig. 5). This discharge is larger than the Volga River ($252 \times 10^9 m^3$), the greatest in Europe, which is analogous to the Mamore River ($256 \times 10^9 m^3$), and smaller than the Beni River ($280 \times 10^9 m^3$). At its head, the Madera River receives a discharge greater than the Ob ($390 \times 10^9 m^3$), the Ganges ($488 \times 10^9 m^3$), and approaches that of the Lena ($514 \times 10^9 m^3$), the Tennessee ($542 \times 10^9 m^3$), the Mekong ($577 \times 10^9 m^3$), the Mississippi–Missouri ($580 \times 10^9 m^3$), and the Bramaputra ($608 \times 10^9 m^3$). Only the discharges of the Orinoco ($946 \times 10^9 m^3$), the La Plata ($725 \times 10^9 m^3$), the Yangtze Kiang ($1104 \times 10^9 m^3$), and the Congo ($1200 \times 10^9 m^3$) are clearly greater (Gac, 1980).

The contribution from the Madera River reprents 9.7% of that discharged to the ocean by the Amazon ($5520 \times 10^9 m^3$), whereas the surface area represents 12.1% of the total Amazon Basin. The mean interannual contribution of the Bolivian Andes to the supply of the Madera River, with $132 \times 10^9 m^3$ or a mean of $4170 m^3 s^{-1}$, represents 25% of the total discharge of the Madera at its head. To this value must be added the contribution of the Peruvian Andes, corresponding to the Upper Madre de Dios Basin, which could not be separated from the total measured in this river, near the confluence of the Beni River (Table 2, Fig. 5).

The Andean Basin of the Beni River exports the greatest quantity ($72 \times 10^9 m^3$, i.e. 13%), followed by the eastern basins ($51 \times 10^9 m^3$, i.e. 10%), even though the specific discharge there ($56 l s^{-1} km^{-2}$) is greater than the Beni. The Andean basin of the Rio Grande, with a semi-arid regime, represents a large part of the basin, but with $8 \times 10^9 m^3$, but supplies only 1.5% of the water to the Madera.

The four large tributaries participate in different ways in supplying the Madera River: 19% is from the Beni with $103 \times 10^9 m^3$, 29% from the Madre de Dios with $155 \times 10^9 m^3$, 24% from the Mamore with $159 \times 10^9 m^3$ and 7% from the Itenez River with $64 \times 10^9 m^3$. The remaining 20%, i.e. $55 \times 10^9 m^3$, corresponds to the tributaries between the confluence of these rivers and the head of the Madera. The uncertainty on the values of the measurements at the upstream and downstream hydrometric stations may also explain in part this difference. At the confluence, the Beni and Mamore, account for water yields of $280 \times 10^9 m^3$, i.e. 52.3%, and $256 \times 10^9 m^3$, i.e. 47.7%, respectively.

At this same site, the Beni and the Mamore, each provide a discharge greater than the Niger River ($195 \times 10^9 m^3$) and the Zambezi River ($131 \times 10^9 m^3$), which are the second and third largest in Africa. The Itenez River has annual discharge between that of the Shari River ($50 \times 10^9 m^3$, in the normal period), and the Nile River ($89 \times 10^9 m^3$). The Mamore, at its confluence with the Itenez, has a discharge comparable to the Niger, the Danube ($198 \times 10^9 m^3$) or the Zambezi.

Throughout the basin of the Beni at its confluence with the Madre de Dios, and the Mamore at its confluence with the Itenez, the contribution of the plain is estimated at $131 \times 10^9 m^3$, i.e. 24.5% of the discharge of the Madera. The Andes and the plain of this system contribute equal parts to the water flowing into the Madera River, though the subbasins have different regimes.

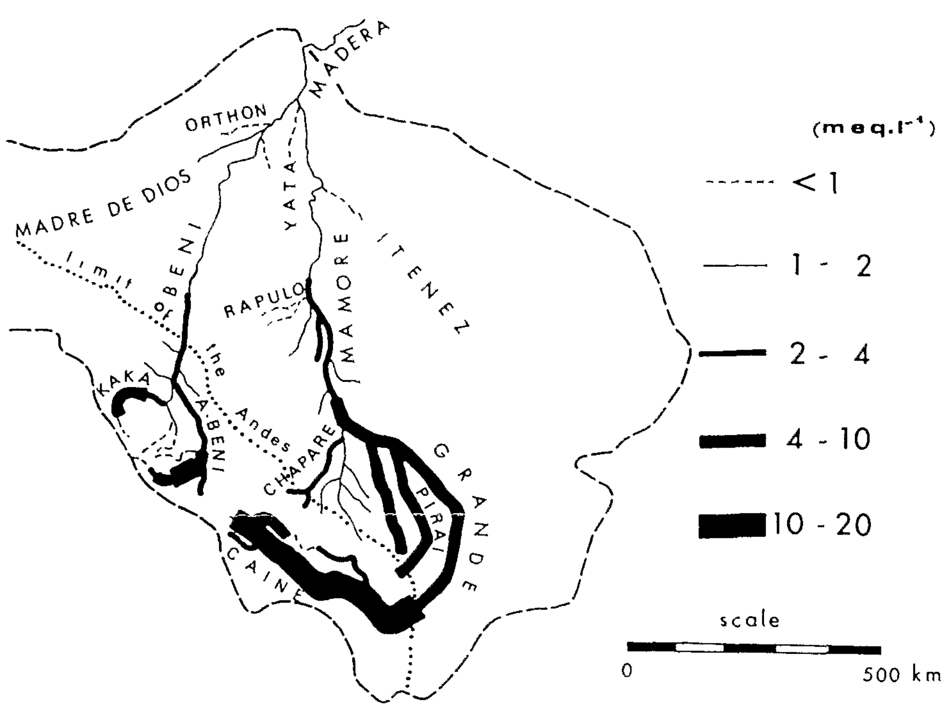


Fig. 6. Ionic contents (meq l^{-1}) in the rivers of the Bolivian Amazon Basin, based on sampling in April/May 1982 (Roche and Canedo, 1984).

The Beni, the Rio Grande and the other tributaries of the Mamore provide, from their Andean Basin, 14, 1.5 and 10%, respectively, of the yield to the Madera.

