SUSPENDED-SEDIMENT BUDGET FOR THE ORINOCO RIVER

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ABSTRACT

In a balanced budget for the Orinoco River, the mean discharge of suspended sediment to the delta is 150 x 10^6 tonnes per year. Of this total, 85 to 90 percent is contributed by the three large tributaries that originate in the Andes: Meta (80 x 10^6 tonnes per year), Guaviare (25-30 x 10^6 tonnes per year), and Apure (20-25 x 10^6 tonnes per year). The remaining 10 to 15 percent is contributed by tributaries that drain the Guayana Shield and the Llanos that lie between the Andes and the Shield. Because the data for water discharge and suspended sediment are sparse for such a large river basin, these estimates all entail considerable errors of about 30 to 50 percent.

Computations of mean annual suspended-sediment discharges are further complicated by a peculiar pattern of temporal variation that is characterized by two maxima and two minima of suspended-sediment concentration per year. One of the minima of suspended-sediment concentration coincides with the annual maximum of water discharge.

INTRODUCTION

On a global scale, the Orinoco River ranks third in terms of discharge of water and perhaps tenth in terms of discharge of suspended sediment to the oceans. In this paper, we focus on three basic issues concerning the movement and storage of suspended sediment in the Orinoco: (1) <u>quantities</u> of suspended sediment transported by the river, (2) <u>sources</u> of suspended sediment in the river system, and (3) <u>storage and remobilization</u> of suspended sediment at seasonal time scales.

Suspended sediment is defined as the material being transported in suspension by the river, and being maintained in suspension by the upward component of the turbulence of the river. It includes the fine-grained component, consisting mainly of silt and clay particles, that is commonly called washload. It also includes sand particles that have been suspended from the river bed. It does not include bedload, the material that is moved along the river bed by rolling, sliding, or slipping, within a few grain diameters of the bed.

Data on suspended sediment in the Orinoco River have been collected in earnest only during the last 20 years. Between the late 1960s and mid 1970s, the Venezuelan Ministerio de Obras Públicas collected and analyzed numerous samples of suspended sediment on a routine basis from the Orinoco River and its principal tributary draining the Andes and Llanos of Venezuela, the Apure River (Figure 1). Between 1976 and 1982, the sampling program in the Orinoco basin languished when the hydrologic effort within the national government was transferred from the Ministerio de Obras Públicas (MOP) to the newly organized Ministerio del Ambiente y de losRecursos Naturales Renovables (MARNR), and, perhaps more important, when a critical mass of hydrologists and hydrologic technicians was lost to the resurging petroleum industry. During the early part of 1982, interest and activity resumed when Proyecto Orinoco of MARNR began sponsoring hydrologic and sedimentologic work by the U.S. Geological Survey (USGS) and hydrochemical and ecological studies by a group from Universidad Simón Bolívar (USB). At the same time, a group from the University of Colorado (UC), sponsored mostly by the U.S. National Science Foundation, began

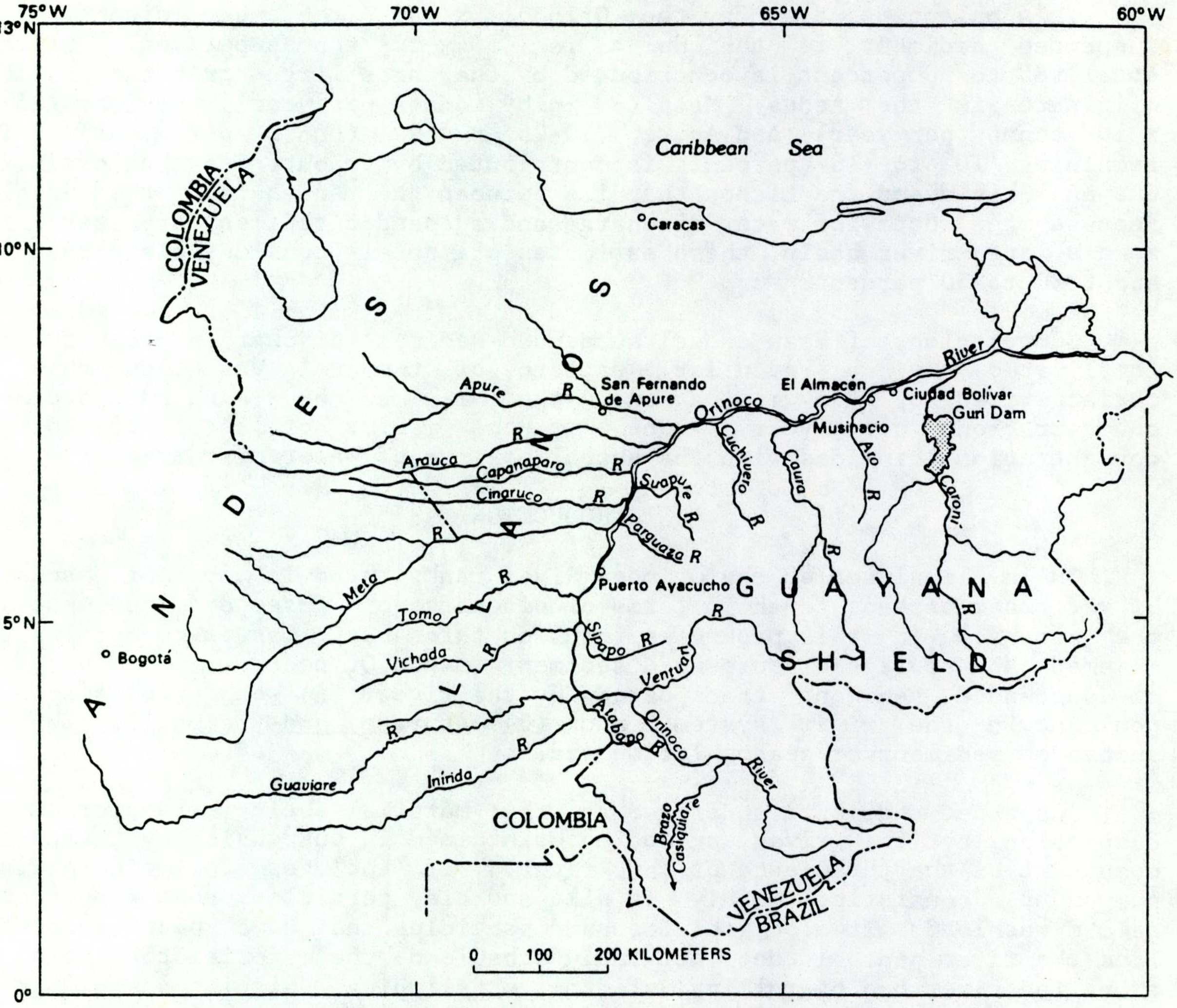

Figure 1. Map of Venezuela and eastern Colombia, showing the locations of the Orinoco River and selected tributaries.

hydrochemical and ecological studies in close collaboration with the USB group. All of these groups collected data on suspended sediment as an integral component of their studies, and the combined efforts of MOP, MARNR, USGS, USB and UC have led to the present paper.

