SUSPENDED SEDIMENTS OF THE MODERN AMAZON AND ORINOCO RIVERS

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The Amazon and Orinoco Rivers are massive transcontinental conveyance systems for suspended sediment. They derive about 90% of their sediment from the Andes that support their western headwaters, transport it for thousands of kilometers across the breadth of the continent and deposit it in the coastal zones of the Atlantic. At their points of maximum suspended-sediment discharge, the Amazon transports an average of 1100–1300 × 10⁶ tons per year and the Orinoco transports about 150 × 10⁶ tons per year. Relations of sediment discharge to water discharge are complicated by unusual patterns of seasonal storage and remobilization, increased storage and reduced transport of sediment in the middle Orinoco during periods of peak water discharge, and storage of suspended sediment in the lower Amazon during rising discharge and reaerosion during falling discharge. Spatial distributions of suspended sediment in cross-sections of both rivers are typically heterogeneous, not only in the vertical sense but also in the lateral. The cross-channel mixing of tributary inputs into the mainstem waters is a slow process that requires several hundred kilometers of downriver transport to complete. Considerable fine-grained sediment is exchanged between rivers and floodplains by the combination of overbank deposition and bank erosion.

INTRODUCTION

Approximately two-thirds of the suspended sediment discharged from the continents to the margins of the Atlantic Ocean is carried there by the Amazon and Orinoco Rivers. The Amazon River, the world’s largest in terms of water discharge, also ranks among the world’s three largest contributors of fluvial sediment (along with the Yellow River of China and the Ganges–Brahmaputra of India and Bangladesh). The Amazon River proper (i.e. not including the Tocantins River basin) drains an area of about 6 × 10⁶ km² and discharges an average of 1100–1300 × 10⁶ tons of suspended sediment per year past the farthest-downstream gauging station at Obidos. The Orinoco River ranks third largest in the world in terms of water discharge and about tenth largest in sediment discharge. It drains an area of about 1 × 10⁶ km² and discharges an average suspended-sediment load of about 150 × 10⁶ tons per year past the gauging station at Musinacão.

This paper reviews the sources, transport, storage and deposition of the suspended sediments of these two great rivers (Fig. 1). Some of the information included herein has been part of the general knowledge of the region for more than two decades—thanks especially to the pioneering studies of the Amazon by Harald Sioli, Hilgard O’Reilly, Sternberg and Ronald Gibbs—but most of it has been newly acquired within the last decade and a half.

GEOMORPHIC AND HYDROLOGIC SETTINGS

Although their basin-wide sediment yields are similar (150–200 tons per square kilometer per year) and the overwhelming preponderance of the suspended sediment in both rivers originates in the tectonically active regions of the Andes, some fundamental geomorphic differences distinguish the channels through which sediments are conveyed in the two river systems. The Amazon, once it leaves the Andes, flows through a subdued landscape that is depositional or residual in character and largely fluvial in origin. Along some 4000 km of the course of the Amazon from Peru to the Atlantic Ocean, most of the landscape features that dominate the views from the river—be they sandbars, floodplains or older fluvial terraces—consist of material that was deposited at one time or another by the river or its tributaries (Baker, 1986, pp. 302–309; Brown, 1879; Holz et al., 1979; Irion, 1976, 1989; Iriondo, 1982; Mauro, 1983; Rässéen, 1993; Rässéen et al., 1990, 1993; Sioli, 1984; Sternberg, 1975; Tricart, 1977). The oldest deposits, which are Cretaceous or younger in age and at least partly fluvial in origin, stand as bluffs and terraces no more than a few hundred meters above the level of the Amazon mainstem. Whether the planar upper surfaces of these older terraces (many of which are now densely dissected) were erosional or depositional in origin is still an unsettled question (Bigarella and Ferreira, 1985; Klammer, 1984).