SALINITY OF THE WATER AND IONIC YIELDS

Global salinity

Figure 6 and Tables 1 and 2 indicate the global salinity (equivalent to dissolved solid content as used herein) and its evolution throughout the entire basin. In the Upper Andean Basin, the salinity is low, about 12 mg l^{-1}. This is the case at the limit of the glaciers. Downstream, in the Andes itself, fluvial water quickly acquires maximum salinity due to solution of altered or evaporitic rocks. This phenomenon thus generates diverse chemical compositions according to the lithology of the basin. The greatest salinity is observed when water flows through lands which contain evaporate deposits such as gypsum, other sulphates, carbonates, and secondarily and locally, sodium chloride. Often, sulphate mineralization comes particularly from gypsum dissolution as well as from the solution of whitish pellicular

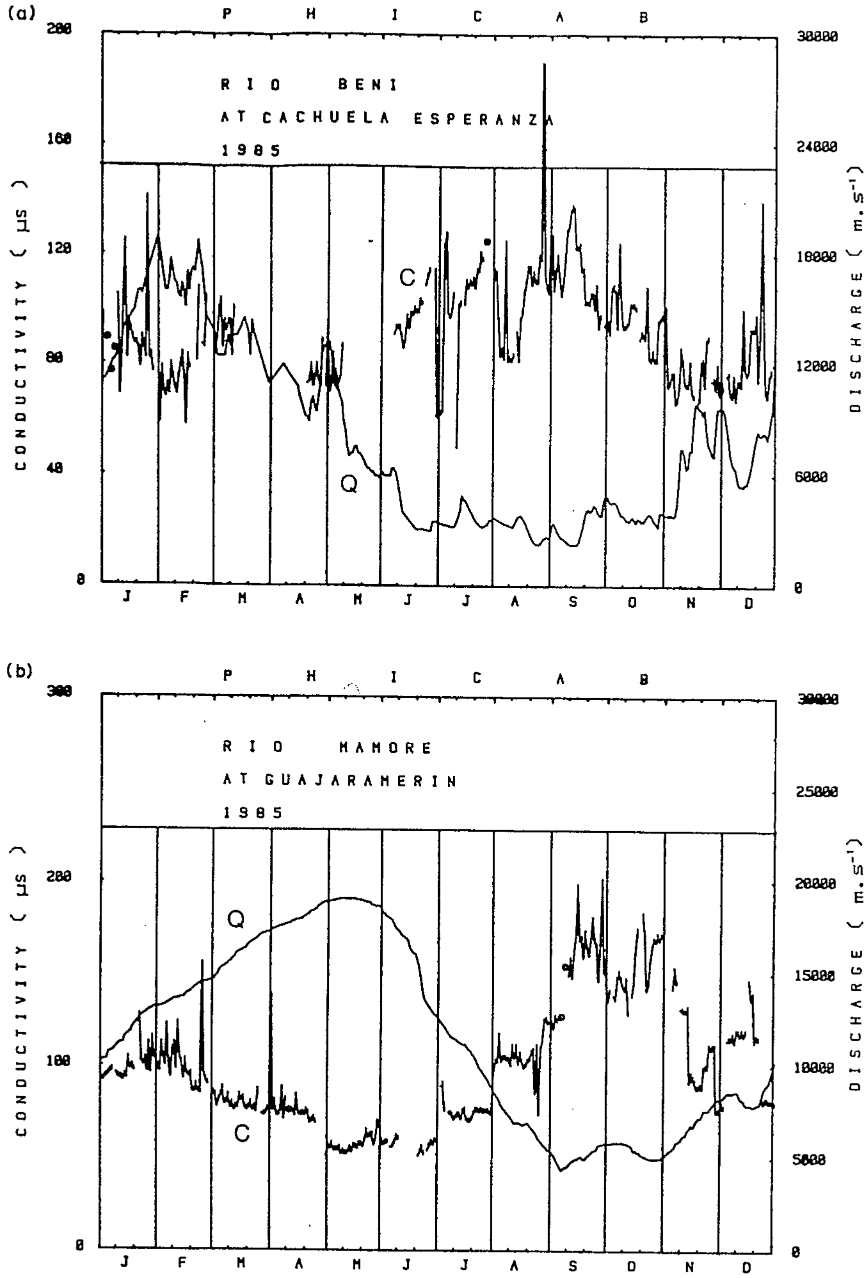


Fig. 7. (a) Daily conductivity (C) and discharge (Q) in the Beni River at Cachuela Esperanza, in 1985. (b) Daily conductivity (C)) and discharge (Q) in the Mamore River at Guayaramerin, in 1985.

efflorescences deposited on different formations, especially on black schists.

The La Paz River, which heads at Chacaltaya glacier, is a typical example. Upon leaving the glacier, salinity increases from 20 to 300 mg l $^{-1}$, few kilometers downstream in the semi-arid zone, reaching 430 mg l $^{-1}$, at the entrance to the humid tropical zone where dilution starts. The increase of the salinity is probably accentuated because of pollution in La Paz city as suggested by abnormal high nitrate contents.

Salinity variation, compared to pluvial and runoff, indicates that the "salt" leaching and simple dilution are the chemical erosion phenomena that predominate in mineralization of fluvial water: the salinity variation generally is inverse to that of discharge (Fig. 7) although there are some exceptions. Thus, the relationship between the monthly mean conductivity and the monthly mean discharge (Fig. 8) is adjusted to a median curve of hyperbolic form. The representative plots for the recession and the low-water phases are above the curve; those corresponding to the rising stage are below the curve. Thus, distribution points follow a "logic circuit" all along the annual cycle, determined by the dissolution and dilution phenomena in the basin.

