WATER, DISSOLVED SOLIDS AND SUSPENDED SEDIMENT DISCHARGE TO VENEZUELAN COASTLINE

Armando J. RAMIREZ[1] , José L. MOGOLLON, Claudio BIFANO, and Carlos E. YANES.

RESUME

Les fleuves transportent vers les océans une charge considérable de sédiments dissous et en suspension. Les activités humaines ont un impact considérable sur la quantité et la qualité de la charge transportée.

Au Vénézuela le fleuve Orénoque est consideré, en termes globaux, comme très représentatif des l'eau et des sédiments transportés vers la mer des Caraïbes. Le premier objectif de ce travail est d'estimer le flux d'eau et des matières en suspension déchargées par les fleuves du Vénézuela vers la mer des Caraïbes et de les comparer avec celui de l'Orénoque.

La part des fleuves vénézuéliens (exception faite de l'Orénoque) été estimée à $8.4* 10^6$ tonnes/an (sédiments dissous) et $173*10^6$ tonnes/an (sédiments en suspension). Le flux et la décharge de l'Orénoque contribuent à eux seuls pour $37*10^6$ tonnes/an des sédiments dissous et $323*10^6$ tonnes/an des sédiments en suspension.

Les décharges annuelles obtenues dans cette étude montrent que le système fluvial de l'Amérique du Sud draînant vers la mer des Caraïbes contribue de façon significative à la charge totale de sédiments dissous et en suspension.

ABSTRACT

The fluvial transport of dissolved and suspended solids from the Venezuelan land into the Caribbean Sea has been estimated in $8.4*10^6$ ton/year and $173*10^6$ ton/year, respectively. These fluxes plus the Orinoco River discharges amounted $37*10^6$ ton/year for the dissolved solids and $323*10^6$ ton/year for the suspended sediment.

The fluvial fluxes estimated for the Caribbean Sea of South America were 343 Km3/year of water, $44*10^6$ ton/year of dissolved solids and $440*10^6$ ton/year of suspended sediments. The water, dissolved solids and suspended sediment discharges estimated for the Atlantic Ocean of South America were 9992 Km3/year, $406*10^6$ ton/year and $1687*10^6$ ton/year, respectively.

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(1) Instituto de Ciencas de la Tierra, Facultad de Ciencias, Universidad Central de Venezuela, Apartado 3895, Caracas, 1010-A, Venezuela

The annual fluvial discharges obtained in this study have permitted to show that the fluvial system of South America draining into the Caribbean Sea has a significant contribution in the fluxes of suspended sediment and dissolved solids

Mots-clés : Eau, sédiments, Vénézuela, systèmes fluviaux, érosion.
Key words : Water, Sediment, Venezuela, Fluxes, Denudation

Instituto de Ciencias de La Tierra, Facultad de Ciencias, Universidad Central de Venezuela, Apartado 3895, Caracas, 1010-A, Venezuela.

INTRODUCTION

Rivers are the major carrier of both dissolved and suspended matter into the oceans. Many estimates have been made of the global fluxes of river water (Korzun, 1978; Berner and Berner, 1987; Tamrazyan, 1989; Tardy et al., 1989), dissolved solids (Meybeck, 1976, 1979) and particulate matter (Milliman and Meade, 1983; Milliman, 1990 ; Tamrazyan, 1989) including the chemical composition of the dissolved (Meybeck, 1979) and particulate (Martin and Meybeck, 1979; Martin and Whitfield, 1983) materials.

As a result of the world human population, rivers have been intensively and extensively affected by activities such as agriculture, domestic, industrial and navigation. These human activities have a considerable impact on the quantity and quality of the fluvial transport of dissolved and suspended matter. This anthropogenic influence in the alteration of the natural environment has happened on a time scale which is very short compared with geological time. In this sense, any geochemical data generated at the present time has to be corrected for pollution before it can be used as representative of the natural environment.

The Orinoco River has been considered, on a global basis, representative of the whole Venuezuela land in terms of water, dissolved and suspended matter discharges into the sea, because there is very little information about the Venezuelan rivers that drain into the Caribbean Sea. Therefore, the first objective of study is to estimate the water, dissolved and suspended matter discharges for the Venezuelan rivers draining into the Caribbean Sea and compare these fluxes with those reported for the Orinoco watershed.