Many people supported our programs by providing encouragement, funding, and help in the field operations. We thank especially Dr. Guillermo Colmenares Finol, who was Director of Proyecto Orinoco, and Abel Mejia B., who was Project Manager during most of the period of our studies. We also thank Carl F. Nordin and C. Clare Cranston (USGS); Omar Alvarado R., Luis H. Bravo, and Omar Hernández (MARNR); Lois Koehnken de Hernández and Juan Posada (USB). The manuscript was reviewed by Nordin (now at Colorado State University), D. E. Hillier (USGS), and R. F. Stallard (USGS). This work is a contribution to Project PECOR (Proyecto Ecosistema Orinoco), a collaborative Venezuelan-North American study of the Orinoco River. Project PECOR has been sponsored by the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables and by Petroleos de Venezuela, S. A. PECOR also thanks the Fondo Nacional de Investigaciones Agropecuarios (FONAIAP)for providing working and laboratory space at the Estación Experimental Amazonas. Financial support for the collection and analysis of samples was provided by the U. S. National Science Foundation through grants DEB8116725, BSR8315410, and BSR8604655.

MEASURING AND ESTIMATING SUSPENDED-SEDIMENT DISCHARGES OF RIVERS: BACKGROUND

Any method for determining suspended sediment in rivers must resolve two types of variation, spatial and temporal. Spatial variation of suspended sediment in a cross section of a river is seen both in the vertical and lateral dimensions. Vertical variation usually takes the form of larger concentrations of suspended sediment (especially the sandy component of suspended sediment) nearer the bed of the river than the surface; effects of vertical variation can be minimized by depth-integrated sampling or by detailed point sampling at a number of discrete depths. Lateral variation is especially common downriver from confluences with large tributaries that transport suspended sediment in concentrations that differ from those in the mainstem river. Effects of lateral variation can be minimized by collecting numerous samples across the river and either analyzing them separately or combining them in such a way as to account for differing water discharges in the different parts of the channel where the samples were collected.

Temporal variability of suspended sediment in rivers is often more extreme than spatial variability. In an ideal study, a river should be sampled for a period of decades to assess the long-term average sediment discharge. Samples should be collected frequently (more than once a day, ideally) when water discharge is changing rapidly, and less frequently (once or twice a week) when water discharge is low. In reality, however, this kind of sampling program is always expensive and often impractical. The more usual course is to collect sediment data over as full a range of water discharges as possible in the time available for a study, and use these data to construct a relation (called a "sediment-rating curve" or "sediment-discharge curve") between sediment discharge (or concentration) and water discharge (Glysson, 1987). The sediment-rating curve is then combined with the available record of water discharge to synthesize a record of sediment discharge.

An example of an almost ideal relation, a near-perfect power relation between suspended-sediment concentration and water discharge is shown in Figure 2A. But in most rivers, large and small, the relation between suspended-sediment concentration or discharge and water discharge is not a perfect power function. In many rivers, the seasonal relation between suspended-sediment concentration and water discharge, when plotted on a log-log-scale graph with suspended-sediment concentration as the ordinate, forms a clockwise loop as shown in Figure 2B. That is, suspended-sediment concentrations when the river stage is rising are greater than at equal discharges when the river stage is falling. This relation usually is explained as the "depletion" or "exhaustion" effect: fine-grained sediment, which is stored on channel beds and along river banks during low-water periods, is in plentiful supply as the river begins to rise, but the stored material is soon resuspended, and it eventually becomes depleted before the river reaches its maximum discharge. Such clockwise looped relations are typical of many large rivers, among them the Amazon and Mississippi Rivers (Meade, 1985, fig. 6; Robbins, 1977, figs. 39-41).

PREVIOUS STUDIES OF SUSPENDED SEDIMENT IN THE ORINOCO RIVER

Studies of suspended sediment in the Orinoco River published before 1983 were based almost entirely on samples and data collected in the lower river at Ciudad Bolivar. Key Sánchez (1950) made early measurements there that resulted in two computations of 1-day sediment loads. Gessner (1965) made twice-monthly measurements of the turbidity of the Orinoco River water at Ciudad Bolivar between October 1960 and September 1962. A group of researchers from the Instituto Venezolano de Investigationes Cientificas (IVIC) reported the suspended-sediment concentrations of 11 samples collected at intervals of 2 months or so between February 1981 and September 1982 (Németh et al., 1982; Paolini et al., 1983). The data collected by Gessner and the IVIC group indicated a peculiar pattern of temporal variation in which suspended-sediment concentrations reached two maxima (in or near June and November) and two minima (in or near March and August) per year. The oddest feature of this pattern was that one of the minima of concentration (August) corresponded to the time of greatest water discharge in the river.

For several reasons, this peculiar pattern of temporal variation was not given much weight by Meade et al. (1983) in their summary of sediment discharge in the Orinoco River. First, the data of the IVIC group had been collected from the river surface at only one point in the cross section beneath the suspension bridge (Puente Angostura) at Ciudad Bolivar; therefore, their reported sediment concentrations may not have been representative of the full depth and width of the river. Furthermore, the samples had been collected at such infrequent time intervals that they may not have accurately represented the temporal variations. The earlier data of Gessner had been collected at more frequent time intervals (twice a month), but they were measurements of optical turbidity which is only a surrogate for actual measurements of suspended-sediment concentration. Furthermore, the peculiar pattern of two maxima and two minima of concentration was clearly apparent in Gessner's data (1965, p. 309) only in the light of hindsight provided by later studies. Finally, such a peculiar