Mineralization ratios can be very different according to the lithology, climatohydrological regime, and vegetation of the basins, characteristics which are

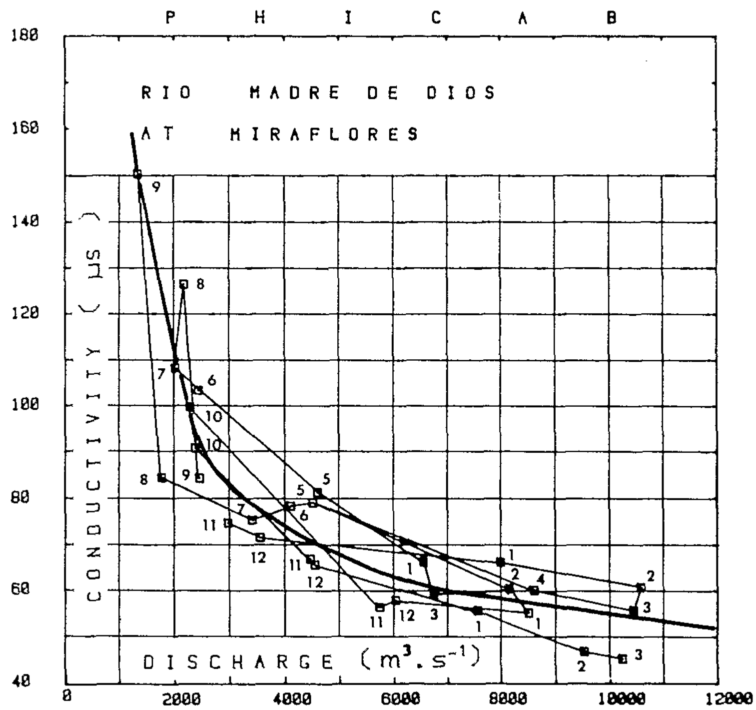


Fig. 8. Relationship between the mean monthly conductivity and discharge in the Madre de Dios River at Miraflores. The number of each plot indicates the month, thus showing the evolution of the conductivity during the annual hydrological cycle.

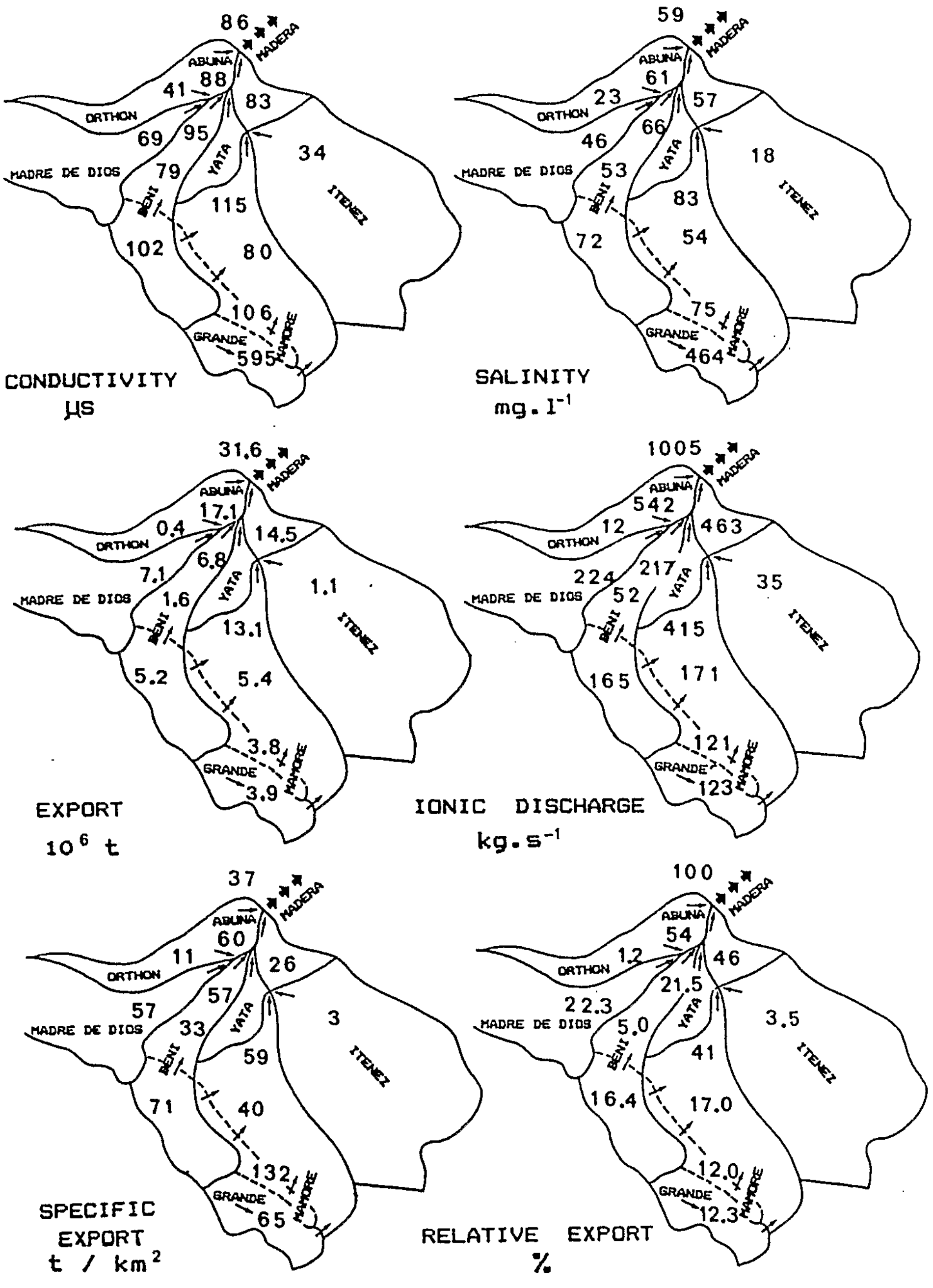


Fig. 9. Interannual salinity and dissolved load of the rivers of the Upper Madera Basin.

themselves diverse in Bolivia (Fig. 9). In this way, two extreme cases can be observed, whether the basins mainly extend through the semi-arid zone, such as the La Paz or Rio Grande, or discharge directly to the Amazon plain, through very rainy areas such as the diverse Andean tributaries of the Beni River. However, in this last case salinities are high in spite of strong discharges, as is observed in the Chapare Basin: the effect of lithology, which is high in evaporites, surpasses that of rainfall.