The Orinoco River, in contrast, flows for a thousand kilometers along the boundary between two markedly different terrains, one of which is among the most ancient landscapes of the world and the other of which is among the world’s youngest (Briceño and Schubert, 1990; Hamilton and Lewis, 1990). The right bank of the Orinoco mainstem or the right edge of its narrow fringing floodplain is formed on the deeply eroded crystalline bedrock of the Guayana Shield, remnants of which extend across the river in places to form rapids. The left bank of the Orinoco from San Fernando de Atabapo to the delta is entirely depositional, having formed, perhaps within the past few centuries or millennia, by the accumulation of alluvial material. This material was derived originally from the Andes, was transported across the wide area of alluvial plains known locally as ‘Llanos’ and accumulated along the distal edge of the plains as floodplain deposits of the Orinoco.

*Contribution 65 of the CAMREX Project.
Another fundamental difference between the mainstem channels of the Orinoco and Amazon that is relevant to sediment transport is the range of seasonal variation in water discharge and river depth. Wet and dry seasons are so distinctly separated in the Orinoco River basin that seasonal contrasts in water discharge and river depth are unusually large. Ratios of wet-season discharge to dry-season discharge of water in the mainstem of the lower Orinoco, as recorded at the Musinacio gauging station during the period 1970–1981, ranged from eight to 54 and averaged 26 (Nordin and Pérez-Hernández, 1989, pp. 4–5). Analogous ratios in the Amazon mainstem of Brazil are much smaller, only two to three, because the complementary seasonal distributions of rainfall in the northern and southern areas of the basin cause compensatory temporal offsets in tributary inflows that regulate the flow of the mainstem river (Nordin and Meade, 1985; Meade et al., 1991).

The Orinoco and Amazon Rivers have different characteristic depths, even though the ranges of the annual rise and fall of river stage (as opposed to the rise and fall of river discharge) are similar in the two rivers. Upriver of the influence of oceanic tides, the range of fluctuation of the levels of both rivers during average years is typically 10–12 m. However, the Orinoco River is so shallow at low water that large areas of the bottom of the high-water channel are exposed, and barge navigation is curtailed, for 3–4 months each year. Large emergent sandbars are visible during low-water months along the full length of the Orinoco mainstem from headwater to nearly tidewater (Nordin and Pérez-Hernández, 1989). Emergent sandbars of this type are much less prevalent in the Amazon mainstem, even during low-water seasons and in the shallower reaches of the river in...
western Brazil and northeastern Peru. In the lower Amazon downriver of Manaus, emergent sandbars are rarely seen in any season, and the river is navigable the year around by oceangoing ships.

**SOURCES OF SUSPENDED SEDIMENT**

Suspended sediment is the particulate material carried by a river that is maintained in suspension by the upward components of turbulence. The suspended sediments in both the Amazon and Orinoco Rivers are derived almost entirely from the parts of their drainage basins that are underlain by the Andes. Gibbs (1967) estimated that 82% of the suspended sediment eroded from the Amazon basin came from the 12% of the basin area that is underlain by the Andes. More recent measurements (Meade, 1985; Meade et al., 1985) lead to the conclusion that an even greater proportion, 90–95%, of the suspended sediment in the Amazon is ultimately derived from the Andes. In the Orinoco River basin, likewise, 90–95% of the suspended sediment seems to be derived from the combined areas of the Andes and Llanos, and only 5% is derived from the tributaries that drain the Guayana Shield (Meade et al., 1990a).

Sources of suspended sediment do not coincide with the principal sources of water in either drainage basin. In the Amazon River of Brazil (Fig. 2), nearly half the annual load of suspended sediment is derived from the Andes of Peru, and most of the other half is derived, via the Madeira River, from the Andes of Bolivia. Sources of water in the Brazilian Amazon show a much different pattern, with only 20 and 10% of the total being supplied respectively by the Peruvian and Bolivian headwaters, and the remaining 70% of the water being supplied by run-off from the low-lying areas of the basin. In the Orinoco River basin (Fig. 3), 85–90% of the total sediment is supplied by the three largest tributaries that drain the Andes (the Guaviare, Meta and Apure Rivers), whereas the sources of water are more evenly divided between tributaries that drain the Andes and those that drain the Guayana Shield.