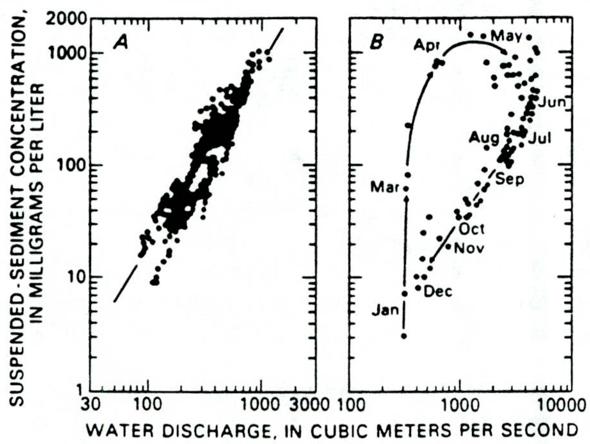

Figure 2. Relations between suspended-sediment concentrations and water discharge in two fairly large rivers (drainage areas 114,000 and 131,000 km²) of Canada. A, North Saskatchewan River at Prince Albert, Saskatchewan, 1966-68 (Abrahams and Kellerhals, 1973, p. 109). B, Fraser River at Marguerite, British Columbia, 1982 (Water Survey of Canada, 1984, p. 87).

pattern was markedly different from the patterns of temporal variability of sediment that Meade and his colleagues had observed or that had been reported for other large rivers throughout the world.

Meade et al. (1983) therefore chose not to place great weight on the pattern of variability indicated by the earlier work of Gessner and the IVIC group. Rather, Meade et al. (1983) based their computations of the sediment discharge of the Orinoco River on about 60 measurements of suspended sediment that MOP had made by depth-integrated sampling and by point sampling at depth at numerous locations across the channel at Musinacio during 1969-76. One further consideration in their computations was the assumption that the relation between sediment discharge and water discharge followed a pattern analogous to that shown by the clockwise loop in Figure 2B. With these data and this assumption, Meade et al. (1983) calculated the mean annual suspended-sediment discharge of the Orinoco River to its delta to be about 200 x 10^6 (± 60 to 70 x 10^6) t. Nordin (1988), using the same data set and assumption, calculated an estimate of mean annual sediment discharge of 240 x 10^6 t, of which 34 x 10^6 t is bed-material load (i.e.,bedload plus suspended sand load). However, as we shall discuss later, we now believe the temporal pattern indicated by Gessner and the IVIC group to be the prevalent one in the Orinoco River. Based on this belief, we have now revised our estimate of the mean suspended-sediment discharge of the Orinoco River downward to about 150 x 10^6 (± 50 x 10^6) t/yr.

More recently published reports on suspended sediment in the Orinoco River system include an extensive compendium of hydrochemical and sedimentary data collected in the upper and middle reaches of the Orinoco River (Weibezahn et al., 1985), and discussions of suspended sediment in three of the largest tributaries, the Apure River (López, 1985), the Caura River (Lewis et al., 1987), and Caroni River (Paolini, 1986). Cross-sectional heterogeneity of suspended sediment has been described by Lewis and Saunders (1984). Mixing of tributary suspended sediment into the mainstem has been described for the upper Orinoco River by Weibezahn et al. (1988) and for the middle and lower Orinoco River by Stallard (1987). Large-scale issues of weathering and denudation in the Orinoco River basin have been discussed by Stallard in two recently published papers (1985, 1988) as well as in a chapter in the present volume.

METHODS OF SAMPLING AND ANALYSIS

Because we were several different groups, working on different schedules in different parts of the river with different equipment and pursuing different goals, our methods of sampling and analysis were not always completely similar. The dominant threads of similarity were that all groups collected samples by some form of depth integration and that all groups determined suspended-sediment concentrations by filtering the samples (or homogenized aliquots) and weighing the material that collected on the filters. However, there were some procedural differences between groups, and consequently there is some disagreement between us concerning the "absolute" values of suspended-sediment concentrations.

Field and Laboratory Methods

The suspended-sediment sampling method used by MOP during 1969-76 was a combination of point-integrating and depth-integrating methods (Guy and

Norman, 1970). Depth-integrating methods were used to sample the water column at numerous locations across the river but only through the uppermost 6 m of water depth. Six meters was the maximum depth at which depth-integrated samples could be collected with the equipment available at that time without incurring an unacceptable distortion of the hydraulics of water flow into the sampler. River waters deeper than 6 m were sampled by a series of point samples collected at several depths at one or two selected locations in the river cross section. Samples were filtered in the laboratory and their suspended-sediment concentrations were determined gravimetrically according to the procedures described by Guy (1969). After all samples were analyzed and their suspended-sediment concentrations were recorded, a coefficient was determined from the relation between the depth-integrated concentrations in the uppermost 6 m at the selected locations and the mean surface-to-bottom concentration determined from the point samples collected at the same locations. This coefficient was then applied to the depth-integrated suspended-sediment concentrations measured at all the other locations across the river, and the coefficient-adjusted concentrations were used, along with the water-discharge measurements that had been made at the same time that the samples were collected, to compute the discharge of suspended sediment.

The USGS-MARNR group made six major sampling campaigns in the Orinoco River basin during 1982-85. Their sampling strategy was a Lagrangian scheme that usually began at some upriver point and sampled an 800-to-1000-km reach of the Orinoco River, as well as the major tributaries, in downriver sequence. The six campaigns were timed so that each one sampled a different stage of the river hydrograph: low flow, middle rising stage, late rising stage, peak flow, early falling stage, late falling stage. Procedures used by the USGS-MARNR group to collect samples during 1982-85 are described by Nordin et al. (1983). The essential sampling equipment consisted of: (1) a large-volume (usually 8-L) collapsible-bag sampler that allowed for depth integration through the full depth of the river, and (2) a hydraulic winch that allowed for sampling at a large number (usually 6 to 12) of equally-spaced locations across the river channel at a uniform rate of vertical integration. Water velocities, river depths, and river widths were measured at the same time that the samples were being collected so that water discharges could be computed. Procedures used by the USGS-MARNR group for processing and analyzing suspended-sediment samples are described by Meade (1985). Samples were poured through a 63-µm sieve to separate the suspended sand fraction. The suspensions that passed the sieve were composited into churn splitters from which representative aliquots could be removed. The aliquots were filtered in the field through preweighed pairs of membrane filters (Millipore HA[1]/, nominal pore diameter 0.45 µm) and returned to the USGS laboratory in Denver to be dried overnight at 105 °C and weighed. The sand fractions were dried overnight at 80 °C and weighed separately.

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[1]/Trade names are used for identification purposes only and do not imply any endorsement by the U.S. Geological Survey, Universidad Simón Bolivar, University of Colorado, or the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables.