In the Amazon Plain, the effects of the climatohydrological regimes and of the vegetation prevail over those of the lithology. The dilution of the Andean yield, by the abundant and less mineralized water of the lateral inputs, appears clearly from upstream to downstream. Rainfall over Quaternary detrital sediments of the plain finds less salt to dissolve than in Andean terranes of varied lithology and very pronounced morphology. Annual recycling in the ponds of the plain, the isolated water of which is concentrated by evaporation during the dry season, is not an effective salt input, during the sweeping by the annual flood. One can find here the notion of "vertical erosion" in the Andes, and "horizontal erosion" in the plain (Sioli, 1984), which is particularly apparent for the suspended matter, but is also applicable to dissolved matter. Salinity downstream decrease appears to be the rule in the Mamore and Beni River systems.

The extreme type of the water of the plain is remarkable because its salinity is among the lowest in the world (13–20 μS at 25°C). It is just accumulated pluvial water that slowly flows toward the drainage axis. Its pH is acid.

Filtered by vegetation, without turbulence, it shows great transparency. A prolongued contact with herbaceous thick vegetation, or with the forest that it soaks in the shallow flatlands, as well as with humus-bearing and often hydromorphic soils, gives a brown-reddish coloration with a black gleam, originating thus the name of "black water".

This water is identified in the inundations occurring in the central plain of Trinidad. Small lagoons, distant from the big stream are fed by this same water, as the Laguna Suarez which presents a conductivity of 18 μS. The black water also exists under the Amazon Forest, north of Bolivia, as in the flooded zone of the Rio Ivon. The water of the Itenez River is nearly alike, although less pure with a slightly higher salinity (34 μS.)

This type of "black" water is also found in flooded grassy plains in Chad and Camerun (Roche, 1975), as well as in the Guyana forest. Its occurrence is extensive in the Amazon, where the name of "Rio Negro" is repeated in most of the great basins. Contrary to the usual practice in Africa, particularly in the Sahelian zone, the practice of burning over large areas is not followed in the Amazon, consequently the characteristic of black water does not require necessarily that the vegetation be transformed into ashes.

Physicochemical characteristics of the black water, and the surfaces that it covers in the intertropical zone, justify an interest in specific research about the origin of such characteristics, especially about interaction phenomena with soil and vegetation.

Depending on the mixtures of diversified inflows, with very varied ionic contents, strong (Rio Grande) to weak (Rio Itenez), the Madera River finally receives water of mean salinity, compared to those of the other great rivers in the world.

Comparisons of salinity and dissolved load with other great rivers of the world

The interannual salinity of the Beni (61 mg l^{-1}) and Mamore (57 mg l^{-1}). Rivers at their confluence, as well as the Madera River (59 mg l^{-1}), is relatively low as compared to those of the great European rivers (180–460 mg l^{-1}), or to some African rivers as the Nile (200 mg l^{-1}), the Orange (133 mg l^{-1}) or the Zambezi (149 mg l^{-1}). Nevertheless, the salinity of these Amazon rivers is greater than that of the Congo (31 mg l^{-1}), Niger (48 mg l^{-1}), and Senegal (42 mg l^{-1}).

Among the rivers of America and Asia, the salinity in the Mamore, Beni and Madera Rivers is greater than the Orinoco (52 mg l^{-1}) but less than that of other great rivers which can reach 223 mg l^{-1}, such as the Mississippi–Missouri. The salinity of the Rio Madera and its two great tributaries is slightly higher than that of the Amazon River, evaluated at 53 mg l^{-1}.

Interannual dissolved solids transport, of 17 × 10^6 t for the Beni River, 15 × 10^6 t for the Mamore River (Tables 1 and 2, Fig. 9), are nearly the same as those of the Rhine (15 × 10^6 t), greater than those of the Rhone (12.5 × 10^6 t) and Shari (2 × 10^6 t), are less than those of the Nile (18 × 10^6 t) and Zambezi (19.5 × 10^6 t) Rivers.

The dissolved annual load, at the head of the Madera, reaches 32 × 10^6 t, i.e. 1 t s^{-1}. This is of the same order as the Congo (37 × 10^6 t) and less than the Ob and Orinoco (50 × 10^6 t), Danube (44.5 × 10^6 t), and Mississippi (130 × 10^6 t) Rivers. This last is second in the world, after the Amazon River. The saline dissolved load, at the head of the Madera represents 10.9% of that of the Amazon River (290 × 10^6 t yr^{-1}). The dissolved concentration and load values relating to the different tributaries of the Madera River in the Andes are shown in Tables 1 and 2. At interannual scale, the Andes (60.2% of the area) exports through the Beni River 72.2 × 10^9 m^3 and 5.2 × 10^6 t of ions, with a mean dissolved content of 72 mg l^{-1} (102 μS).

The plain, as such (39.8% of the area), exports through the Beni River 30.5 × 10^9 m^3 of water, and 1.6 × 10^6 t of ions, with a mean dissolved content of 53 mg l^{-1} (79 μS).

The entire Beni Basin, at the confluence with the Madre de Dios River, exports 103 × 10^9 m^3 of water and 6.8 × 10^6 t of ions, with a mean dissolved content of 66 mg l^{-1} (95 μS). In this basin, the water and dissolved exports are 70 and 76%, respectively, from the Andes which comprises 60% of the area.

The total yield of the Madre de Dios River reaches 155 × 10^9 m^3 of water and 7.1 × 10^6 t of dissolved load, with a mean dissolved content of 46 mg l^{-1} (69 μS). At the confluence of the Madre de Dios and Beni Rivers, 60% of the water