This objective in conjunction with the recent fluvial fluxes reported for the Orinoco and for the Amazon Rivers are enough reasons to compile the available fluvialfluxes for the Caribbean Sea and Atlantic Ocean coastline of South America.

DESCRIPTION OF THE STUDY AREA

The Venezuelan fluvial systems can be divided into three groups, contributories to the Atlantic Ocean, the Caribbean Sea and to Lake Valencia (Zinck, 1982). The Atlantic Ocean basin is integrated by the Orinoco, San Juan, Cuyuni and Negro Rivers watersheds. The rivers draining into the Caribbean Sea are subdivided into those rivers draining directly into sea (Caribbean Sea basin) and those draining through Lake Maracaibo (Fig. 1). The Caribbean Sea basin (Fig. 2) has an area of 85700 Km2 and has been divided into eight subbasins: Maticora-Mitare, Ricoa-Hueque, Tucurere-Tocuyo, Aroa-Yaracuy, Litoral Central, Curiepe-Uchire, Unare and Neveri-Cariaco. All the rivers investigated in this study are under pristine conditions, except the Yaracuy and Tuy Rivers, because most of the largest cities, except Caracas, are located along the coastal areas or river mouths (Ramírez et al., 1988; Colina et al., 1989).

The Caribbean Sea and Atlantic Ocean drainage basins of South America have been divided into 10 subbasins (Fig. 3). Colombia and Venezuela integrate the Caribbean Sea basin of South America whereas the Orinoco, The Guianas, The Amazon-Tocantins, the Northeastern and Southeastern Brazil, the Sao Francisco, the La Plata and Southern Argentina constitute the Atlantic Ocean watersheds.

The Caribbean Sea drainage basin has an area of $515 * 10^3$ Km^2 and a coastline length of 2630 Km whereas the Atlantic Ocean watershed has an area of $14.64 * 10^6$ Km^2 and a coastline length of 11500 Km.

METHODOLOGY

Water samples have been collected since march of 1987 in 27 rivers draining directly into the Caribbean Sea (Fig. 3), except the Tuy River which has been monitored since April of 1979. A water sampling campaign was also conducted in 11 rivers (Palmar, Apon, Lora, Catatumbo, Oso, Frío, Tucaní, Poco, Motatán, Misoa and Machango) of the Lake Maracaibo basin during the period of 1981-1982. The water samples were filtered through a 0,45 µm membrane filter. The filtrate was analyzed by atomic absorption spectrometry for Na, K, Ca and Mg; by colorimetry for SiO_2 and by ion chromatography for F^-, Cl^-, HCO_3^-, NO_3^- and SO_4^{2-}. The membrane filters were dried (40-45 °C) in the laboratory and weighed on an analytical balance.

The concentration of dissolved solids was obtained by adding together the cations (Na, K, Ca, Mg), the anions (Cl^-, HCO_3^-, $SO4_2^-$) and the silica (SiO_2). The concentration of suspended solids was calculated by dividing the weight of total suspended matter over the total volume of water filtered and it was only performed in the water samples from the Caribbean Sea watersheds.

The grain size distribution of the suspended particles was measured by Coulter Counter in 16 water samples from the Tuy River mouth, containing a wide range of concentration (100-18000 mg/l) of suspended solids.

RESULTS

The annual weighted average concentration of dissolved constituents was calculated by using the water chemistry and the monthly runoff data for each river studied. The annual average runoff and sediment discharge data for each river watershed were calculated by using the data generated by the Ministerio del Ambiente y de los Recursos Naturales Renovables (MARNR) and reported by Chacón-Mendoza et al. (1979), MARNR (1979) Chacón Mendoza (1982a,b,c), and Zinck (1982). Then, the runoff and the dissolved and suspended matter yield values obtained for each river watershed under pristine conditions were used to estimate the weighted average data of each subbasin reported on Tables 1 and 2. The sediment yield for the Lake Maracaibo basin was estimated by using the particulate phosphorus yield (400 Kg/Km^2 year) and concentration (485 mg/Kg) data reported by Ramírez (1991).