The USB group conducted an intensive program of repeated sampling at 11 stations in the upper and middle Orinoco River basin during February 1984-February 1985. Six of these stations were on the Orinoco River, and five were located on major tributaries (Ventuari, Atabapo, Guaviare, Vichada, and Meta Rivers). Mainstem stations were sampled every 2 weeks, and tributary stations were sampled once a month. Sampling and analytical procedures of the USB group are described by Weibezahn et al. (1985). Depth-integrated samples were collected from a 5-m boat, using a small battery-powered electric winch and a 3-L collapsible-bag sampler, usually at three locations spaced more or less equally across the river. Water velocities were measured at the three locations, and a fathometer profile of river depth was collected at each cross section, so that a first-order estimate of water discharge could be computed. Samples were poured through a 63-μm sieve to separate the suspended sand; suspensions that passed the sieve were composited into a churn splitter from which representative aliquots were removed. In the laboratory, the aliquots were filtered through preweighed and calcined Whatman GF/C glass-fiber filters whose pore size, although described by the manufacturer as 1.0 to 1.2 μm, was probably 0.7 μm or less (Sheldon, 1972). The filters were dried in an oven at 80 °C for 24 hours and then weighed.

The UC group conducted an intensive program of repeated sampling at seven stations in the middle and lower Orinoco River basin during 1982-85. Four of the stations were located on the Orinoco River, and three were on major tributaries (Apure, Caura, and Caroni Rivers). Samples were collected every 2 weeks during the first 2 years, and once a month during the last 2 years. Sampling and analytical procedures of the UC group are outlined by Lewis et al. (1987). Because the UC study was closely coordinated with the USB study, the procedures and techniques used by these two groups were identical in most respects. The only differences between the UC and USB procedures that could be germane to the discussion of suspended sediment were: (1) the UC depth-integrating sampler was lowered and raised through the river with a hand-operated (rather than electric) winch; (2) the UC sampler was not lowered all the way to the river bed but was stopped 1 to 2 m above the bottom; (3) samples in the UC study were not poured through a 63-μm sieve to separate the sand fraction; and (4) the filters and the sediment collected on them were dried to constant weight at 60 °C (rather than 80 °C).

Intercomparisons of Data

An attempt at intercomparison of the different data sets is presented in Table 1. The UC and USB groups did not collect samples at any common localities, so their results cannot be compared directly. However, the sampling network used by USGS-MARNR overlapped those of both UC and USB, and many of the sampling localities used by the different groups were either identical or sufficiently near to each other to not introduce significant error into the comparisons. Times of sampling, however, were a different matter. Very few comparable pairs of samples were collected by different groups at the same location on the same day. Most of the comparisons in the table are made by comparing a single concentration measured by the USGS-MARNR group with a range (actually a pair) of values consisting of concentrations measured by the USB or UC group some days before and some days after the USGS-MARNR measurement.

Table 1. Comparison of concentrations of suspended sediment, as measured by USB, USGS-MARNR, and UC at approximately similar locations and times in Orinoco River basin, 1982-85.

River location and date[1]	Suspended sediment (mg/L): Finer than 63 µm: USB [2]	Finer than 63 µm: USGS-MARNR	Total sediment: UC[2]	Total sediment: USGS-MARNR
<u>Orinoco above Guaviare</u>				
18 Oct 1984	13-14	14	--	15
<u>Guaviare at mouth</u>				
19 Oct 1984	171-179	134	--	157
<u>Orinoco above Vichada</u>				
17 Oct 1984	89	89	--	101
<u>Orinoco above Meta</u>				
15 Oct 1984	54-63	69	59-70 (USB)	81
<u>Meta at mouth</u>				
14 Oct 1984	420-482	401	--	477
<u>Orinoco below Meta</u>				
13 Oct 1984	120-124	129	--	155
<u>Orinoco above Apure</u>				
11 Oct 1984	--	130	98-130	147
5 Jun 1985	--	212	170-185	254
<u>Apure at mouth</u>				
10 Oct 1984	--	355	237-310	436
6 Jun 1985	--	559	301-393	570
<u>Orinoco above Caura</u>				
21 Jun 1982	--	174	153	220
19 Aug 1982	--	72	66-81	108
<u>Caura at mouth</u>				
21 Jun 1982	--	17	13	19
2 Dec 1982	--	16	19-23	18
19 Mar 1983	--	11	9-17	12
<u>Orinoco at El Almacén/Ciudad Bolivar</u>				
20 Mar 1982	--	--	18	29
24 Jun 1982	--	144	104-144	183
22 Aug 1982	--	67	51-58	120
5 Dec 1982	--	142	104-118	146

1/ Dates show when USGS-MARNR samples were collected.

2/ Where only single values are listed, USB and UC samples were collected on same dates as USGS-MARNR samples. Ranges of values show concentrations in the latest USB or UC sample collected before the USGS-MARNR sample and the earliest USB or UC sample collected after the USGS-MARNR sample.

Comparisons between concentrations of suspended sediment determined by USB and those determined by USGS-MARNR are shown in the first six rows of numbers in Table 1. These comparisons are restricted to the size fractions finer than 63 μm. In general, the differences between the two data sets seem to be random: sometimes the USB value exceeds the USGS-MARNR value, and sometimes the USGS-MARNR value is greater. We are reassured by the identical concentrations that were measured in the single instance where both groups sampled the same locality on the same day (Orinoco above Vichada). Differences at the other three mainstem stations are on the order of 10 percent or less. Larger differences show in the comparison of samples collected in the tributaries, but, considering that the scale of temporal variation of suspended-sediment concentration is likely to be greater in the Andean tributaries than in the Orinoco mainstem, and that the times between the relevant pairs of USB measurements in the Guaviare and Meta Rivers were respectively 24 and 28 days, the 20-percent difference between the USGS-MARNR concentrations and what one might interpolate from the USB data is not overly disturbing.

Comparisons between concentrations determined by UC and those determined by USGS-MARNR are rather more unsettling (lower 13 rows of figures in Table 1). Not only are the differences between the data of the two groups fairly large but the differences generally are consistent. In all but the three samples from the Caura River, the USGS-MARNR values are substantially greater than the UC values. A likely explanation for part of the difference in measured concentrations is the difference between the filters that were used to separate the suspended sediment from the water. In a comparative study in which separate aliquots of water from the Orinoco River were passed through Millipore filters (as used by USGS-MARNR) and glass-fiber filters (as used by UC), the Millipore filters trapped an average of about 10 percent more suspended sediment than did the glass-fiber filters (Jorge Paolini, oral communication, 1986). Furthermore, the difference could be as large as 25 percent when concentrations were small and very fine material represented a large proportion of the total sediment. As of now, we are inclined to accept the differences in measured concentrations listed in Table 1 as an object lesson in the differences inherent in data that are collected to satisfy different goals. Both analytical methods are considered "standard," but in different fields--the USGS-MARNR methods reflect the standards in the fields of hydraulics and water quality, whereas the UC methods are standard in the fields of limnology and oceanography.