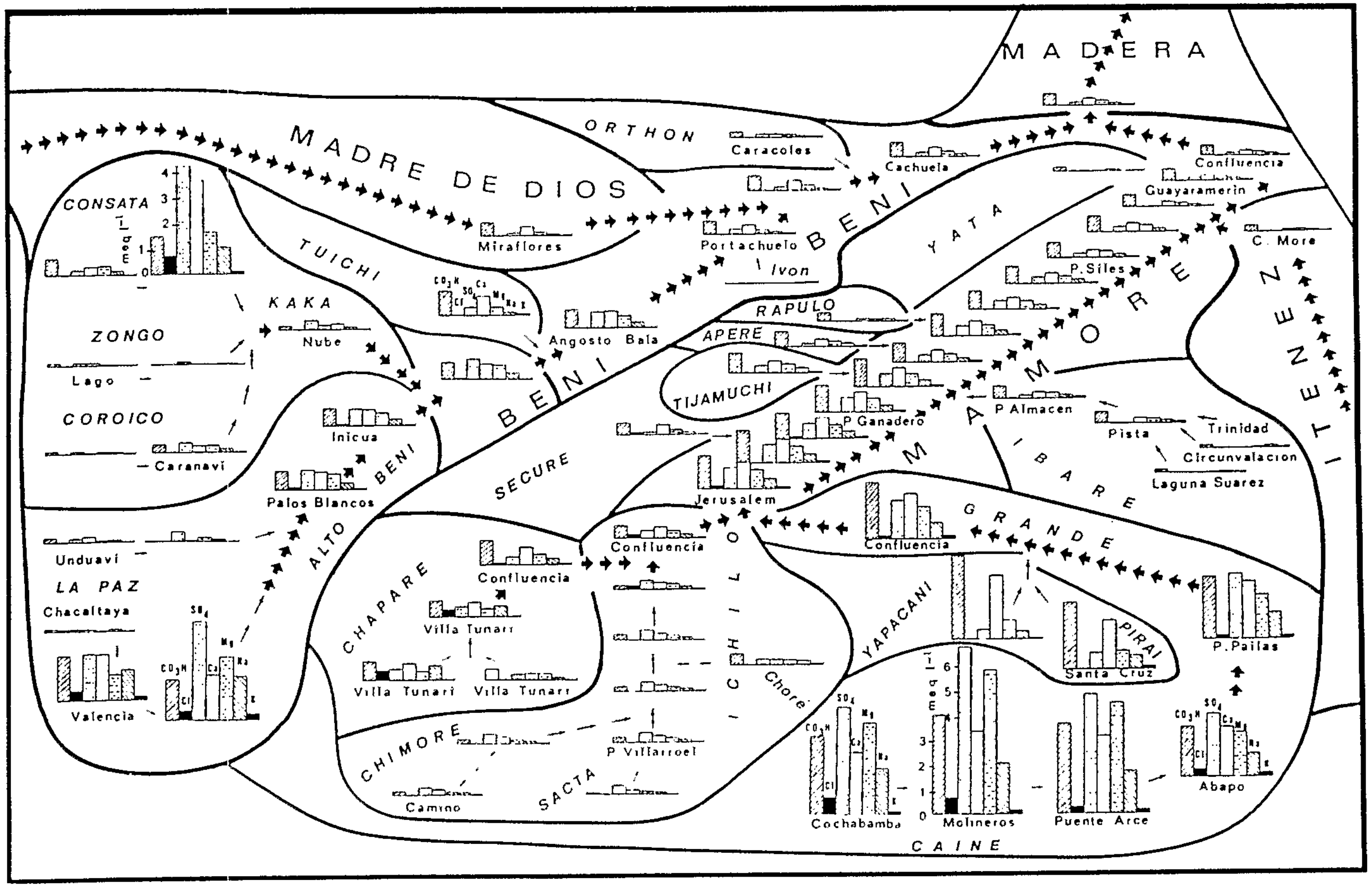


Fig. 10. Specific ionic contents of the rivers upstream to downstream in the Bolivian Amazon Basin. Each histogram indicates the dissolved contents of bicarbonate, chloride, sulphate, calcium, magnesium, sodium and potassium in milliequivalents per liter.

inflow arises from the first river, while the dissolved contributions are better balanced, closer to 50% for each river.

The Orthon River basin is of special interest as it is almost entirely a plain under the Amazon Forest. It contributes to the discharge of the Beni River, above its confluence with the Madera, a water yield estimated at 15.6 × $10^9 m^3$, a dissolved load of 0.37 × 10^6 t and a mean dissolved content of 23.4 mg l^{-1} (41 μS).

Specific ionic contents

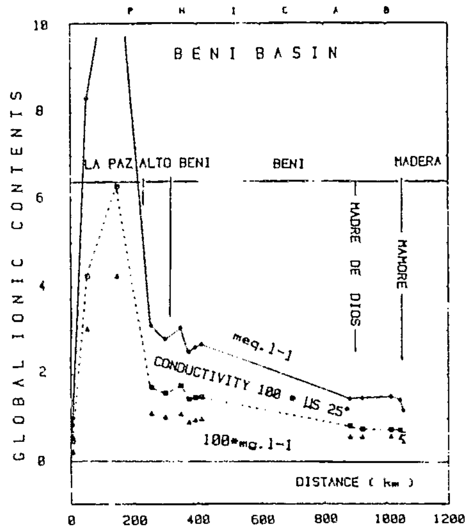
The evolution of specific ionic contents from upstream to downstream is shown on histrograms of these contents in the main subbasins of the Bolivian Amazon (Fig. 10). The downstream evolution of the hydrochemistry of the large rivers is likewise illustrated through graphics, indicating the concentrations of the different ions with respect to the distance counted from the crest line to the Madera River (Fig. 11). Colored maps were published on this subject (Roche et al., 1986a).

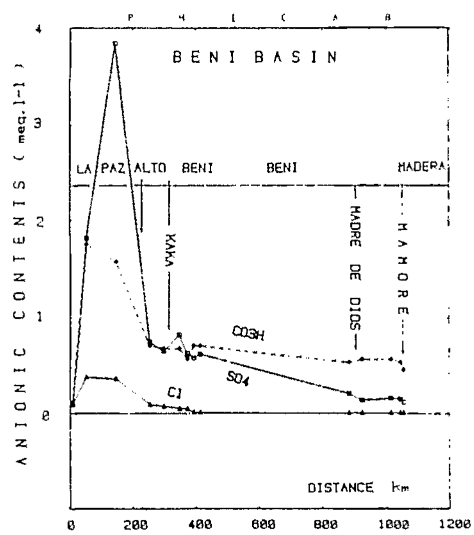
The alkalinity (CO_3H) shows variable values, from 0 to 260 mg l^{-1}. Very low values are found at the head of the Andean basins. Nevertheless, the "black" water presents the lowest alkalinities (6 mg l^{-1}). Certain authors (Meybeck, 1984) mention, for this type of tropical water, alkalinities that can be zero. This water also presents acid pH, about 5 ± 0.5. Given the total salinity, it should be pointed out that other anions are not identifiable either. The water of the Itenez River is different from the pure type of the "black" water by a bicarbonate concentration of 15 mg l^{-1} and a calcium concentration of 1.6 mg l^{-1}. Likewise, the Rio Yata water, draining the Rogagua Lakes, has a lower alkalinity than that of the Itenez River. The highest alkalinities are those of the Grande River. The water of the Madera River contains 28 mg l^{-1}.