The Colombian Caribbean Sea drainage basin has an area of $340 * 10^3\ Km^2$ and is integrated by the Magdalena (257 x 103 Km2), the Atrato ($36 * 10^3\ Km^2$), the Sinu ($11 * 10^3\ Km^2$) and others ($36 * 103\ Km^2$) river watersheds. The water (229 Km^2/year) and sediment (202 * 10^6 ton/year) discharge data for the Magdalena River have been estimated from the data reported by Milliman and Meade (1983) and García-Lozano and Dister (1990). These results, in conjunction with the average concentration of dissolved solids of 120 mg/l (Meybeck, 1979) have been used to estimate the fluvial fluxes for the whole basin, assuming that the Magdalena River represents the total drainage area.

The Orinoco River watershed has an area of 990 * 10^3 Km^2, an annual stream flow of 36000 m^3/sec (Meade et al., 1983), a sediment discharge of 150 * 10^6 ton/year (Meade et al., 1990) and an average concentration of dissolved solids of 25 mg/l (Paolini et al., 1987; Lewis and Saunders, 1989, 1990).

The area (6.93 * 10^6 Km^2) and water discharge (7000 Km^3/year) of the Amazon-Tocantins drainage basin represent the average values of the data reported by Korzun (1978) and Vorosmorty et al., (1989). The sediment discharge (1.3 * 10^9 ton/year) has been taken as the upper value reported for the Amazon River by Meade (1985) and Meade et al. (1985) in order to account the sediment discharge of the Tocantins River. An average concentration of dissolved solids of 40 mg/l (Gibbs, 1967; Kempe, 1982; Stallard and Edmond, 1983) has been estimated in this study.

The runoff (980 mm/year) for the Guianas region has been estimated from the runoff map of South America (Vorosmorty et al., 1989) and from the data reported by Meybeck (1980) for Guyana watersheds. The sediment yield was estimated by assuming that the Guianas basin behaves in a similar way as the Orinoco and Amazon do. The dissolved solids flux was estimated by assuming an average concentration of dissolved solids (36 mg/l) equal to that reported by Meybeck (1980) for the Guyana drainages.

The Sao Francisco drainage basin has an area of 631 * 10^3 Km^2, an annual stream flow of 3760 m^3/sec (Paredes et al., 1983), a sediment discharge of 6 * 10^6 ton/year (Milliman and Meade, 1983) and a dissolved solids concentration of 43 mg/l (Paredes, 1982).

The runoff, the suspended and dissolved solids yields for the Northeastern and Southeastern drainage basins of Brazil were considered to be the same as those values reported for the Sao Francisco River basin.

The La Plata watershed has an area of 2.97 * 10^6 Km^2 and an annual stream flow of 23 * 10^3 m^3/sec (Bonetto, 1975; Korzun, 1978). The average concentration of dissolved (70 mg/l) and suspended (170 mg/l) solids have been estimated from the data reported by Depetris and Griffin (1968), Bonetto (1975), Depetris (1976), Depetris and Lenardon (1982, 1983) and Cascante et al. (1985).

The runoff (220 mm/year), sediment yield (12 ton/Km^2-year) and dissolved solids yield (10 ton/Km2-year) for the Southern Argentina watershed were estimated by assuming that these values should be between those reported for the Sao Francisco and La Plata watersheds.

The Tables 3 and 4 show all the estimated data for the 10 drainage basins of South America and for the whole Caribbean Sea and Atlantic Ocean basin.

The average particles size obtained for the suspended sediments was 10 µm and it was independent of the concentration of suspended solids. The fraction of suspended particles finer than 2 µm was about 2%.

DISCUSSION

The data presented on Tables 1 and 2 illustrate the variation in runoff, sediment and dissolved solids yields found for the Venezuela Caribbean Sea drainages. The western rivers (Maticora-Yaracuy) supply the 43% of the water, 87% of the sediment and 76% of the dissolved solids discharged into the Caribbean Sea. In other words, the eastern rivers (Curiepe-Cariaco) deliver a small fraction (11.5 * 10^6 ton/year) of the total (99 * 10^6 ton/year) sediment flux estimated for this region of Venezuela. These results indicate that the western terrane is more chemically and physically reactive than the eastern terrane. These findings are in agreement with the lower vegetation cover, lower precipitation and higher abundance of sedimentary materials found in the western terrane in comparison with the easthern terrane. The abundance of carbonate rocks with significant amounts of pyrite and gypsum controls the high concentration values of dissolved solids whereas the abundance of easily erodable sedimentary materials is responsible for the high sediment yield.

