WATER AND SALT BALANCES OF THE BOLIVIAN AMAZON

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ABSTRACT

The Bolivian Amazon region lies in the upper middle part of the Madeira River basin (850,000 km^2), a portion of which extends in the Andes (24%), and also in Peru and Brazil. The water and salt balances of the main sub-basins and the entire basin of the upper Madeira River are established for the interannual period 1968/1970 to 1982.
The mean interannual precipitations on the great basins vary from 750 to 3000 mm, the entire upper Madeira basin receiving 1705 mm yr^{-1}. The biggest extremes of the rainfall reach 490 and more than 7000 mm. At its head, the Madeira River is yet one of the largest rivers of the world, with a mean interannual discharge of 17,000 $m^3 s^{-1}$, i.e. 536 x 10^9 m^3 yr^{-1}, approximately half the discharge of the Congo River. The mean interannual contribution of the Bolivian Andes is 4170 $m^3 s^{-1}$, i.e. 132 x 10^9 m^3 yr^{-1}, representing 25% of the discharge of the entire upper Madeira basin. The values of actual evapotranspiration vary from 615 mm in the driest Andean basin to 1520 mm yr^{-1} in a forest and low drainage basin. Global ionic contents, with values of 59 mg l^{-1}, 61 mg l^{-1}, and 57 mg l^{-1} for the Madeira, the Beni and the Mamoré Rivers respectively, out of any contamination, are somewhat higher than for the Amazon River. Interannual dissolved ionic transport is evaluated to 32 x 10^6 t at the begining of the Madeira River, i. e. 1 t s^{-1}.
The contribution of the upper Madeira River to the Amazon system, at the ocean, is evaluated to 9.7% of the water and 10.9% of the ions, whereas the surface represents 12.1%.

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INTRODUCTION

The Bolivian Amazon region lies in the upper middle part of the Madeira River basin (Sioli, 1984), a portion of which also is in Peru and Brazil. The basin extends through the Eastern Cordillera of the Andes, the adjoining Plain, and the Brazilian Shield. Mean drainage axes are constituted by the Madre de Dios, Beni, Mamoré and Itenez Rivers which join to become the Madeira River, the more important south affluent of the Amazon. At the confluence of the Beni and Mamoré Rivers, the Madeira River drains a basin of 850,000 km^2, 24% of which lies in the Andes. The water flows through varied zones of relief, lithology, climate and vegetation which determine diverse hydrological and hydrochemical characteristics.

The international Project PHICAB, conducted by ORSTOM, IHH and SENAMHI, under agreement with the International Hydrological Programme of UNESCO, studies climate, hydrology, hydrochemistry and sediment transport in Bolivia, in particular the Amazon part (Roche, 1982; Roche and Canedo, 1984). Thanks to measurements and the compilation of other available data, the PHICAB has established the water and salt balances of the main sub-basins and the entire basin of the upper Madeira River (Espinoza, 1985; García, 1985; Abasto, 1987; Cruz, 1987; Roche and Fernández-Jaúregui, 1988). In the Amazonian region of Bolivia, climatological data is available since 1945 at many stations. The hydrometric measurements have been made in the Andes since the 1970's but, in the plain, they began in 1982. However, three hydrometric stations, among a PHICAB network of 15 stations, have been observed there before over a 15 to 20 years period. Then, the values obtained over the whole basin are adjusted for a first evaluation to the interannual period 1968/1970 to 1982, according to the UNESCO recommendations for the water balance of South America.

Differents periods have also been considered in other studies for sub-basins (Bourges et al., 1987, 1990; Guyot et al., 1987, 1990; Roche et al., 1989). Details of the water and salt balances for an hydrological division in 16 sub-watersheds are presented in Tables I and II.

PHYSICAL AND BIOLOGICAL CONDITIONS

The surface of the whole basin is 850,000 km^2 of which one third is represented by the Beni basin and two thirds correspond to the Mamoré basin. The Andes occupy 205,000 km^2, i. e. one fourth of the surface.