The great contrasts in sediment yield ultimately reflect contrasts in the erosion rates of different parts of the river basins. In the Guayana Shield, at one extreme, erosion rates are among the slowest on earth: a meter per million years on the flat tops of mountains such as Roraima and Auyan Tepui (Brown et al., 1992), and only a few meters or tens of meters per million years over substantial areas of the Shield (Lewis et al., 1987). Consequently, the rivers flowing out of these areas are extraordinarily free of sediment under natural conditions, being colored only by the fulvic and humic acids dissolved from their soils. In the Andes, on the other hand, the typical characteristics of regions of active tectonism—sheared bedrock, high relief, oversteepened slopes, frequent earthquakes and ongoing volcanism—give rise to erosion rates that are at least two orders of magnitude greater than those on the Shield (Stallard et al., 1990). The Andean rivers, as a consequence, are proportionately muddier.

Suspended sediment is a principal criterion used in classifying Amazonian rivers into the traditional categories of whitewater, blackwater and clearwater (Sioli, 1957, 1984), although other characteristics such as acidity and dissolved matter also enter into the classification. Examples of all three types are portrayed in Figs 2 and 3. Tributaries that bring large quantities of sediment from the Andes, such as the Madeira and Apure, are clearly whitewater. Tributaries that contribute large amounts of water and virtually no suspended sediment, such as the strongly acid Negro and the less acid Caroní, are clearly blackwater. Although the intermediate clearwater tends to be a catch-all category rather than a clearly defined river type, we can confidently assign to it the Tapajós (the type example) and the upper Orinoco (Weibezaehn et al., 1989).

**QUANTITIES OF SUSPENDED SEDIMENT IN TRANSPORT**

The average quantities of suspended sediment portrayed in Figs 2 and 3 disagree with some previously published

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**FIG. 2.** Spatial distributions of average discharges of water and suspended sediment in the Amazon River of Brazil. Water-discharge data from unpublished records of Companhia de Pesquisas de Recursos Minerais, Manaus and Belém. Sediment data from Meade (1985). Presumptive losses of suspended sediment by deposition in the delta or on the floodplains of the lowermost river are not shown here (see Fig. 8).

**FIG. 3.** Spatial distributions of average discharges of water and suspended sediment in the Orinoco River of Venezuela and Colombia. Water-discharge data from Avellán Vegas et al. (1969). Sediment data from Meade et al. (1990a). Possible loss of suspended sediment by deposition on the floodplains of the lowermost river is not shown here (see Fig. 8).
estimates. In the case of the Amazon, our estimates of suspended-sediment discharge disagree by a factor of 2 with the previous estimates of Gibbs (1967). Because he operated virtually alone with very limited budget and resources, Gibbs was obliged to collect most of his samples from river surfaces rather than from the full depth of flow. However, suspended sediment in the Amazon is not uniformly distributed with depth; the sand fraction (> 63 μm) of the suspended sediment is many times more concentrated near the river bed than at the water surface (Meade et al., 1979, pp. 17–25); even the suspended silt fraction (10–63 μm) is usually more concentrated nearer the river bed (Curtis et al., 1979; Meade, 1985, pp. 19–22). Because our data were collected by depth integration at multiple points across the river by methods that weighted the sample for water discharge (Meade, 1985; Richey et al., 1986), they are more accurate for computing sediment discharges. In any event, the differences between Gibbs' estimates and ours are related to differences in sampling procedures; they should not be interpreted as evidence of any increase (caused by deforestation, etc.) in sediment loads during the two decades between his samplings and ours.