The data obtained for the Orinoco and Venezuela watersheds (Tables 3 and 4) has permitted to estimate the total fluvial water (1190 Km^3/year), suspended matter (323 * 10^6 ton/year) and dissolved solids (37 * 10^6 ton/year) fluxes to the Venezuelan Coastline. The Orinoco contributes with 97% of the water, 78% of the dissolved solids and 46% of the sediment discharges. These results clearly illustrate how the Orinoco drainage basin differs entirely from the whole Venezuela Caribbean Sea basin in terms of runoff, denudation rate and water quality.

The data for the whole Caribbean Sea (Colombia and Venezuela) and for the Northern (Orinoco, Guianas and Amazon Tocantins) and Southern (Northeastern Brazil through Southern Argentina) Atlantic Ocean drainages of South America is summarized on Table 5. These results can be used to show that the Caribbean Sea receives 3.3% of the total water, 21% of the total sediment and 9.8% of the total dissolved solids. This reflects a significant contribution of dissolved and suspended solids by the fluvial systems of the Caribbean Sea even though they contribute with a very small fraction of the water discharge.

The sediment discharge reported by Milliman and Meade (1983) for the Caribbean Sea and Northern Atlantic Ocean was of 1311 * 10^6 ton/year. This value is lower than the value of 1970 * 10^6 ton/year estimated in this study. The difference between both estimates is attributed to the more recently data reported for the Amazon River by Meade et al. (1985) and the new data for the Venezuelan Caribbean Sea estimated in this work.

The data for the annual sediment discharge per unit of coastline indicates tha the Northern Atlantic is 3 and 30 times greater than the Caribbean Sea and Southern Atlantic, respectively. This gives and idea of the possible relative order of sedimentation rates taking place in those coastal areas.

Eisma et al. (1978) and Milliman et al. (1982) have pointed out the accumulation of sediments from the Amazon River in the easthern Caribbean Sea (Margarita Island, Venezuela) as a product of the large dispersion of the sediments transported into the Northern Atlantic Ocean. The total sediment discharged (1529 * 106 ton/year) into the Northern Atlantic is 120 times greater than the total sediment transported annually (12.9 * 10^6 ton/year) into the Easthern Caribbean Sea of Venezuela. If, the presence of the Cariaco Trench and Cariaco Gulf is taken into consideration, then the amount of fluvial sediment that might cross those boundaries is very low. Additionally, the fraction of clay-sized particles (< 2 μm) is very small for the fluvial sediment from this region of

Venezuela. Therefore, the findings by Eisma et al. (1978) that about 1% of the Amazon sediment flux is dispersed along the easthern Caribbean Sea seems reasonable because this small fraction is a relative large quantity when compared with local sources.

The quality of the suspended matter transported into the Atlantic Ocean by the Orinoco and Amazon Rivers, in terms of grain size distribution, has been investigated by Nordin et al. (1983) and Meade (1985). The suspended solids from the Orinoco is, on average, 66% smaller than 63 μm (silt and clay) while the suspended sediment from the Amazon presents two seasonal grain size distribution. During the stream flow rising stages, 92% and 51% are finer than 63 μm and 2 μm, respectively; and during the peak and falling stages, 77% is finer than 63 μm and 24% is smaller than 2 μm. This indicates that the fluvial particulates from the Amazon are smaller than the ones from the Orinoco.

If the suspended sediment supply by the Amazon during the rising stages is considered to be equal to the flux during the peak and falling stages, then 38% and 85% of the particles are smaller than 2 μm and 63 μm, respectively. This permitted to calculate a discharge of $494 * 10^6$ ton/year for the suspended particles finer than 2 μm from the Amazon. This calculation reflects that a large quantity of clay-sized sediment can be dispersed along the Atlantic coastline and can be used as a tracer because there is very little mixing with clay-sized particles from other fluvial sources.