Between the glaciers of the andean crests and the tropical rainy forest of the piedmont, the rivers drain frequently semi-arid areas of high altitude, particularly in the south west of the Beni basin and in the Rio Grande basin. In the center of the eastern plain of Bolivia, the forest is interrupted by savanna with forest gallery but resumes in the Brazilian Shield and to the north where the great amazon forest begins.

The andean rocks are of all geological times: Paleozoic, Mesozoic, Tertiary and Quaternary. They were affected by Pliocene folding, with locally upper Cretaceous and Eocene folding. Intrusive rocks constitute the highest mountains of the head-watersheds. The Permian and Cretaceous sections contain gypsiferous red clays where the gypse is locally exploited. White exudations in the dry periods cover diverse terrains in the semi-arid areas, especially the black Paleozoic schists.

RAINFALL

The spatial rainfall distribution over all Bolivia and the parts of the basin situated in the border countries has been displayed on maps at 1/4,000,000 scale (Roche and Rocha, 1985) and for each of the four main basins at 1/1,000,000 scale. The Figure 1 is a simplification of maps drawn at 1/5,000,000 scale. This distribution of the precipitation differs greatly according to the regions, the dynamics of air masses and orographic phenomena. However, the monthly distribution in the course of the year presents a similar pattern over the entire Bolivian Amazon basin, showing that it is part of a same pluviometric regime (Roche et al., 1990).

The Madre de Dios basin receives yearly heavy rainfall from 2500 mm to more than 7000 mm on the andean flank, and from 1800 to 2500 mm on the plain, with an average of 2380 mm.

The Beni River basin, in its andean part, receives between some 800 and 1000 mm on the summit, and more than 4000 mm in the upper part of the hot valleys (Yungas). The most protected zones due to its western situation behind the upper summits of the Cordillera, such as the valleys of La Paz and Luribay, have rainfall in the range of 350 to 500 mm. The main rainfall in the andean basin is estimated at 1720 mm. Rainfall in the plain ranges from 1650 to 2000 mm, with a mean precipitation evaluated at 1810 mm, and at 1755 mm in the entire Beni basin, at the confluence with the Madre de Dios river.

The mean precipitation in the Beni and the Madre de Dios basins, as a whole, is 2060 mm.

The Mamoré andean basin, with extrem values of 480 mm in the most semi-arid zone to 6000 mm at the foot of the Andes, receives a mean rainfall of 750 mm in the Río Grande basin and 3000 mm on the oriental watersheds. The Amazon plain has rainfall between 800 mm in the Río Grande basin, 3000 mm in the Ichilo basin and 1900 mm at the head of the Madeira river. The increase in rainfall is remarkable toward the north (800 to 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 1520 mm over the entire Mamoré basin.

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

The mean precipitation on the upper Madeira basin is 1705 mm.

EVAPOTRANSPIRATION

Evapotranspiration has been evaluated in two ways: the water balance, by the difference between precipitation and discharge, furnishes a value of the actual evapotranspiration that has been compared to that obtained by formulas (Figure 2). According to the recommendations of UNESCO for the water balance of South America, the formula of Thornthwaite or Turc has been used for land, and of Penman for free-water.

Interannual values vary from 610 mm, in the semi-arid Río Grande basin where the water deficit is high, to 1520 mm in the Orthon River basin, characterized by a very flat relief, low drainage and rainy forest covering. The andean part of the Beni River basin shows a value of evapotranspiration of 780 mm, just a little higher than that of the previous basin. The evaluation of 1220 mm, made for the rainy oriental basins of the Mamoré River, increases the global value of evapotranspiration in the Bolivian andean part of the upper the Madeira River basin, where it is estimated at 800 mm.

The actual evapotranspiration in the plain, varies from 1075 mm to 1520 mm and tends to increase from South to North. This highest value is similar to that evaluated at 1470 mm for the Amazonian forest in French Guiana (Roche, 1982 a, b).

The comparison of the evaluations obtained by the two methods, shows differences included between zero and 14%. Evapotranspiration remains the most difficult evaluation of the water balance, compared to the other terms that can be more easily measured.