Recently published estimates of the average annual discharge of suspended sediment carried by the Orinoco River past Ciudad Bolívar range from 90 × 10^6 tons per year (Lewis and Saunders, 1989) to more than 200 × 10^6 tons per year (Nordin, 1988). Our best estimate, independently computed from some of the same data used by Lewis and Saunders and Nordin, is 150 × 10^6 tons per year (Meade et al., 1990a). Although the samples on which the lowest estimate (90 × 10^6 tons per year) is based were collected by partial depth integration, they were not collected from the full depth of the river; the waters within a few meters of the river bed, where sediment is most concentrated, were not sampled. The largest estimates (> 200 × 10^6 tons per year) did not take fully into account the peculiar relation shown in Fig. 4B, wherein a secondary minimum suspended-sediment concentration usually corresponds to the annual maximum of water discharge. Our estimate of 150 × 10^6 tons per year is based on fully depth-integrated and discharge-weighted sampling (Nordin et al., 1983a), and it takes into account the seasonal cycles of concentration shown in Fig. 4B.

Although the sediment–discharge data portrayed in Figs 2 and 3 come from the most representative samplings and most reasonable estimates available, the numbers are subject to large errors. The averages for the Amazon are based on no more than eight to 10 measurements at most stations (Meade, 1985; Meade et al., 1985). The estimate of 1200 × 10^6 tons per year for the Amazon at Obidos, for example, is based on only 10 measurements and is probably subject to an error of about ± 200 × 10^6 tons per year. The estimates for the Orinoco probably contain errors that are proportionately even larger. The estimate of 150 × 10^6 tons per year for the Orinoco at Ciudad Bolívar should be considered accurate within ± 50 × 10^6 tons per year.

Although few data exist on bedload in the two mainstem rivers, we can say that bedload represents only a small proportion of the total load. Bedload is defined as the sediment that is moved along a river bed by rolling, sliding or skipping, within a few grain diameters of the bed. Bedload is so difficult to measure directly in large rivers that it is usually calculated by one of several methods (Vanoni, 1975). Conventional suspended–sediment collection equipment usually does not sample the 0.1–0.4 m of the river water nearest the river bed. The Modified Einstein Method uses the measurements of the discharge of water and the discharge and properties of the sampled sediment to extrapolate measured suspended-sediment load down to the bedload layer. It adds an increment of bedload to provide the total sediment discharge. The difference between the calculated total sediment discharge and the measured suspended-sediment discharge is called the 'unmeasured load'. Using the Modified Einstein Method, Posada and Nordin (1992) calculated that unmeasured loads in the mainstem Amazon and Orinoco Rivers varied from 2 to 15% of the measured sediment load, and averaged 6%. These percentages are well within the range of errors of the measured suspended-sediment loads.

RELATIONS OF SUSPENDED SEDIMENT TO SEASONAL CYCLES OF WATER DISCHARGE

The concentration and discharge of suspended sediment in rivers vary in response to the discharge of water. Their responses are not uniform in all rivers. In the simplest case, the response is a linear power function and plots as a straight line on a log-log graph of sediment concentration (or sediment discharge) versus water discharge. Such a simple case, however, is not commonly observed in large rivers, where the maxima and minima of water discharge and suspended-sediment concentration usually do not coincide because of offset tributary inputs or because of time lags related to the storage and depletion of sediment supply in the system. The typical relation in the Amazon mainstem upriver of the mouth of the Negro River, first described by Schmidt (1972), is one in which the maximum concentrations of suspended sediment precede the maximum water discharge by several months, and the relation between the two parameters graphs as a clockwise loop (Fig. 4A). This clockwise pattern is typical of other large rivers such as the Mississippi and Fraser in North America (Robbins, 1977; Mossa, 1989; Meade et al., 1990b, p. 258). Looped patterns

![Fig. 4. Relations between suspended-sediment and water discharge, showing different annual cycles. (A) Solimões River (Amazon mainstem) below Manaus, December 1982–January 1984 (Meade, 1985). (B) Orinoco River below Puerto Ayacucho, March 1984–February 1985 (data from Weibezahn, 1985, plus unpublished data).](image-url)
of this sort are usually explained as expressions of the ‘depletion’ or ‘exhaustion’ effect: fine-grained sediment, which is stored on channel beds and along river banks during low-water periods, is resuspended as the river begins to rise, and the supply becomes depleted before the river reaches its maximum discharge.