SUMMARY

The results obtained in this study have permitted to illustrate the significant contribution in sediment ($440 * 10^6$ ton/year) and dissolved solids ($44 * 10^6$ ton/year) fluxes by the fluvial system of South America draining into the Caribbean Sea. This fact is well illustrated in the case of Venezuela coastlines, where the Caribbean Sea receives the 54% and 22% of the total suspended sediment and dissolved solids discharges, respectively.

The fluvial transport into the Atlantic Ocean of South America constitutes the 97% of the total water (10335 Km^3/year), 90% of the dissolved solids ($450 * 10^6$ ton/year) and 79% of the sediment ($2127 * 10^6$ ton/year) supplied to both seas, Caribbean Sea and Atlantic Ocean.

The Northern Atlantic drainages surpasses the Southern Atlantic in terms of water, sediment and dissolved solids discharges. Additionally, within the Northern Atlantic, the annual fluxes are controlled by the Amazon River, especially the fluxes of clay-sized particles.

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TABLE I

AREA, RUNOFF, SEDIMENT YIELD AND DISSOLVED SOLIDS YIELD DATA OBTAINED FOR THE VENEZUELAN CARIBBEAN SEA BASIN

CARIBBEAN SEA DRAINAGE SUBBASINS OF VENEZUELA	AREA (10^3 Km2)	RUNOFF (mm/Year)	SEDIMENT YIELD (Ton/Km^2-Year)	DISSOLVED SOLIDS (Ton/Km^2-year)
Lake Maracaibo	89.8	301	825	44
Maticora-Mitare	12.0	110	2850	139
Ricoa-Hueque	10.0	130	900	37
Tucurere-Tocuyo	18.0	92	2200	45
Aroa-Yaracuy	5.2	203	650	98
Litoral Central	3.3	218	430	23
Curiepe-Uchire	8.4	410	760	51
Unare	22.3	65	151	14
Neverí-Cariaco	6.5	240	260	37
TOTAL-VENEZUELA	175.5	225	987	48

TABLE II

COASTLINE LENGTH AND ANNUAL DISCHARGES OF WATER, SUSPENDED AND DISSOLVED SOLIDS ESTIMATED FOR THE CARIBBEAN SEA DRAINAGE BASINS OF VENEZUELA

CARIBBEAN SEA DRAINAGE SUBBASINS OF VENEZUELA	COASTLINE (Km)	WATER DISCHARGE (Km^3/Year)	SEDIMENT DISCHARGE SOLIDS (10^6 TON/YEAR)	DISSOLVED SOLIDS DISCHARGE (10^6 TON/YEAR)
Lake Maracaibo	190	27.0	74.0	3.95
Maticora-Mitare	191	1.3	34.2	1.67
Ricoa-Hueque	338	1.3	9.0	0.37
Tucurere-Tocuyo	60	1.7	39.6	0.81
Aroa-Yaracuy	38	1.1	3.4	0.51
Litoral Central	233	0.7	1.4	0.08
Curiepe-Uchire	124	3.4	6.4	0.43
Unare	34	1.5	3.4	0.31
Neverí-Cariaco	390	1.6	1.7	0.24
TOTAL VENEZUELA	1598	39.6	173	8.37

TABLE III

AREA, RUNOFF, SEDIMENT YIELD AND DISSOLVED SOLIDS YIELD DATA ESTIMATED FOR THE CARIBBEAN SEA AND ATLANTIC OCEAN BASINS OF SOUTH AMERICA

CARIBBEAN SEA AND ATLANTIC OCEAN BASINS OF SOUTH AMERICA	AREA (10^3 km^2)	RUNNOF (mm/Year)	SEDIMENT YIELD (Ton/Km^2-year)	DISSOLVED SOLIDS YIELD (Ton/Km^2-year)
COLOMBIA	340	893	785	106
VENEZUELA	175	225	987	48
ORINOCO	990	1150	150	29
GUIANAS	495	980	160	35
AMAZON-TOCANTINS	6930	1010	188	39
NORTHEASTERN BRAZIL	860	180	10	8
SAO FRANCISCO	631	189	10	8
SOUTHEASTERN BRAZIL	870	180	10	8
LA PLATA	2970	244	31	17
SOUTHERN ARGENTINA	889	220	12	10
TOTAL	15150	680	139	29