TEMPORAL VARIATIONS OF SUSPENDED SEDIMENT

Despite the differences between them, the different data sets can be used conjunctively to estimate a suspended-sediment budget for the Orinoco River. The USGS-MARNR data were collected with particular attention to sampling details and in close conformity with procedures used elsewhere to measure and calculate sediment loads, but they were collected at such sporadic intervals (2 to 19 months apart) that no time series can be constructed from them. The UC and USB data, in contrast, were collected at sufficiently frequent time intervals to provide a clear and internally consistent indication of the patterns of temporal variation.

Patterns of temporal variation of suspended sediment during three different periods in three different locations in the Orinoco River basin

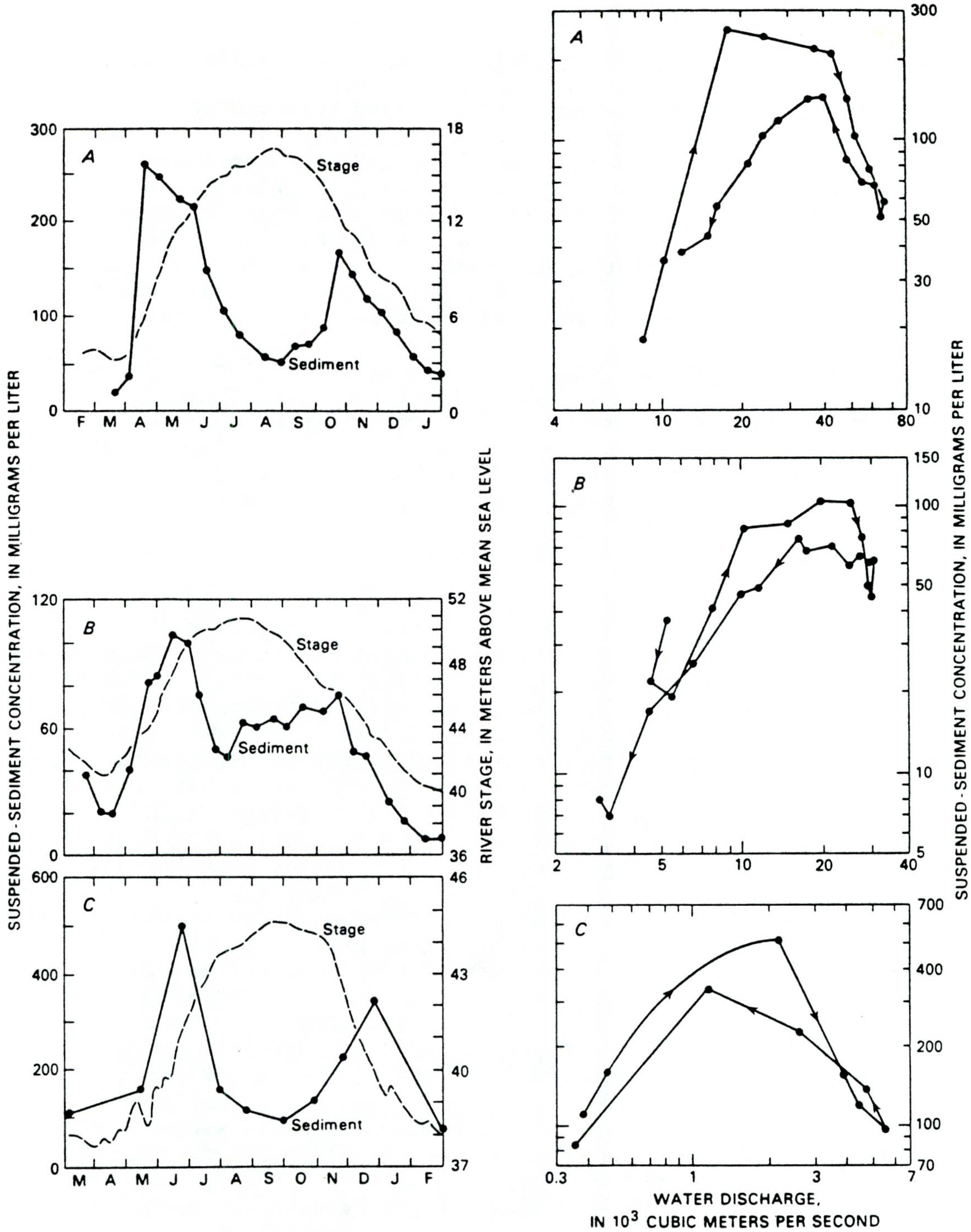

Figure 3. Relations between suspended-sediment concentration, river stage, and water discharge, as shown by time series (left side) and sediment-rating graphs (right side) at three locations in the Orinoco River basin. A, Orinoco River at Ciudad Bolivar, 1982-83 (UC data). B, Orinoco River below Puerto Ayacucho, 1984-85 (USB data). C, Apure River at San Fernando de Apure, 1970-71 (MOP data).

are shown in the three time-series graphs on the left side of Figure 3. All three graphs show the peculiar pattern of two maxima and two minima of suspended-sediment concentration per year that was indicated earlier by the data of the IVIC group (Paolini, et al., 1983). In each instance, the August-September minimum of suspended-sediment concentration coincides with the time of maximum river stage, which is also the time of maximum water discharge. This coincidence of minimum suspended-sediment concentration and maximum water discharge may be unique to the Orinoco River. It is probably related to the occurrence of backwater in the mouths of some of the major sediment-contributing tributaries during peak flow and the temporary storage of tributary sediment loads during the backwater periods.

Log-log plots of suspended-sediment concentration versus water discharge are shown in the right side of Figure 3. These three graphedrelations are clearly unlike the examples shown in Figure 2. Yet, on the basis of the evidence we have so far, this pattern is the prevalent one in the Orinoco River basin, and our calculations of the sediment budget must be based on it rather than on assumptions derived from patterns that prevail in other large rivers.