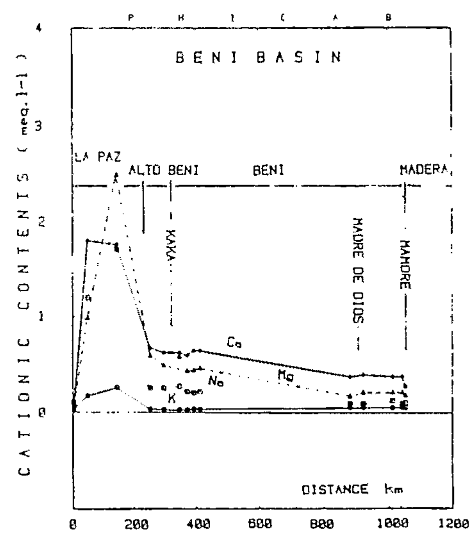
Chloride (Cl) contents (0.7–37 mg l^{-1}) are observed in numerous rivers of the Andes, but Cl generally is lower than the sulphate and alkalinity contents. In the plain, the inflow of chloride is diluted. In the Mamore River, the values are less than 0.7 mg l^{-1} at the confluence of the Grande and the Ichilo Rivers, since, after having increased with the yield of the Secure River, the Cl content is diluted from Trinidad onwards. The Alto Beni River contains chloride concentrations between 0.7 and 3 mg l^{-1} as a result of the inflow from the La Paz and the Consata Rivers. The Cl content of the Beni River is diluted to less than 0.7 mg l^{-1} east of its exit from the Andes. It should be noted that the most mineralized and sulphate-rich water is the one that contains higher chloride concentrations. Chloride thus is associated with sulphate (gypsum) in the evaporate deposits. The four tributaries of the Madera River, at its confluence, contain less than 0.7 mg l^{-1} of chloride.

The sulphate (SO_4) contents range between 0 and 355 mg l^{-1} in the Bolivian Amazon Basin. Very low concentrations are frequent in the Upper Beni Basin. But they increase rapidly, as does the total mineralization, after transit through terranes rich in evaporites or characterized efflorescences. The

(a)







analysis of efflorescent salts has revealed the following composition (% of weight):

SO_4	Mg	Fe	Ca	Mn	Sn	Pb	Zn
78.4	12.5	8.2	0.8	0.1	0.07	0.02	0.03

Such efflorescences should arise in part from the oxidation of pyrite, which yields sulfate solutions. These precipitate on the surface of the ground, as a result of a capillary upward motion and evaporation. In the Rio Grande Basin, this phenomenon is characteristic of the semi-arid type of climatohydrological

(b)

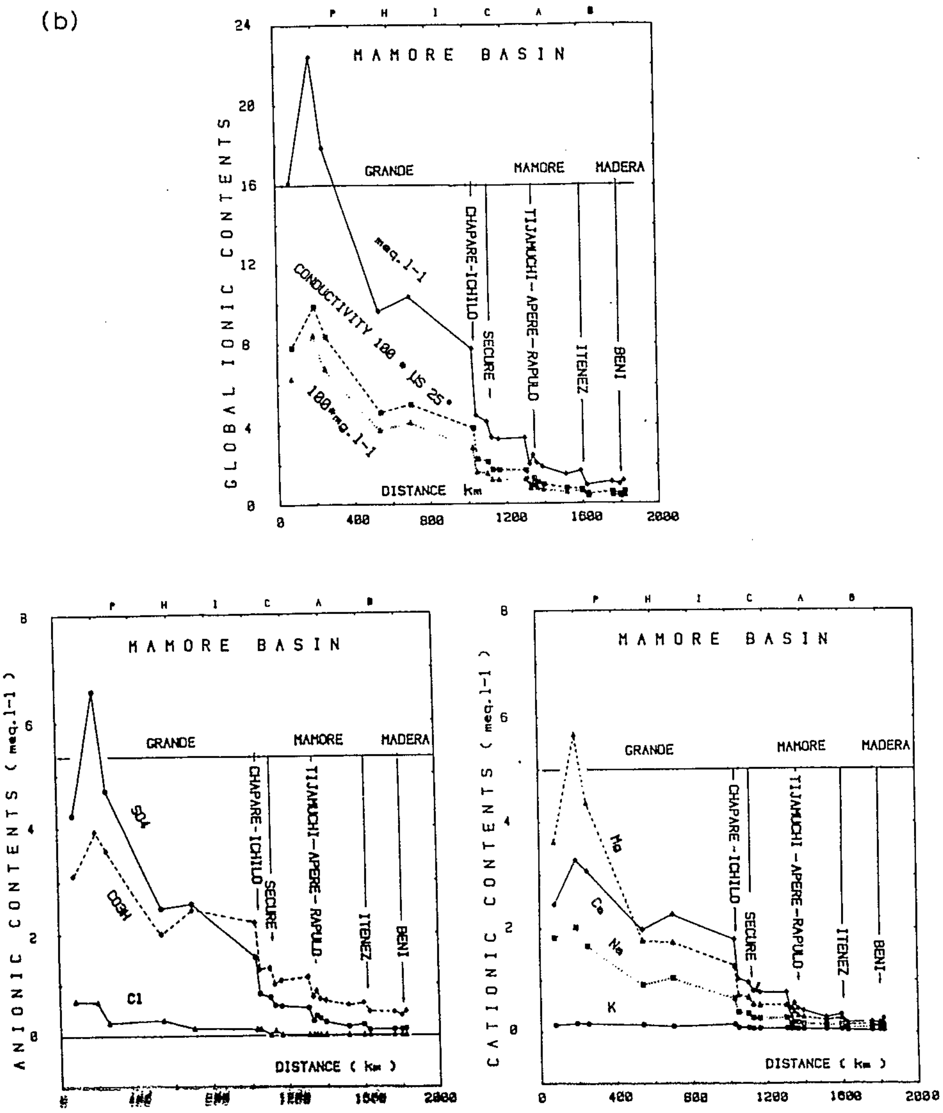


Fig. 11. (a) Longitudinal evolution of the ionic composition in the Beni River, from the Andean source to the Madera River. (b) Longitudinal evolution of the ionic composition in the Mamore River, from the Andean source to the head of the Madera River.

regime. In the plain, one sees a progressive dilution: at their confluence the [illegible] present concentrations ranging between 5 and 9 mg l^{-1}, with a value of [illegible] for the Madera River.