In the typical relation in the Orinoco River, the suspended-sediment concentration reaches two maxima and two minima per year (Fig. 4B). The concentration minima coincide approximately with minimum and maximum water discharges. The concentration maxima occur during actively rising and actively falling water discharges. To my knowledge, such a pattern has been observed in only one other river, the Niger (Martins, 1988). In the Orinoco, the relation is probably due to the partial ponding of backwater in or near 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. As the mainstem river passes its peak discharge and begins to fall, slopes are increased and the sediment is remobilized, causing the suspended-sediment concentrations to increase even though the water discharge is falling.

**SPATIAL DISTRIBUTIONS AND MIXING OF SUSPENDED SEDIMENT WITHIN RIVER CHANNELS**

Suspended-sediment concentrations in rivers are spatially heterogeneous because of the hydraulics of sediment transport and because of inputs from tributaries that carry sediment in concentrations that differ from those of other tributaries or those of the mainstem river itself. Two examples of the heterogeneity of suspended-sediment concentrations in cross-sections of the Amazon River mainstem are shown in Fig. 5. The cross-section below Manacapuru (Fig. 5, left) is on a fairly straight reach of the Solimões River (Amazon River mainstem), and the section at Obidos (Fig. 5, right) is near the crest of a large bend of the Amazon River that curves downriver to the right. Concentrations of suspended sediment in both sections are greater near the river bottom than near the river surface. This vertical difference in concentration was to be expected in the sand fraction, based on many previous observations in other large rivers, but we were surprised to discover that it also applied to the finer fractions. Depth-integrated average concentrations of the fraction of suspended sediment finer than 63 μm in the Amazon are approximately twice the concentrations of the same size fraction suspended at the same time and place near the river surface (Curtis et al., 1979; Meade, 1985, p. 22).

Details of the cross-sectional distributions of sediment concentration may show the influences of tributary inputs or of local hydraulic conditions. As we were sampling the Manacapuru section on 27 May 1977 (Fig. 5, left), we observed secondary upwelling at horizontal distances of 2200–2300 m because we were having difficulty in holding the ship on station during sampling. Secondary downwelling was evident from a line of concentrated surface debris (floating grasses, trees) that was traveling downriver through the section at distances of 400–500 m from the left bank. These two zones correspond respectively to the maximum and minimum concentrations in the cross-section of suspended sediment finer than 63 μm. In the Obidos section on 15 June 1976 (Fig. 5, right), the higher concentrations of suspended sediment on the right side may have represented either one or a combination of two effects: (1) a more concentrated input from the Madeira River which enters the right side of the Amazon 310 km upriver of Obidos (although we doubt that such a strong cross-channel gradient—a threefold difference in concentration—would persist unmixed for such a long distance downriver), or (2) secondary circulation (helical flow) in the large river bend that transported near-bottom sediments toward the right side of the channel.

![Diagram](https://example.com/diagram.png)

**FIG. 5.** Cross-sections of the Solimões–Amazon River, showing vertical and lateral heterogeneity of suspended-sediment concentrations. Based on individual point-sample data. Viewer is facing downstream. Vertical scale is exaggerated 10 times relative to horizontal. (A) Total suspended sediment, in mg/l. (B) Suspended sand (> 63 μm), in mg/l. Left, Solimões River below Manacapuru, 27 May 1977; data from Meade et al. (1979, p. 21). Right, Amazon River at Obidos, 15 June 1976; data from Meade et al. (1979, pp. 22–23).
FIG. 6. Downriver mixing of inputs of suspended sediment from tributaries to the Orinoco River. Widths of graphs show water discharges. Solid bars show concentrations of suspended sediment finer than 63 μm in depth-integrated samples. Scales of discharge and distance in B are one-half and one-quarter of those in A; scale of concentration is the same in both A and B. Distances taken from navigation charts of U.S. Army Corps of Engineers (1943; upriver of Puerto Ayacucho) and Proyecto Orinoco-Apure (1987; downriver of Puerto Ayacucho). (A) Cross-channel mixing of suspended sediment, mostly from Guaviare River, in 101 km reach of Orinoco River below the Orinoco–Atabapo–Guaviare confluence, June 1983 (data from Weilbeznth et al., 1989). Suspended-sediment concentrations were measured in the Upper Orinoco, Atabapo and Guaviare Rivers above their confluence, and in the Orinoco mainstem below the confluence. (B) Cross-channel mixing of suspended sediment, mostly from Meta River, in 800 km reach of Orinoco River between Puerto Ayacucho and Ciudad Guayana, August 1982 (data from Nordin et al., 1983b). Suspended-sediment concentrations were measured in the Orinoco mainstem above and below the principal tributaries (Meta, Apure and Caura Rivers), but not in the tributaries themselves.