RUNOFF

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 dowstream to originate the large annual flood of tropical type, preceded or followed by small well-differentiated floods. 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 Mamoré and Itenez Rivers mainly because of longer courses and above all because of lateral extension of broad flooded areas. This also explains the delay of the floods of the Mamoré and Itenez Rivers versus those of the Beni and Madre de Dios Rivers. This can represent a two-month difference of phase (Roche and Fernández-Jaúregui, 1986; Bourges et al., 1988).

These floods of a remarkable magnitude, extend over surfaces in the order of 100,000-150,000 km^2, particularly in the Mamoré and Itenez River basins. These are mainly produced starting at the confluence of the Chapare, Ichilo and Grande Rivers, and extending up to the Mamoré 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 Mamoré River which, having very slight slope, does not allow the prompt discharge of water of the upstream tributaries and rainfall from the lateral plain. Floods on the plains, originating from local rains, are transparent and reddish-black. The mixture of "white" and "brownish-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.

The Madeira at its head is one of the world largest rivers, with a mean interannual volume of 536×10^9 m^3, i.e. 17,000 $m^3 s^{-1}$, 52% of which is contributed by the Beni River and 48% by the Mamoré River (Figure 3). The Mean interannual contribution of the Bolivian Andes represents 132×10^9 m^3, i.e. 1170 $m^3 s^{-1}$, i.e. 25% of the total discharge of the Madeira. In Bolivia the Andean basin of the Beni River exports the greatest amount (72×10^9 m^3 i.e. 13%), followed by the eastern basin (evaluated to 51×10^9 m^3). The Andean basin of the Río Grande, with semi-arid regime in its largest part, supplies 8×10^9 m^3, only 1.5% of water of the Madeira. To these inputs have to be added those of the Peruvian Andes which feed the upper Madre de Dios River.

Like the Madeira, the Beni and the Mamoré (both of same discharge) 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 Madeira represents almost half the discharge of the Congo River.

SALINITY

The low salinity observed at the limit of the glaciers, covering intrusive rocks of the crest, increases quickly dowstream due to the dissolution of altered or evaporitic varied rocks. Often, high contents of sulphate comes from gypsum dissolution as well as from the leaching of whitish pellicular efflorescences exuded by capillarity from different formations, especially from black schists (alteration of sulphure). The pollution by La Paz city is locally strong but disappears some hundreds of kilometers downstream.

In the Amazon plain, the effects of the climatohydrological regimes and of the vegetation prevail over those of lithology. It occurs a continuous dilution of the andean inputs by the abundant and less mineralized water of the lateral yields, on Quaternary detrital sediments. The extreme type of water of the savanna and forest has salinity among the lowest in the world (13-20 uS at 25 C). Filtered by vegetation, without turbulence, it shows great transparency. A prolonged 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". With low pH, they show high relative contents in potassium due to interaction with vegetation (Roche et al., 1986; Guyot et al., 1988).

The global salinity of the Madeira River at its begining has been measured and evaluated at 59 mg l^{-1} (Figure 3). It is a value higher than that of the Amazon, Orinoco, and Congo Rivers evaluated at 53 mg l^{-1}, 52 mg l^{-1}, and 31 mg l^{-1}, respectively (*in* Gac, 1980). The interannual salinity of the Beni (61 mg l^{-1}) and Mamoré (57 mg l^{-1}) are both similar.

The mean annual dissolved transport, at the head of the Madeira, reaches 32 x 10^6 t, i. e. 1 t s^{-1}. The Beni and Mamoré River yield, each one, 17 x 10^6 t and 15 x 10^6 t. An estimation made for another period (1983-1987) by Guyot (1988), leads for the Madeira River to 41 x 10^6 t of dissolved ions and silica. These values can be compared to those of the Amazon River (290 x 10^6 t), Orinoco (50 x 10^6 t), Congo (37 x 10^6 t). It represents 10.9% of the total load of the Amazon.