SUSPENDED-SEDIMENT BUDGET

We begin at the Orinoco River near Puerto Ayacucho, which is the farthest point upriver where the essential data are available to compute an estimate of long-term suspended-sediment discharge. These data are: (1) a long and continuous record of daily river stage; (2) an established correlation between river stage and water discharge (rating curve, or curva de gastos); and (3) a clearly defined relation between water discharge and suspended-sediment concentration. The numbers used to compute the estimate are listed in Table 2. For each month, the mean river stage was computed from 22 or 23 years of continuous daily readings of the gage maintained at Puerto Ayacucho by MOP and MARNR. The water discharge that corresponded to each of these mean stages was obtained from the stage-discharge rating curve and listed in the table as the mean water discharge for that month. The suspended-sediment concentration that corresponded to the mean monthly water discharge was obtained from the right graph of Figure 3B (taking into account which part of the sediment-rating loop was pertinent) and was listed in the table as the mean suspended-sediment concentration for that month. The product of the mean water discharge, the mean suspended-sediment concentration, a units-conversion constant (0.0864), and the number of days in the month is the suspended-sediment discharge for that month.

The resulting estimate of the mean suspended-sediment discharge of the Orinoco River at Puerto Ayacucho is 32 x 10^6 t/yr. Of this total, the overwhelming preponderance, some 25 to 30 x 10^6 t/yr, comes from the basin of the Guaviare River, which has its headwaters in the Andes of Colombia. Only about one-half the river water that passes Puerto Ayacucho comes from the Guaviare basin, which includes the Inírida River. Other tributaries upriver from Puerto Ayacucho, such as the Ventuari River that drains the Guayana Shield and the Vichada and Tomo Rivers that drain the Colombian Llanos, as well as the headwaters of the Orinoco River, are characterized by sediment concentrations that are much smaller (by factors of 6 to 9) than those of the Guaviare (Weibezahn et al., 1985). Even within the Guaviare River basin, nearly all the suspended sediment is contributed by the Guaviare River itself, which drains the Andes, whereas very little is

Table 2. Computation of estimate of mean annual suspended-sediment discharge of the Orinoco River below Puerto Ayacucho (above the Meta River)

Month	Mean river stage[1/] (m)	Mean water discharge[2/] ($10^3 m^3/s$)	Mean suspended-sediment concentration[3/] (mg/L)	Suspended-sediment discharge (10^6 t/mo)
January	42.2	6.2	25	0.42
February	41.0	4.1	20	0.20
March	40.8	3.8	20	0.20
April	41.9	5.5	20	0.29
May	45.2	13.0	85	2.96
June	48.4	22.4	100	5.80
July	50.6	29.5	70	5.53
August	50.9	30.3	55	4.46
September	49.9	27.3	60	4.25
October	47.8	20.5	70	3.84
November	45.9	14.9	70	2.70
December	44.2	10.4	50	1.39
Total for year	--	--	--	32.04

[1/] Mean stage at Puerto Ayacucho gage, based on stages recorded daily by MOP and MARNR during 1963-85.

[2/] Discharge that corresponds to mean stage on stage-discharge rating curve (MARNR-USGS) for Orinoco River at Puerto Ayacucho (Bachaquito).

[3/] Estimated from USB data (station ORIBAB), using sediment-rating curve shown in Figure 3 B (right side).

contributed by the large tributary, the Inírida River, which drains an area of lowlands.

Downriver from Puerto Ayacucho, the next large inflow of suspended-sediment to the Orinoco mainstem comes from the Meta River, which also has its headwaters in the Colombian Andes. Compared with the data we have for the Orinoco River at Puerto Ayacucho, data for the Meta are less coherent. The stage record for the Meta River at Las Caracaras gage (10 km upriver of the mouth of the Meta) is not as long or as complete as the record at Puerto Ayacucho. The data available to construct a stage-discharge rating curve for Las Caracaras are scattered, especially at the upper end of the curve. The suspended-sediment data for the Meta River do not show a consistently clear relation between concentration and water discharge. However, from the 15 measurements made by USB and the 6 measurements made by USGS-MARNR, we know that suspended-sediment concentrations are large in the Meta River--mostly between 200 and 700 mg/L. By using a month-by-month accounting that is roughly similar to the procedure shown in Table 2, we estimate the mean suspended-sediment discharge of the Meta at its mouth to be about 80 x 10^6 t/yr. This estimate contains a considerable error of at least ± 20 x 10^6 t/yr, but, regardless of the error in the estimate, we can state unequivocally that the Meta River contributes substantially more suspended sediment to the Orinoco River than any other tributary.

Between the Meta and Apure Rivers, the Orinoco River receives inflows from small rivers that drain the Guayana Shield (Parguaza and Suapure Rivers) and the Venezuelan Llanos (Cinaruco, Capanaparo, and Arauca Rivers). None of these rivers appears to contribute much sediment to the Orinoco River. None of them originates in the Andes, which apparently are the major sources of suspended sediment in the Orinoco River basin. Furthermore, the sediment that is brought down from the upper Llanos by rivers like the Capanaparo and Arauca may well be deposited on their lower flood plains before ever reaching the Orinoco River. This lower flood-plain area was described by Humboldt and Bonpland (1884) as an inland delta, and it must be accumulating sediment during the annual high-water periods when several thousand square kilometers of this area are flooded. We suspect that no more than 3-5 x 10^6 t of suspended sediment are contributed to the Orinoco mainstem by these rivers each year.

The Apure River drains most of the eastern slope of the high Andes of Venezuela, and it is the last tributary downstream to contribute large quantities of suspended sediment to the Orinoco River. Data for computing an estimate of the mean annual sediment discharge of the Apure River are fairly complete. A long and continuous record of river stage is available at San Fernando de Apure, and the stage-discharge rating is well established. Suspended-sediment data are available from San Fernando de Apure (MOP, 26 measurements, 1969-73) and from near the mouth of the Apure River (UC, 22 measurements, 1984-85; USGS-MARNR, 7 measurements, 1982-86). A month-by-month accounting of the type presented in Table 2 yields an estimate of the mean suspended-sediment discharge of the Apure River of 20 to 25 x 10^6 t/yr.