Several hundred kilometers of downriver transport are required for the thorough mixing of tributary inputs across the mainstem channels of the Amazon and Orinoco Rivers. The most complete studies of mixing have been made in the Orinoco River and are shown in Fig. 6. The simpler example is the mixing below the confluence where the clearwater upper Orinoco River is joined by the blackwater Atabapo River and the whitewater Guaviare River (Fig. 6A). This convergence of three different water types is among the great hydrologic spectacles of the Amazon–Orinoco region, especially when viewed from the air during high-water season. The overwhelming preponderance of the suspended sediment at and below this confluence is contributed by the Guaviare River, which drains an area of the Colombian Andes. About 30 km before they reach the Orinoco, the sediment-laden waters of the Guaviare are diluted by the clear waters of the Inirida River, which drains the lowland shield of southeastern Colombia. So, the waters of the Guaviare are not uniformly mixed as they join those of the Atabapo and Orinoco. Even after 100 km of downriver transport below their confluence with those of the Atabapo and upper Orinoco, the waters of the Guaviare are not mixed uniformly across the Orinoco mainstem (Fig. 6A). By the time they have traveled an additional 140 km, moving over two sets of large rapids and flowing past the town of Puerto Ayacucho, the Guaviare sediments have been mixed uniformly across the Orinoco channel, as shown in the uppermost row of concentration data in Fig. 6B.

The data represented in Fig. 6B were collected by following the annual crest stage of 1982 down the Orinoco mainstem, sampling above and below the major tributaries but not in the tributaries themselves. The data represent a sampling series that was perfectly Lagrangian in terms of river stage. The Meta River was contributing high concentrations of suspended sediment at the time. The Apure River, on the other hand, was sufficiently backed up by the high water in the mainstem that little of its suspended-sediment load was reaching the Orinoco. The highest concentrations of suspended sediment measured in the Orinoco mainstem above and below the Apure River were in midchannel; these indicated that the high concentrations of suspended sediment contributed by the Meta River were being diluted by waters from smaller and less sediment-laden tributaries flowing into the Orinoco from both sides. The strong contrasts in suspended-sediment concentration were nearly mixed out by the time the waters had traveled another
150 km downriver to a point just above the confluence with the Caura River. The inflow from the Caura, a blackwater river with typically low concentrations of suspended sediment of the order of 10–15 mg/l (Lewis et al., 1987), diluted the right side of the Orinoco below its confluence. Within another 150–200 km of downriver flow, however, the suspended-sediment concentrations became fairly uniform, being only slightly higher nearer the left descending bank.

Stallard (1987) combined data on water chemistry with the sediment data shown in Fig. 6B to demonstrate that the mixing of fine-grained suspended sediment was not as conservative a process as the mixing of the dissolved constituents and the waters themselves. Not only were the sediment-laden rivers such as the Apure backed up by the mainstem so that some of their sediment load was deposited (temporarily stored) before it reached the Orinoco, suspended sediment was also lost during downstream transport in the Orinoco itself. Most of this latter loss was along the left side of the channel, and it probably represented overflow and deposition onto the fringing floodplain. Stallard’s conclusion that ‘significant sediment loss or storage probably occurs only near flood stage’ is supported by data discussed below and shown in Fig. 7.