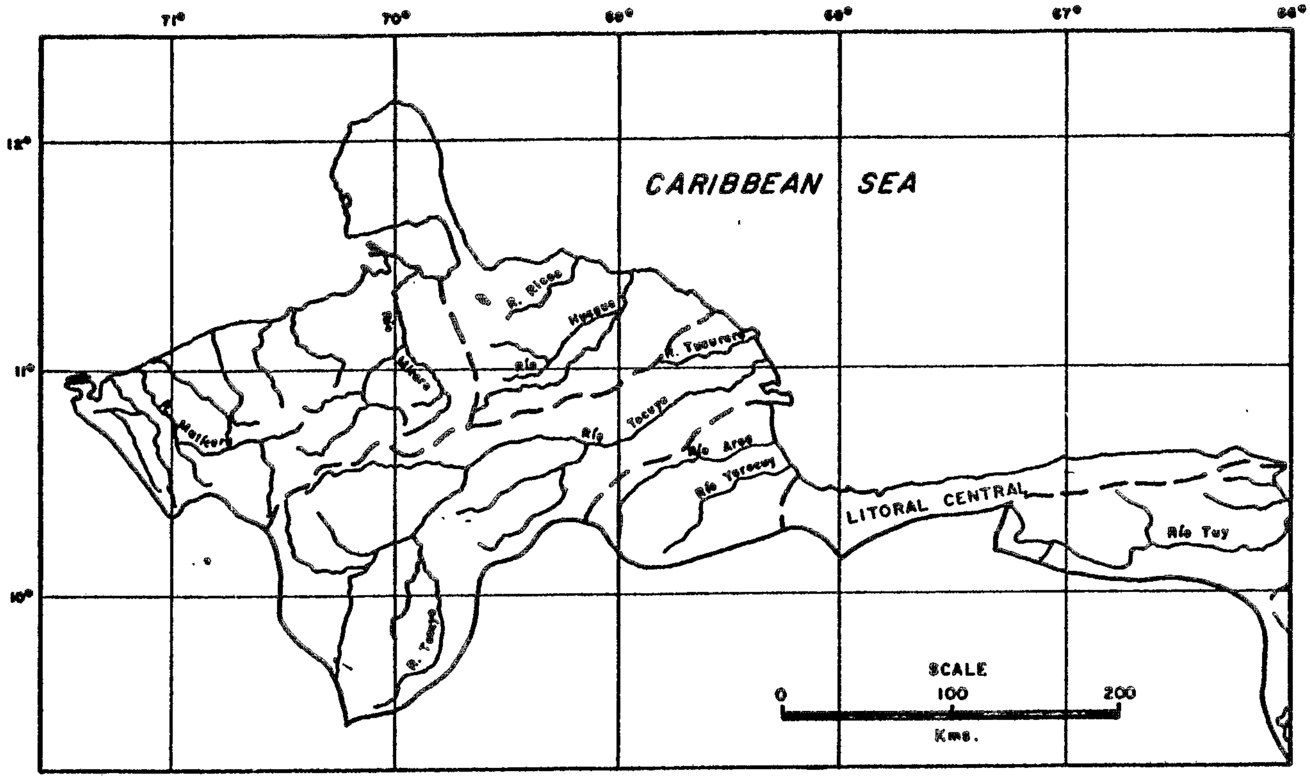
TABLE IV
COASTLINE LENGTH AND ANNUAL DISCHARGES OF WATER, SUSPENDED AND DISSOLVED SOLIDS ESTIMATED FOR THE CARIBBEAN SEA AND ATLANTIC OCEAN BASINS OF SOUTH AMERICA

CARIBBEAN SEA AND ATLANTIC OCEAN BASINS OF SOUTH AMERICA	COASTLINE (Km)	WATER DISCHARGE (Km^3/Year)	SEDIMENT DISCHARGE (10^6 TON/YEAR)	DISSOLVED SOLIDS DISCHARGE (10^6 TON/YEAR)
COLOMBIA	1030	303	267	36
VENEZUELA	1600	40	173	8
ORINOCO	620	1150	150	29
GUIANAS	1160	485	79	18
AMAZON	1240	7000	1300	280
NORTHEASTERN BRAZIL	1740	155	9	7
SAO FRANCISCO	220	119	6	5
SOUTHEASTERN BRAZIL	3330	162	9	7
LA PLATA	540	725	123	51
SOUTHERN ARGENTINA	2650	196	11	9
TOTAL	14130	10335	2127	450