The nitrate (NO_3) contents are less than 1.25 mg l^{-1}, except in the Andes where locally values between 1.25 and 15 mg l^{-1} are observed. These are due then to urban pollution, because they only are found downstream from cities and towns. The highest pollution is that of the La Paz River, the effect of which remains over 100 km downstream from the city of La Paz. As a matter of fact, this city, with over one million inhabitants, does not have a treatment system of the waste waters which are wholly drained by the La Paz River. The same phenomenon is evident in the overpopulated valleys of Cochabamba where contamination is probably also aggravated by the use of fertilizers in agriculture. In the Amazon Plain such pollution is not evident. The water of the Madera River contains nitrate below 0.6 mg l^{-1}.

The phosphate (PO_4) contents are between values of less than 0.06 and 0.44 mg l^{-1}. The maximum concentrations are observed in rivers that are very different from the ones in the Andes and in the plain. The water of the Madre de Dios and the Orthon Rivers, with values of 0.10 and 0.25 mg l^{-1}, respectively, contains more phosphate than that of the other three main tributaries of the Madera, the concentrations of which are less than 0.06 mg l^{-1}. The water of the Madera has a concentration of 0.06 mg l^{-1}.

The maximum values of calcium (Ca) content (41 mg l^{-1}), found in the Andes (Grande, La Paz and Consata Rivers), correspond to high mineralization and sulphate contents, mainly related to dissolution of gypsum. Downstream, extremely low concentrations of calcium, 0.4–1 mg l^{-1}, characterize the Rapulo, Itenez and Yata Rivers, while the "black" water of the flood plains can be considered negligible in calcium, with contents below 0.2 mg l^{-1}. At their confluence, the Beni and Mamore Rivers have calcium concentrations of 7.5–4 mg l^{-1}, respectively, the mixture of which determines a concentration of 5.5 mg l^{-1} in the Madera River. The calcium contents of the Beni River are thus twice as much of that of the Mamore River where the inundations are more important.

The magnesium (Mg) contents are between 0.06 and 78 mg l^{-1}. The distribution Mg in space, especially the evolution from upstream to downstream, is similar to that of the calcium. In the Andes, Mg contents are sometimes higher than those of calcium, as in the Kaka or Grande Rivers, probably due to leaching of saline efflorescences. There also is a tendency to a relative enrichment in the plain, although minimum contents are also found in the streams of the Amazon Forest. The Beni and Mamore Rivers at their confluence contain 2.25 and 1.95 mg l^{-1}, respectively, and determine, for the Madera, a content of 2.2 mg l^{-1}. For magnesium, as for calcium, the concentrations are more important in the Beni River than in the Mamore River, although in a smaller ratio.

The sodium (Na) contents vary between values below 0.2 mg l^{-1} in the rivers of the plain and 47 mg l^{-1} in the Andean rivers (La Paz and Grande Rivers). Similar distribution of sodium and chloride is a sign of a halite dissolution in the lands with evaporitic facies. In the plain, the minimum sodium concentrations as well as the chloride contents, are below the threshold of detection. Where possibilities of dissolution of such ions are low, the main source is of direct marine origin. Humid air masses from the Atlantic transported by the trade winds and diverted toward the south over Bolivia because of an inflection of the Intertropical Convergence Zone, could account for some sea salt. However, the very low sodium and chloride contents suggest recycling of the water vapor by evaporation and evapotranspiration from vegetation on their path over the Amazon. Local precipitation induces on the plain a dilution of sodium contents issuing from the Andes. Thus, the Na concentrations are 2.3 mg l^{-1} in the Beni and Mamore Rivers at their confluence, and in the Madera River.

The potassium contents range between 0.35 and 10 mg l^{-1}. These extreme values are observed throughout rivers of the Andes. Dilution leads to a value of 1.96 mg l^{-1} in the Beni, Mamore and Madera Rivers.