**STORAGE AND REMOBILIZATION OF SUSPENDED SEDIMENT**

The two most significant loci of storage of suspended sediment in river systems are channels and floodplains. Sediment is stored and remobilized in these two loci by different processes that operate at markedly different time scales: seasonal to annual in the channels, and centennial to multimillennial in the floodplains.

**Storage in Channels**

Fine-grained sediment is stored on the beds and banks of river channels and resuspended on seasonal time scales. A peculiar pattern of seasonal storage and remobilization of suspended sediment in the Orinoco River was shown earlier in Fig. 4B. An example of this type of storage can be seen to occur during peak flow in the 200 km reach of the middle Orinoco at downriver distances between 300 and 500 km on the ordinate scale in the upper row of Fig. 7. When the river stage is near its annual peak, this reach of the Orinoco forms a large area of backwater that includes the lower reaches of a number of tributaries (including the Apure River) as well as large tracts of intervening floodplain—an area described as an ‘inland delta’ by Alexander von Humboldt when he visited it in 1800 (Humboldt and Bonpland, 1884). During peak stage, nearly half the inflowing sediment is stored in this reach. During subsequent falling stages and during the early part of the next rising stage, this reach of the Orinoco yields sediment from storage to be transported farther downriver. Sediment loads in the lower Orinoco, therefore, are smaller at peak water discharge than during rising or early falling discharges.

In the Amazon mainstem, different patterns of seasonal storage and remobilization of suspended sediment characterize different parts of the river. In the Brazilian Amazon (Solimões River) upriver of the gauging station at Manacapuru, the seasonal pattern follows the common sequence shown in Fig. 4A, wherein fine sediment is stored during low-water seasons and resuspended as the river rises. Downriver of Manacapuru, as shown in the lower row of Fig. 7, the relation is different. In the 750 km reach of the lower Amazon between Manacapuru and Obidos, suspended sediment is stored during rising river stages. This seasonal
pattern, which is contrary to the usual expectations, seems less correlated with water discharge than with river slope. Because of the timing of inflows from large tributaries such as the Madeira, Tapajós and Xingu Rivers, which reach their annual peak flows several months before the peak flow in the mainstem (Meade et al., 1985, 1991), the slope of the surface of this reach of the Amazon is smaller on rising stages than on falling stages. The resulting sequence of sediment storage and remobilization regulates the discharge of sediment to the delta and the Atlantic Ocean. During rising river stages, when sediment loads in the upper Amazon are large, the lower Amazon stores part of the sediment (approximately \(10^6\) tons per day) before it reaches the sea. During falling stages, when sediment loads from the upper river are smaller, the lower river augments the loads being transported seaward by resuspending sediment from its bed.

Storage on Floodplains

Floodplains are dynamic, continually gaining sediment by vertical accretion during periods of overflow and losing it by the lateral erosion of river banks as the river falls. Floodplains may be more dynamic in the Amazon than in the Orinoco, judging from their greater extent both in terms of total area (170,000 vs. 7000 km\(^2\)) and of floodplain area per unit channel length (40 vs. 9.3 km\(^2\)), both comparisons from Hamilton and Lewis (1990, p. 499).

In a recent study of the alluvial lowlands along the Solimões (mainstem Amazon) River between the mouths of the Purús and Negro Rivers, Mertes (1990) concluded that floodwaters deposited about 80% of the sediment loads that they transported over nonchannelized areas of the floodplain. During 71 days of 1986 when the river stages exceeded 17.5 m on the gauge at Manacapuru, 3800 km\(^2\) of inundated floodplain accumulated an average of 8 mm of new silt and clay (finer than 0.063 mm), which amounted to a total deposition of 38 million tons of new sediment. However, the total amount of silt and clay lost from the floodplain through bank erosion during the same year in the same reach of river (Purús to Negro) was estimated at 35 million tons. Mertes concluded, within the limits of the probable errors of the two measurements, that the accretion of new fine-grained material on the floodplain was equivalent to the removal of older fine-grained material by bank erosion. Even though there was no net increase or decrease in the load of sediment being carried by the river, the amount of fine material being exchanged (new material being brought in from upriver and older material being remobilized for transport downstream) was equivalent to about 10% of the annual discharge of fine suspended sediment through the Manacapuru reach.