TABLE V
AREA, COASTLINE AND FLUVIAL FLUXES FOR THE CARIBBEAN SEA AND ATLANTIC OCEAN OF SOUTH AMERICA

	CARIBBEAN SEA	NORTHERN ATLANTIC OCEAN	SOUTHERN ATLANTIC OCEAN
AREA($10^3 Km^2$)	515	8415	6220
COASTLINE (Km)	2630	3020	8480
WATER DISCHARGE (Km^3/Year)	343	8635	1357
SEDIMENT DISCHARGE (10^6 Ton/Year)	440	1529	158
DISSOLVED SOLIDS DISCHARGE (10^6 Ton/Year)	44	327	79
CONCENTRATION OF SUSPENDED SOLIDS (mg/l)	1283	177	116
CONCENTRATION OF DISSOLVED SOLIDS (mg/l)	128	38	58
SEDIMENT DISCHARGE PER UNIT OF COASTLINE (10^3 Ton/Km/Year)	167	506	17

Figure 1.- Map of the Venezuelan hydrographic basins


71°
70°
69°
68°
67°
66°
12°
11°
10°
CARIBBEAN SEA
R. Ricoa
Río Tocuyo
Río Aroa
Río Yaracuy
LITORAL CENTRAL
Río Tuy
SCALE
0
100
200
Kms.

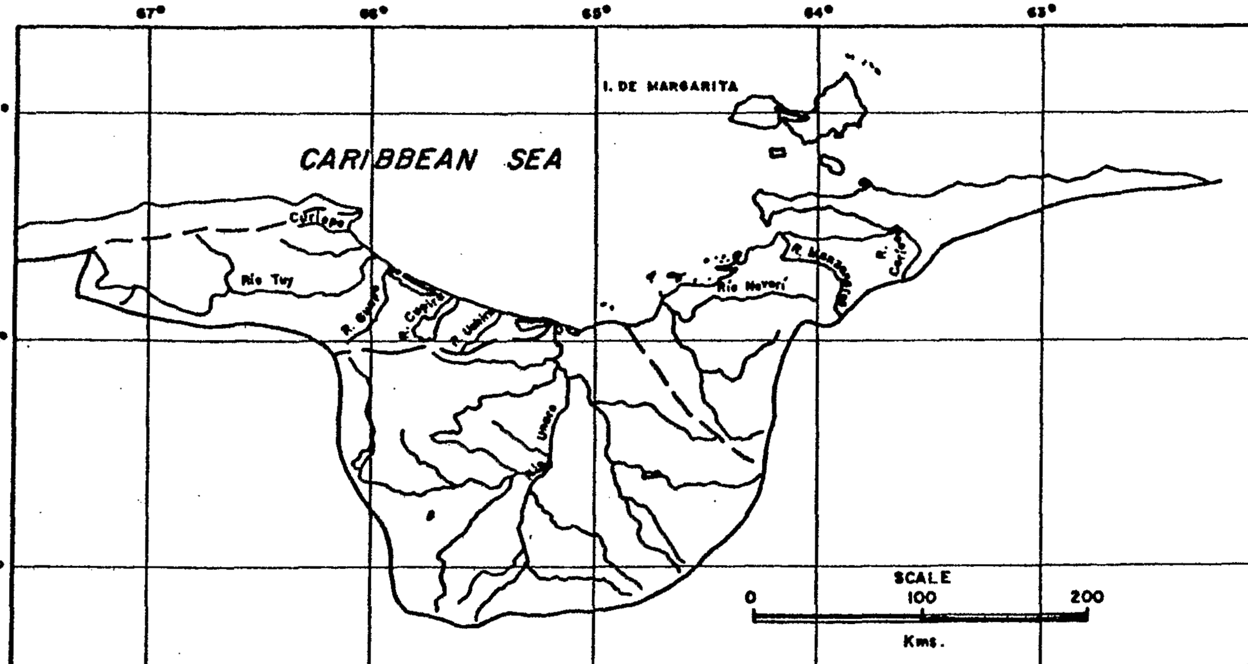


Figure 2.– Map of the Venezuelan Caribbean Sea Wateshed.