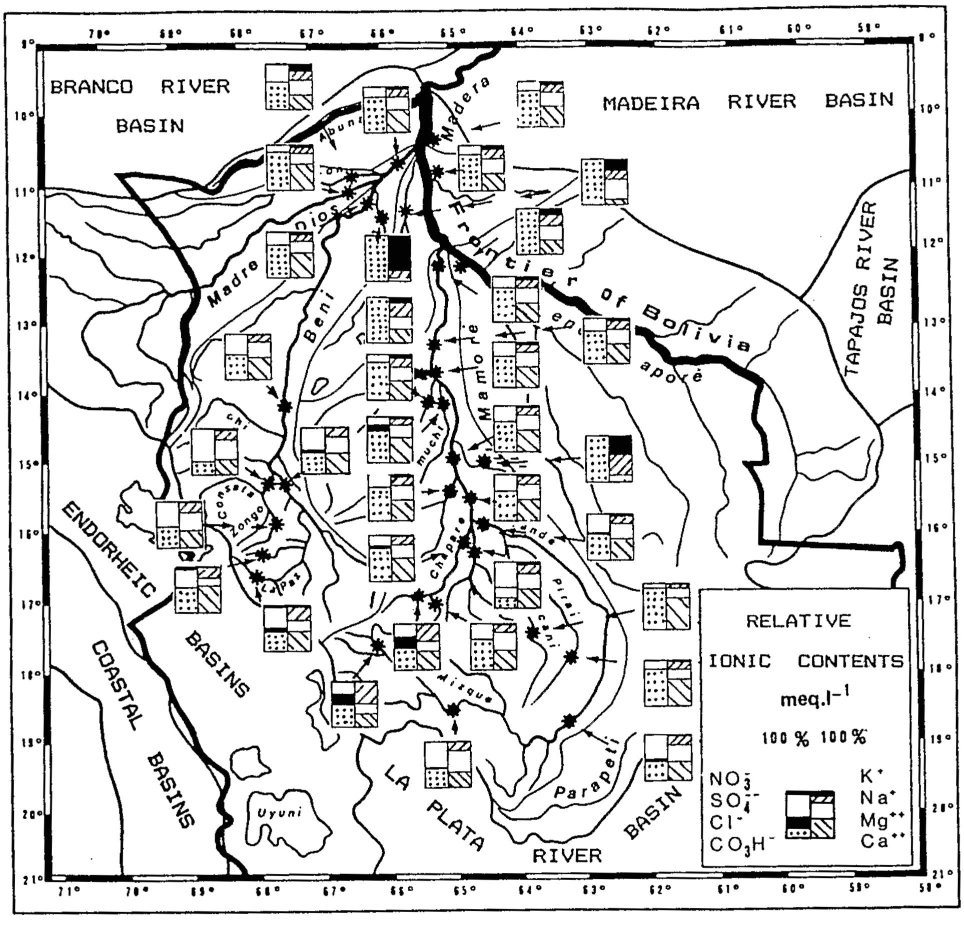


Fig. 12. Relative ionic contents in the rivers of the Bolivian Amazon Basin. Each diagram represents the percentage of specific ions (meq l^{-1}) of cationic or anionic contents (%), at the indicated sampling sites.

Relative ionic contents and water types

Relative ionic contents[1] of the water in the Amazon Basin are represented by percentage diagrams in map, for the most representative sites (Fig. 12).

Beyond the classification, according to Sioli (1984), into "white water" (Great Andean rivers, large drainage basins), "black water" (floods and rivers which drain those floods), "green water" (Itenez River), water is characterized by hydrochemical spectrum[2], according to the basin and its particular situation.

In the Andes, river water generally contains mainly bicarbonate, sulphate, calcium and magnesium. Thus the evolution of the hydrochemical spectrum from upstream to downstream in the Cordillera is determined by mixtures of successive contributions of different compositions at each confluence, leading to more or less marked modifications of the hydrochemical spectrum.

On the contrary, in the large rivers of the plain, the evolution of the spectrum is less accented and dilution is the predominant phenomenon because of lateral and local slightly mineralized yields. Several hydrochemical types of water can be distinguished, on the basis of predominant ions:

(1) Streams of the Andes: (a) calcium sulphate: Consata, Kaka, Alto Beni, Chimore, Ichilo Rivers; (b) magnesium sulphate, changing to calcium sulphate downstream: La Paz–Boopi, Grande Rivers; and (c) calcium bicarbonate: Unduavi, Rocha, San Mateo, Espiritu Santo Rivers.

(2) Streams of the plain: (a) calcium bicarbonate: large rivers, such as the Beni, Chapare, Mamore, Madre de Dios Rivers; (b) calcium–magnesium bicarbonate: Orthon River; and (c) anionic spectrum often indeterminate because of low concentrations, but of better identifiable cationic spectrum: "black" water in the grassy plains and forest; (i) sodium changing to potassium and magnesium without calcium: Trinidad floods; (ii) potassium changing to magnesium, with low contents of calcium: Yata River; and (iii) highly potassic changing to sodium, without calcium, and low contents of magnesium: Ivon River. The high relative contents of potassium is due to interaction with the vegetation.

Attempt to evaluate specific ionic exportation

Evaluation of mean annual transport of individual ions has been tried by multiplying the available relative contents (by weight) by the global transported tonnage. These values represent only provisional magnitudes, however (Table 3).

CONCLUSIONS

Water and dissolved solids transport (salt export) have been measured for the first time in the entire Upper Madera Basin, which constitutes the Bolivian

[1] An ion content, in meq l^{-1}, versus the addition of the ionic contents.
[2] Classification of ionic contents, in meq l^{-1}, in a decreasing order.

TABLE 3

Dissolved solid transport ($10^6\,t\,yr^{-1}$) of the Bolivian Amazon Basin

Rivers	CO_3H	SO_4	Ca	Mg	Na	K
Amazon–Andes	3.6	2.8	1.1	0.8	0.5	0.12
Entire Beni	10	2.3	2.2	0.8	0.8	0.6
Entire Mamore	9	2.0	1.4	0.7	0.9	0.7
Madera	19	4.3	3.6	1.5	1.7	1.3

Amazon, in the Andes and the eastern plain. This hydrological system appears remarkable because of its size and runoff.

The Madera River, at the confluence of its main tributaries, is among the greatest in the world because of its capacity, $17{,}000\,m^3\,s^{-1}$ of water, and $1\,t\,s^{-1}$ of dissolved salts: nearly half of the volume and a comparable dissolved discharge to that of the Congo.

Its two main tributaries, the Beni River with $8890\,m^3\,s^{-1}$ and $0.54\,t\,s^{-1}$, and Mamore River with $8100\,m^3\,s^{-1}$ and $0.46\,t\,s^{-1}$, are also world-class rivers. The contribution to Amazon River transport ($175{,}000\,m^3\,s^{-1}$ and $9.2\,t\,s^{-1}$) represents 9.7% for water, and 10.9% for ions while the area involved represents 12.1% of the entire Amazon Basin.

Salinity, with values of 59, 61, and $57\,mg\,l^{-1}$ for the Madera, Beni and Mamore Rivers, respectively, are relatively low compared to most large rivers, but are somewhat higher than the Amazon River, evaluated at $53\,mg\,l^{-1}$.

The Upper Madera water carries in solution mainly bicarbonate (61%), sulphate (14%), calcium (11%), sodium (5%), magnesium (5%) and potassium (4%). The "black" water of the plain constitutes the most unique water type, which because of its wide distribution, justifies a thorough study of its geochemistry and interactions with the soil and the vegetation.

The Upper Madera Basin, in its Andean and plain portions, contributes also in an important way to the transfer of water and dissolved matter through the Amazon and in the world. These water masses and the generated floods over tens of thousands of square kilometers for many months in the year, emphasize the important phenomenon of recycling of water vapor in the Amazon Basin, even in the absence of thick forest. All these climatic and hydrological conditions should be taken into consideration to understand the determinant meteorological factors of the South American continent.

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