In the Beni River basin at its confluence with the Madre de Dios, the Andes (60% of the surface) exports yearly 5.2 x 10^6 t of ions, whereas the plain yields 1.6 x 10^6 t. The total input of the Madre de Dios River is evaluated at 7.1 x 10^6 t of dissolved ions. At the confluence of the Madre de Dios and Beni Rivers, 60% of the water inflow arises from the first river, while the dissolved contributions are better balanced, closer to 50% for each river.

The contribution of the Bolivian Andes is evaluated at 12.9 x 10^6 t (i.e. 80 t km^{-2}), with a mean salinity of 98 mg l^{-1}, and respective yields of 40% by the Beni River, 30% by the Grande River, and 30% by the eastern watershed.

The Upper Madeira water carries in solution mainly bicarbonates (61%), sulphate (14%), sodium (5%), magnesium (5%), and potassium (4%).

CONCLUSION

The upper Madeira River, in its Andean and plain basins, has yet an important role for the yield of water and dissolved matter through the Amazon and the Atlantic Ocean. The contribution to Amazon River transport (175,000 $m^3 s^{-1}$ and 9.2 $t s^{-1}$) is 9.7% for water, and 10.9% for dissolved ions, while the surface involved represents 12.1% of the entire hydrological system. These evaluations are the first made in the basin as a whole.

In this large basin, evapotranspiration removes 1075 to 1155 mm (according to the way of evaluation), i. e. 63 to 68% of the 1705 mm of the precipitation. Then, runoff as complement, evacuates 33 to 37%, according to the two ways of evaluation of actual evapotranspiration. The losses are assumed at two thirds by evapotranspiration. The region includes high and cold mountains, semi-arid zones, and flooded savannas and forest over tens of thousands of square kilometers for many months in the year. Taking in account this great variety of factors, the global value is compatible with those of the Amazon, Orinoco, Paraná, and San Francisco Rivers, estimated at 49%, 48%, 72% and 70% (UNESCO, 1980) or that on the continents of the planet for which authors agree for values between 60% and 65%. This term of the water balance emphasizes the important phenomenon of recycling of water vapor in the Amazon basin, even in the absence of thick forest.

Complementary new data are soon ready to be published by the PHICAB staff in climatology, hydrology, hydrochemistry and sediment transport. But beyond these results and the necessity to lengthen the series of data, the difficulties and incertitudes of evaluating regional evapotranspiration remain. They justify to continue to carry out, by classical and up-to-date technics, thorough studies of this so important term of the water and energy balances. The regionalization should be the guide-line of a new state of such studies.