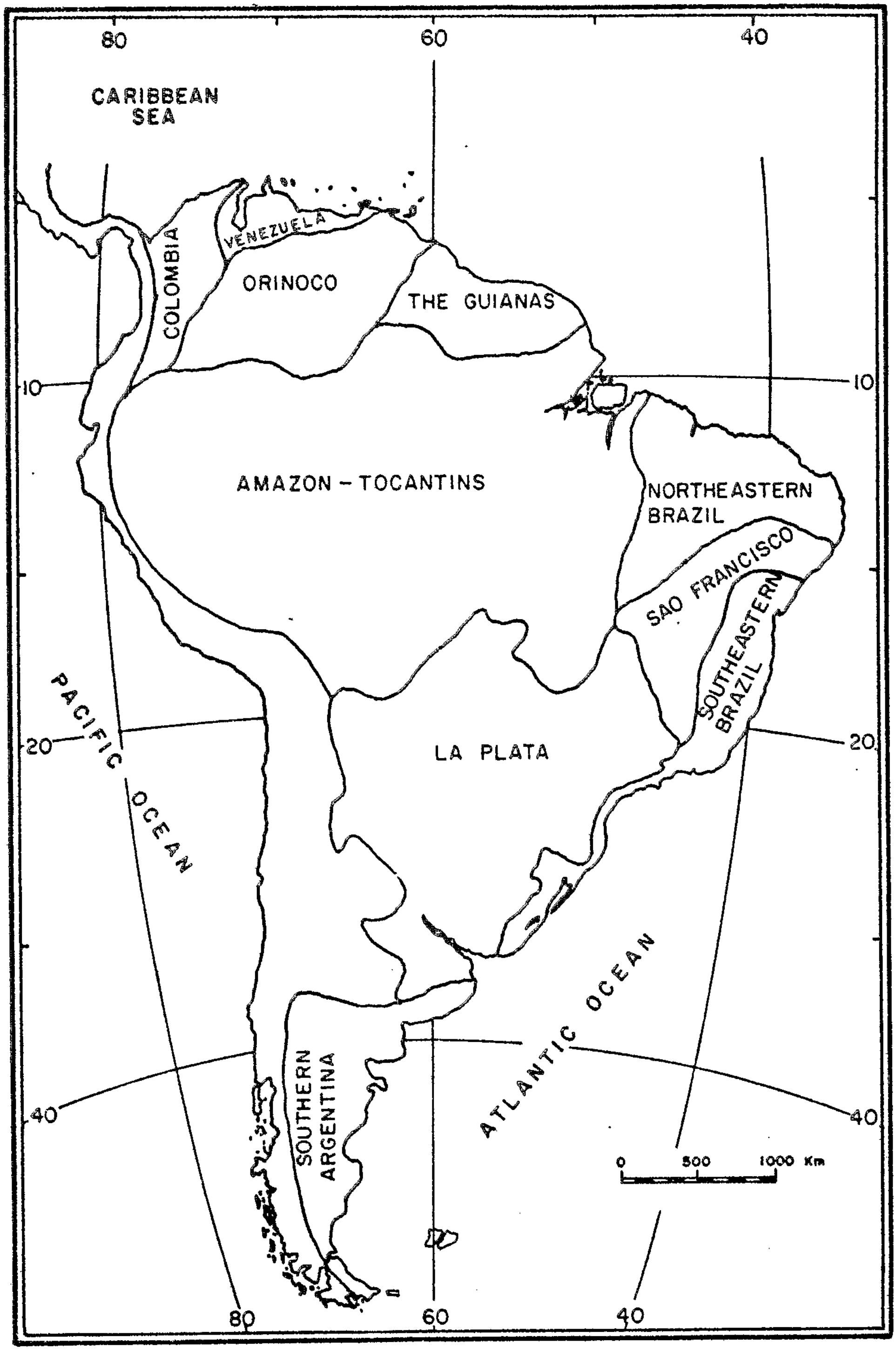


FIG. 3.-CARIBBEAN SEA AND ATLANTIC OCEAN DRAINAGE BASINS OF SOUTH AMERICA.