As indicated by the graphs in Figure 3C,, the inflow of suspended-sediment from the Apure River is decreased substantially during the time of maximum water discharge. We were able to observe this effect qualitatively when we visited the confluence of the Apure and Orinoco Rivers on 17 August

1982 (which was within 1 to 2 days of the time of highest river stage for 1982) and saw that the water of the Apure River contained distinctly less suspended sediment than that of the Orinoco River. Furthermore, in samples collected across the width of the Orinoco River in a section 19 km downriver of the Orinoco-Apure confluence, the concentration of suspended silt and clay (finer than 63 μm) measured in the individual depth-integrated sample nearest the left bank (representative of the inflow from the Apure River) was only 41 mg/L, as compared with a discharge-weighted concentration of 76 mg/L for the full width of the section (Meade <u>et</u> <u>al</u>., 1983, fig. 5, Cabruta section).

During peak flows in the Orinoco River, the flow of the Apure River is so slowed by backwater at its mouth that much of its suspended sediment settles out--either in the channel or on the flood plain, which is inundated during these periods. The sediment that is deposited in the channel is probably resuspended within a few months as the river stage in both rivers falls and the slope of the lower Apure River increases. The sediment that is deposited on the flood plain, however, probably remains in place for substantially longer periods (decades to centuries) until it is remobilized by lateral shifting of the Apure River channel. In any event, the storage of sediment in the lower reaches of major tributaries must be the principal cause of the coincidence between maximum water discharge and minimum suspended-sediment concentration.

Downriver from the Apure, the Orinoco receives large inflows of water but only relatively minor inflows of suspended sediment from tributaries that drain the Guayana Shield. The suspended-sediment discharge of the Caura River is about 2×10^6 t/yr. Not only are sediment concentrations in the Caura River consistently small (5 to 25 mg/L), but they show an inverse correlation with water discharge (Lewis <u>et</u> <u>al</u>., 1987). The Caroní River, likewise, with its consistently small suspended-sediment concentrations near 10 mg/L (Paolini, 1986) and its water discharge regulated at about 5000 m^3/s by the Guri Dam, probably contributes no more than 2×10^6 t/yr of suspended-sediment. The Cuchivero River transports somewhat larger concentrations of suspended sediment (50 to 100 mg/L) but its water discharge is much less than that of the Caura and Caroní Rivers. The combined suspended-sediment discharge of the Cuchivero and that of another smaller tributary, the Aro River, must be on the order of 1 to 2×10^6 t/yr. In total, the rivers draining the Guayana Shield that enter the Orinoco River downriver from the Apure River contribute 5 to 6×10^6 t/yr of suspended-sediment.

The small rivers that drain the eastern Llanos and flow into the north side of the Orinoco between the Apure River and the delta contribute even less suspended sediment than do the rivers that drain the Shield. Although these rivers are rather muddy, they discharge such small quantities of water that their contributions to the total sediment budget is probably negligible.

The final step of this exercise is to "balance" the suspended-sediment budget by making an independent estimate of the mean annual sediment discharge in the lower Orinoco somewhere downriver from the mouths of most of the major tributaries. The two localities where data are available for such an estimate are Musinacio and Ciudad Bolívar. Musinacio is the

Table 3. Computations of estimates of mean annual suspended-sediment discharge of lower Orinoco River

		Musinacio (USGS-MARNR)		Ciudad Bolivar (UC)	
Month	Mean water discharge[1/]	Mean suspended-sediment concentration[2/]	Suspended-sediment discharge	Mean suspended-sediment concentration[3/]	Suspended-sediment discharge
	($10^3 m^3/s$)	(mg/L)	(10^6 t/mo)	(mg/L)	(10^6 t/mo)
January	13.4	85	3.1	53	1.9
February	8.0	65	1.3	29	0.6
March	6.3	65	1.1	30	0.5
April	9.4	95	2.3	103	2.5
May	21.6	300	17.4	200	11.6
June	35.6	220	20.3	186	17.2
July	50.8	120	16.3	100	13.6
August	60.8	100	16.3	72	11.7
September	60.3	135	21.1	60	9.4
October	49.3	190	25.1	87	11.5
November	34.5	190	17.0	113	10.1
December	21.7	130	7.6	87	5.1
				Unadjusted total	95.7
				Adjustment factor[4/]	x 1.52
Total for year	--	--	148.9	--	145.4

[1/] Mean monthly discharges at Musinacio for 1970-76 (Meade <u>et al</u>., 1983, p. 1137).

[2/] Estimated from Figure 4.

[3/] Averages of measurements made at Ciudad Bolivar by UC group during 1982-85.

[4/] Mean ratio of 10 USGS-MARNR concentrations to interpolated UC concentrations, as listed in Table 1.

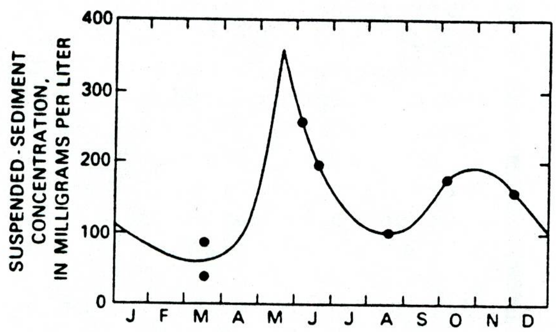

Figure 4. Curve of assumed pattern of temporal variation fitted to seven values of suspended-sediment concentration measured in the Orinoco River at Musinacio during 1982-85 (USGS-MARNR data).

farthest point downriver where water discharge is measured systematically. A long record of river stage and a well-established stage-discharge rating curve are available from Musinacio. Furthermore, seven comprehensive measurements of suspended sediment were made at Musinacio by the USGS-MARNR group during 1982-85. Ciudad Bolivar is the site at which 67 samples of suspended sediment were collected by the UC group during 1982-85. Comprehensive measurements of water discharge are not made regularly at Ciudad Bolivar, but the discharge record at Musinacio can be taken as representative of the Orinoco River between the Caura and the Caroní Rivers.

The details of two separate computations--one involving the USGS-MARNR measurements at Musinacio and the other based mostly on the UC measurements at Ciudad Bolívar--are presented in Table 3. The USGS-MARNR data from Musinacio have been fitted to a curve (Figure 4) of temporal change of suspended-sediment concentration that is inferred from the pattern determined by the UC group at Ciudad Bolívar and by the USB group downriver from Puerto Ayacucho. The assumptions made in fitting this curve were: (1) that the principal maximum of suspended sediment occurs in mid-May and the secondary maximum occurs at the end of October; and (2) that the suspended-sediment concentration at the principal maximum is approximately twice the concentration at the secondary maximum. Once the curve was drawn, the monthly mean concentrations could be estimated from it and applied to the computations shown in the second and third columns of numbers in Table 3.