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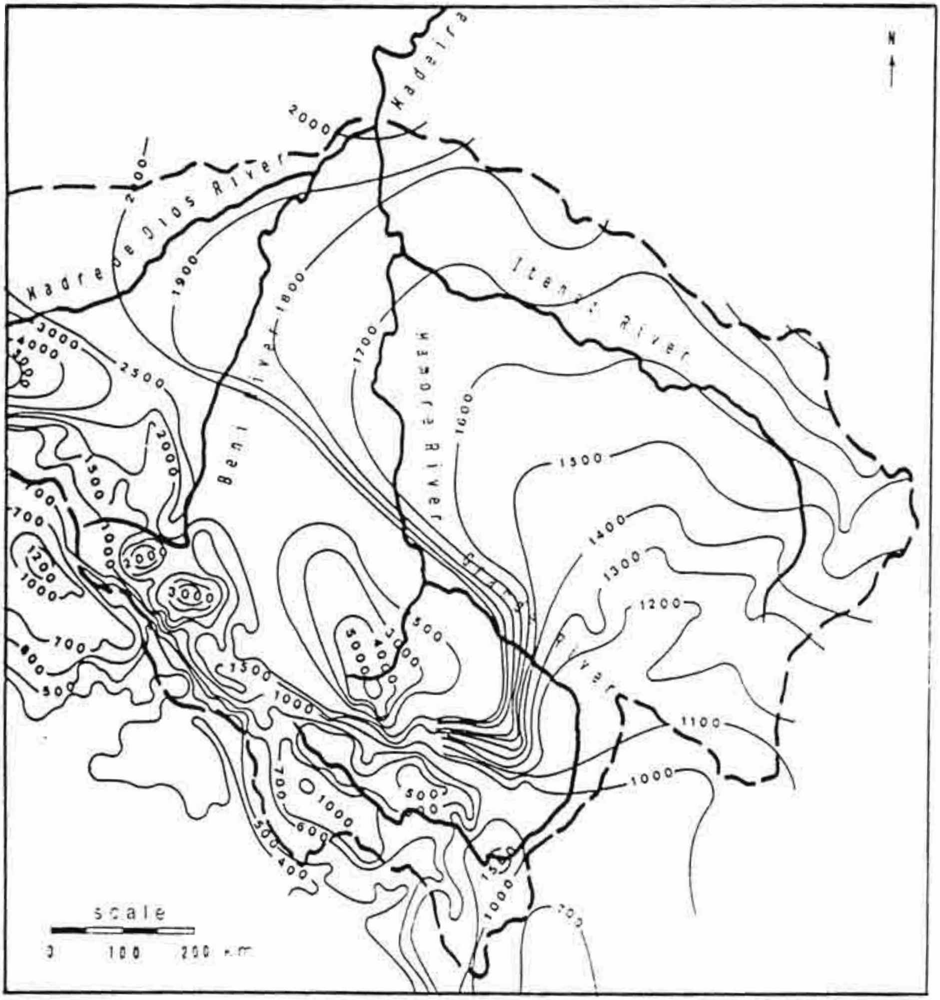


Figure 1 - Map of interannual rainfall in the upper Madeira River basin, in mm yr^{-1} (period 1968-1982).

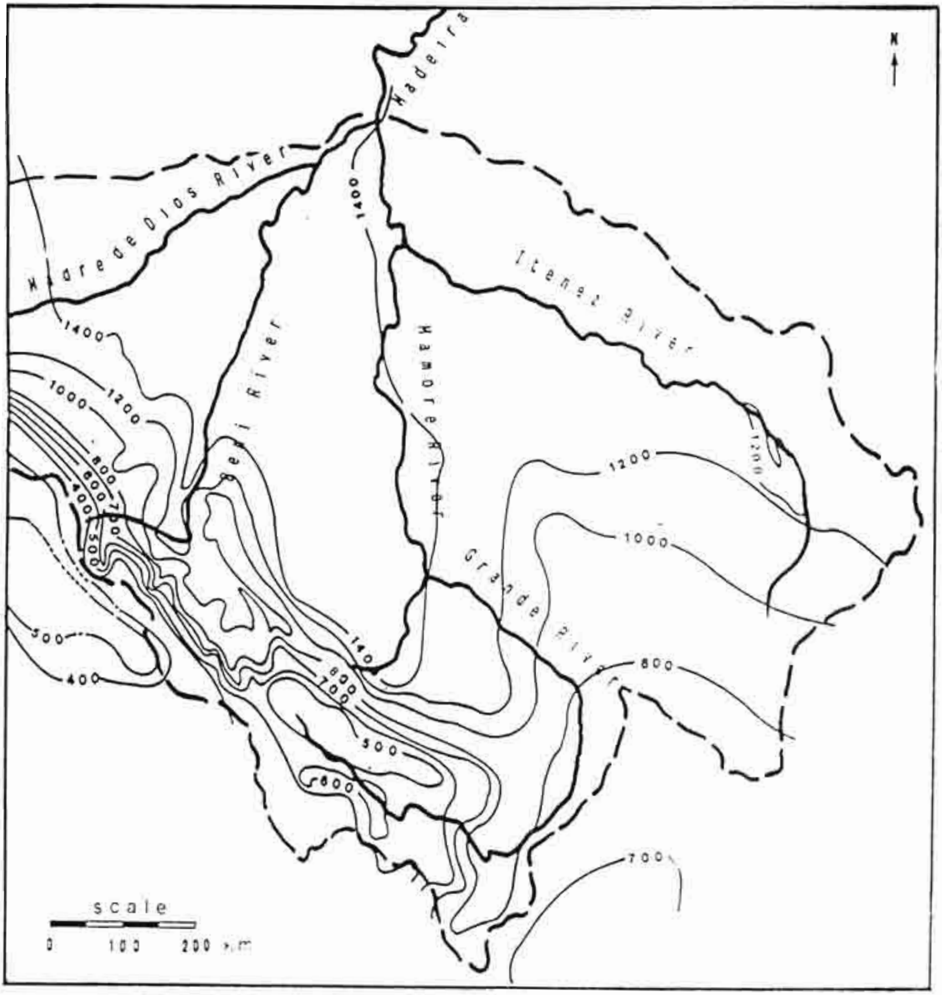


Figure 2 - Map of interannual actual evapotranspiration in the upper Madeira River basin, in mm yr^{-1}, evaluated by Turc and Thornthwaite formulas