The second computation is based on the 67 measurements of suspended-sediment concentration made at Ciudad Bolívar by the UC group. Details are shown in the last two columns of Table 3. The mean monthly concentrations listed in the fourth column of figures in Table 3 are simply the arithmetic averages of all measurements made during the listed month for 1982-85. These mean concentrations were then multiplied by the mean monthly water discharges at Musinacio (which are reasonable approximations of the discharges at Ciudad Bolívar because no large tributaries enter the Orinoco River between the two places) to compute mean monthly discharges of suspended sediment. The total of all these monthly sediment discharges (designated "unadjusted total" in Table 3) was then adjusted to account for the differences in the sediment concentration measured by the two groups (UC and USGS-MARNR) as presented in Table 1. For purposes of estimating suspended-sediment discharge, we assumed that the USGS-MARNR data were more compatible with data used elsewhere in the world to compute river-sediment discharges, and we have applied an adjustment factor which is the mean ratio of the 10 comparisons (excluding those from the Caura River) between USGS-MARNR concentrations and interpolated UC concentrations listed in the lower part of Table 1.

The totals computed by the two methods are 149×10^6 and 145×10^6 t/yr. We round these totals to 150×10^6 t/yr, and this number is our best estimate of the total discharge of suspended sediment by the Orinoco River to its delta. Considering all the uncertainties involved in its computation, the error in this estimate may be as great as $\pm 50 \times 10^6$ t/yr.

SUMMARY

The upper map in Figure 5 serves as a graphical summary of this paper by showing the distribution of suspended-sediment loads in the Orinoco River basin. Of the 150×10^6 t/yr of suspended sediment that is discharged to

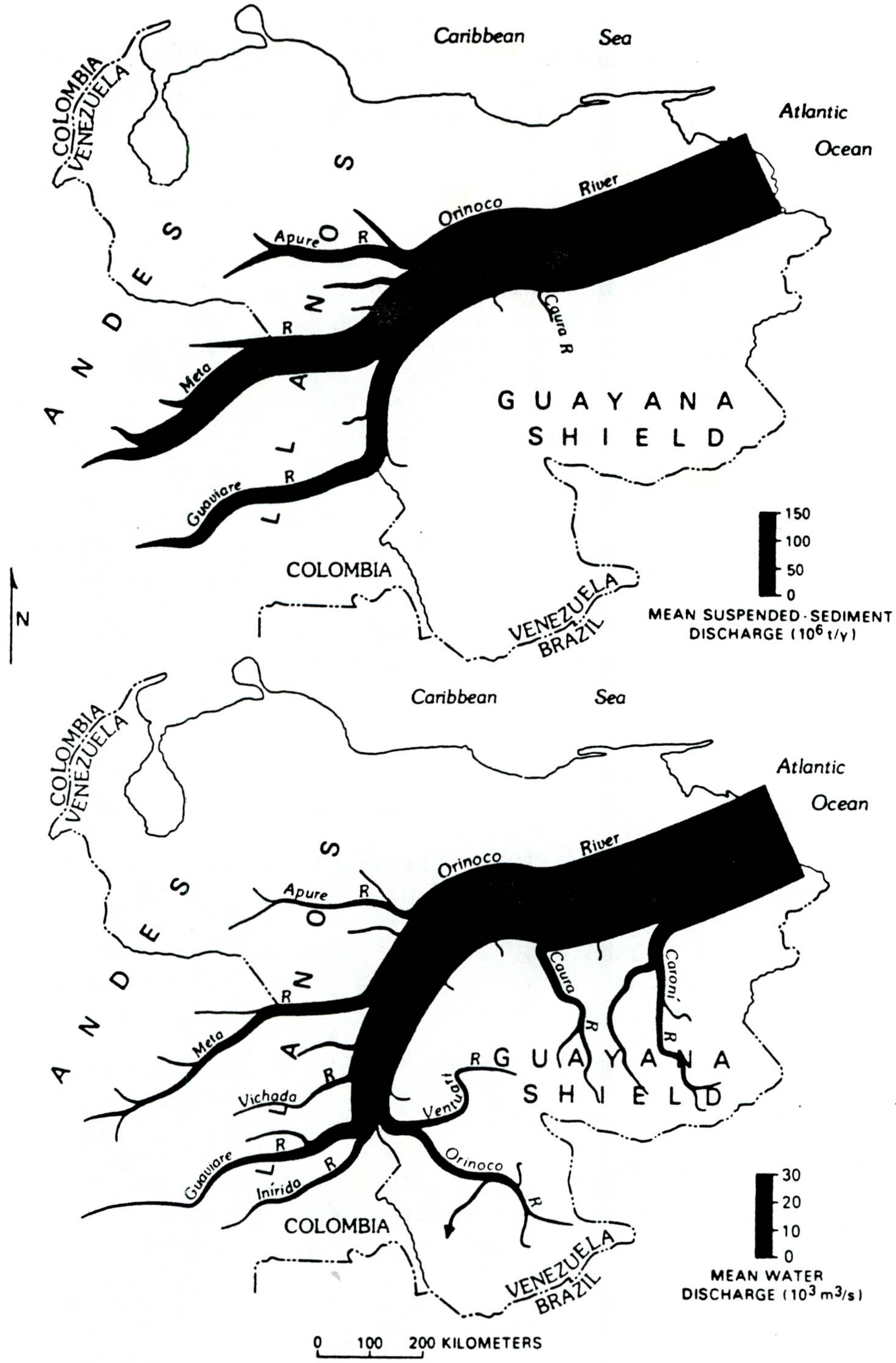

Figure 5. Maps showing mean discharges of suspended sediment (upper) and water (lower) in the Orinoco River basin. Width of river patterns indicate quantities of mean discharges. Water-discharge data from Avellán Vegas et al. (1969).

the Orinoco River delta, about half is contributed by the Meta River, and about 20 percent each are contributed by the Guaviare and the Apure Rivers. All the other tributary rivers combine to supply the remaining 10 percent.

The contrast between sources of water and sources of sediment in the Orinoco system is shown by comparing the lower and upper maps in Figure 5. Water sources in the Orinoco River system are evenly divided between the Guayana Shield on the right side of the mainstem and the combined Andes and Llanos on the left side. Suspended-sediment sources, however, are almost exclusively in the Andes and, to a lesser extent, the Llanos. Probably no more than 5 percent of the suspended sediment in the Orinoco River system is derived from the Guayana Shield.

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