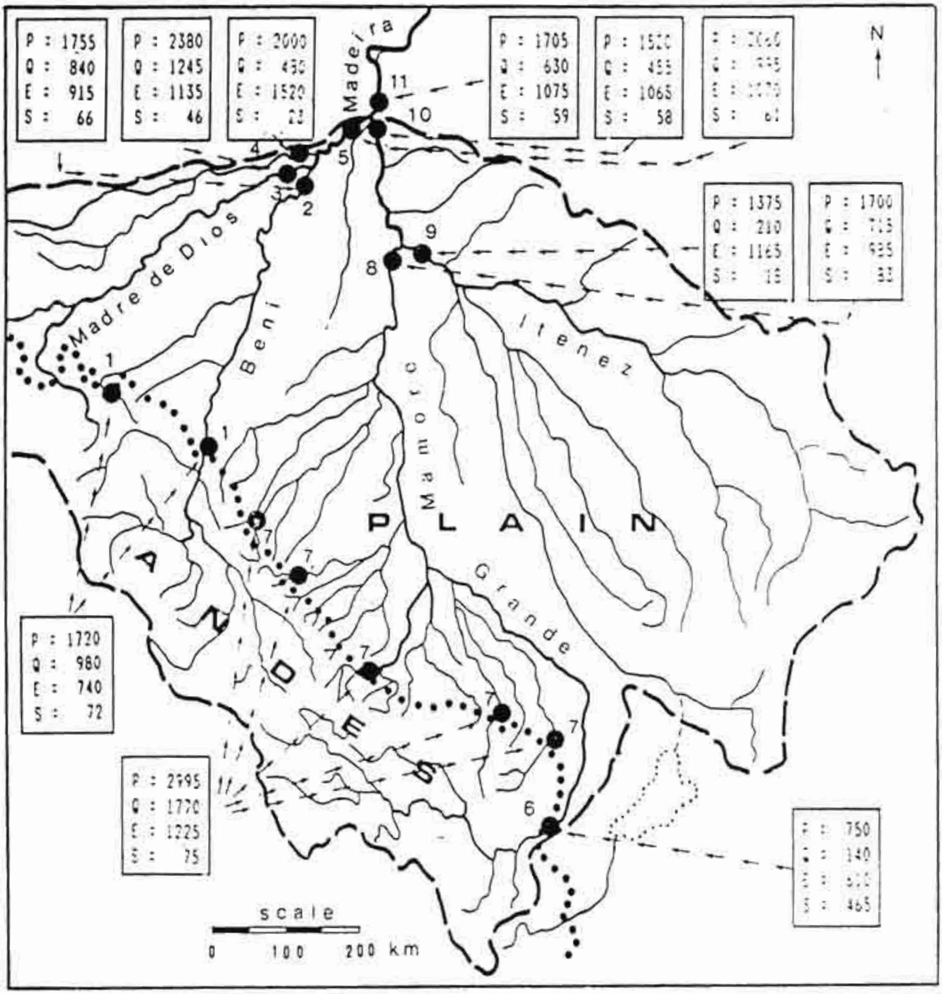


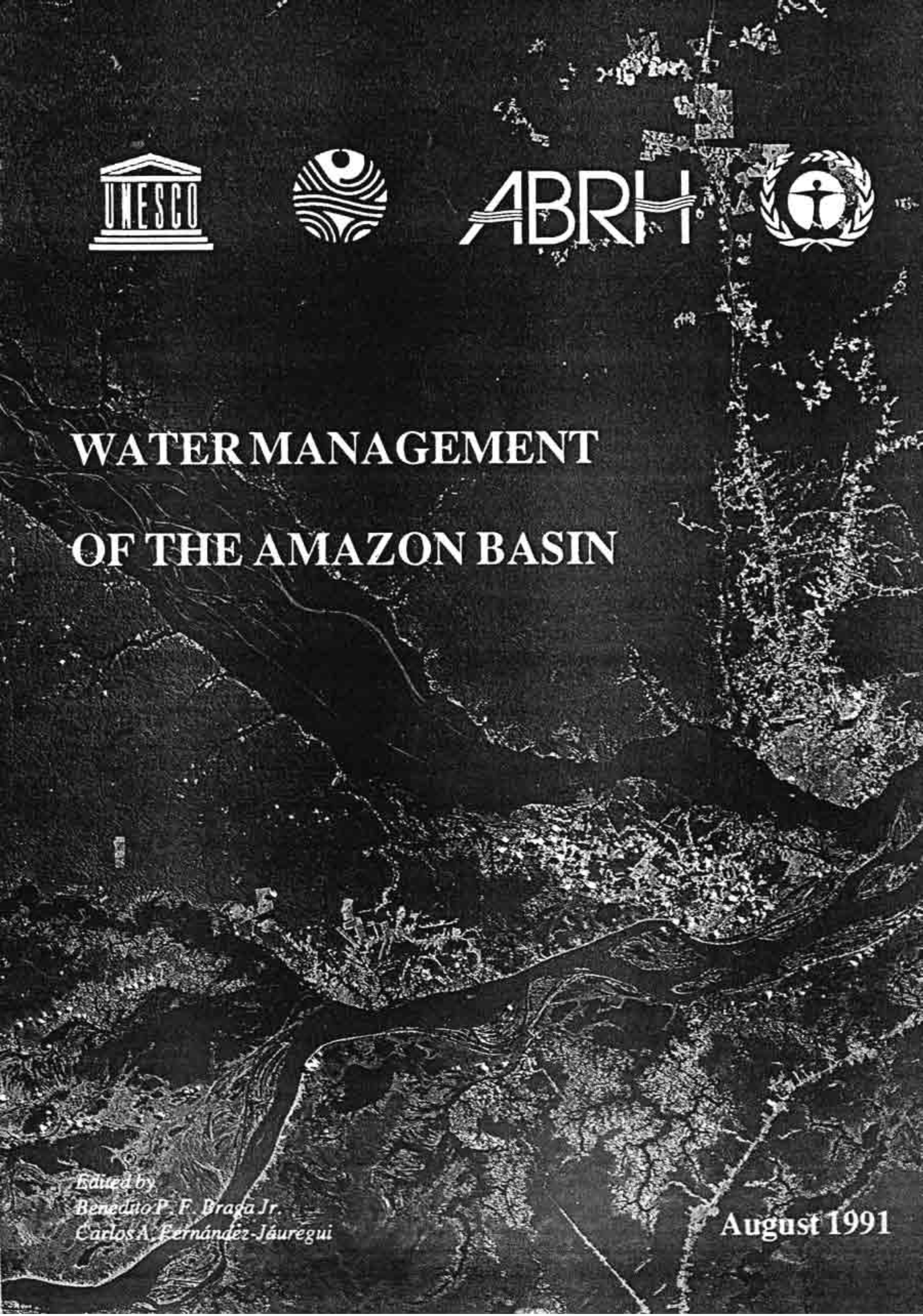
Figure 3 - Water balance: Rainfall (P); Depth of runoff (Q); and Evapotranspiration (E), in mm yr^{-1}, and salinity (S), in mg l^{-1}, in the basins of the Upper Madeira River (period 1968-1982). 1: Beni River at the limit of the Andes. 2: Beni River at the confluence with the Madre de Dios River. 3: Madre de Dios River. 4: Orthon River. 5: Beni River at the confluence with the Mamoré River. 6: Río Grande at the limit of the Andes. 7: Oriental Watersheds at the limit of the Andes. 8: Mamoré River at the confluence with Itenez River. 9: Itenez River. 10: Mamoré at the confluence with the Beni River. 11: Madeira River at its head.

Table I - Interannual Salinity, Water and Ionic Yields of the Upper Amazonian Basin of Bolivia (period 1968/70-1982).

ENTIRE MADEIRA RIVER / UPPER BASIN		SURFAC.	WATER									SALT					
			CLIMATOLOGY			RUNOFF						SALINITY		EXPORTATION				
Period 1968/70-82		km²	Rain mm	Actual Evapot. mm Balance	formula	mm	10^9 m³	%	%	Module m^3s^{-1}	Module sp $ls^{-1}km^{-2}$	Cond. pond. µS	Salin. pond. mgl^{-1}	Exp.sal. 10^6t	%	%	Mod. ion kgs^{-1}	Mod. ion sp. tkm^2
Beni	Andes	73670	1719	739	781	980	72.2	13.5	25.7	2228	31.1	102	72	5.2	16.4	30.4	165	71
Beni	Plain	48710	1806	1180		626	30.5	5.7	10.9	966	19.8	79	53	1.6	5	9.4	52	33
Beni	s/total	122380	1754	915	1043	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	2378	1136		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	2000	1518		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 s.l.	total	283350	2061	1069	1140	993	280.4	52.3	100	8885	31.5	88.1	60.9	17.1	53.9	100	542	60.3
Grande	Andes	59840	751	612	614	139	8.3	1.5	3.2	264	4.4	595	464	3.9	12.3	26.7	123	65
Eastern Basins	Andes	29000	2992		1225	1767	51	9.5	19.9	1617	55.7	106	75	3.8	12	26	121	132
Andes	s/total	88840	1480	812	813	669	59.3	11.1	23.2	1880	21.2	175	130	7.7	24.3	52.7	244	87
Mamore	Plain	133230	1847	1100	1211	747	99.6	18.6	39	3155	23.7	80	54.2	5.4	17	37	171	40
Mamore	s/total	222070	1700	984	1052	716	158.9	29.6	62.1	5033	22.7	115	82.5	13.1	41.3	89.7	415	59
Itenez	total	303280	1373	1162	1223	211	63.9	11.9	25	2021	6.7	34	17.6	1.1	3.5	7.5	35.3	2.8
Mamore	Guayaramerin	547060	1519	1064	1155	455	248.7	46.5	97.4	7880	14.4	84.6	58.1	14.5	45.7	99.3	459	26.5
Yata + B.Brazil	Llanos	20770	1690	1350		340	7	1.3	2.7	222	10.7	37	20	0.14	0.4	0.9	4.4	6.7
Mamore s.l.	total	567830	1525	-1075	1162	450	255.7	47.7	100	8105	14.3	83.4	57.2	14.6	46.1	100	463	25.7
Madeira	Confluence	851180	1704	-1073	1154	631	536	100	-	17000	20	86	59	31.7	100	-	1005	37

Table II - Interannual Salinity, Water and Ionic Yields of the Andean Upper Basins in Bolivia, for the period 1968/70-1982.

Bolivian Amazon, Andes	SURFACE	WATER							SALT					
		Rainfall	Actual evapot.	Runoff					Salinity		Exportation			
	km^2	mm	mm	mm	$10^9\ m^3$	%	m^3s^{-1}	$ls^{-1}km^{-2}$	μS	$mg\,l^{-1}$	$10^6 t$	%	kgs^{-1}	tkm^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	38.8	11617	56	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



WATER MANAGEMENT OF THE AMAZON BASIN

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