A logical extension of this argument would be that the entire 3800 km\(^2\) of floodplain (assuming an average thickness of 20 m for the floodplain sediments) might be recycled in a period of about 2500 years. Although any such extrapolation of a single year’s worth of data to a period of 2–3 millennia is extremely tenuous, it does suggest that the time scale of the dynamic recycling of the central Amazonian floodplain might be on the order of millennia or tens of millennia. The millennial-to-multimillennial time scale is supported by the radiocarbon dates of 1100–2050 BP obtained by Sternberg (1960) on floodplain deposits near the downriver end of the Purús-Negro reach. Areas nearest the active river are probably recycled faster than areas of the floodplain farthest from the river. Near-river areas of floodplain along the Amazon mainstem of Peru seem to have recycling rates measurable in centuries (Ford et al., 1983, pp. 102–103; Kalliola et al., 1992; Lathrap, 1968; Räsänen et al., 1991; Salo et al., 1985). Other floodplain deposits in central Amazonia demonstrate degrees of mineral weathering that support recycling rates measurable in many tens of millennia (Johnsson and Meade, 1990).

A less tenuous extrapolation can be made concerning the exchanges of fine-grained sediment between the river and its floodplains during an average annual cycle of sediment transport. If it is true:

1. that 10% of the annual load of silt and clay being transported by the Solimões River into the upper end of the mainstem reach between the mouths of the Purús and Negro Rivers is deposited (stored) on the floodplains that border that reach;
2. that 10% of the annual load of silt and clay being transported out the lower end of the Purús-Negro reach is material remobilized by bank erosion from the floodplains of that reach; and
3. that the same exchange between sediment transport and floodplain storage is occurring in 10–20 other similar reaches of the Amazon mainstem (the Purús-Negro reach is only 130 km of a total lowland river length greater than 3000 km);

then the probability is small (certainly less than 50%, possibly less than 20%) that any given particle of silt or clay that is eroded from the Andes into the Amazon headwaters during any given year will be transported completely down the Amazon and into the Atlantic Ocean within the same year. Once the particle has been transported across the river bank and deposited on the floodplain, it is likely to remain there for decades, centuries or even millennia. Meanwhile, its ‘place’ in the suspended-sediment load of the river has been taken by another particle newly mobilized by bank erosion from the older floodplain. Thus, while the total quantity of fine-grained sediment being transported downriver may not change significantly, less than half of the individual particles being discharged to the ocean in a given pulse of water are likely to be the same individuals that were being transported by that pulse of water when it was still 2000–3000 km upstream.

SUSPENDED-SEDIMENT DISCHARGES TO DELTAS, COASTLINES AND THE ATLANTIC OCEAN

Although the sediment discharges of the world’s large rivers are commonly reported in terms of delivery ‘to the oceans’ (Milliman and Meade, 1983), this practice can be misleading. A river usually delivers different quantities of sediment to its delta, to the coastline, to the open ocean and to the deep sea.
Amazonian sediment to the submerged delta of the Orinoco is supported by the mineralogical analyses of Eisma et al. (1978), who reported clay–mineral assemblages in recently-deposited muds, from which they concluded that the Amazon River supplies twice as much mud as the Orinoco River to the submerged delta of the Orinoco.

Although only a small percentage will make the entire trip, it is impressive to imagine the progress of fine particles of suspended sediment, originally dislodged from a hillside of the Andes somewhere in Peru, being carried down into the large alluvial valley of the Amazon, spending several centuries or millennia in storage in a floodplain, being remobilized by bank erosion and transported to the ocean to become part of the mudbanks that are moved slowly north-westward along the coast of the Guianas to come to rest eventually in the delta of the Orinoco—a journey of some 6000 km.

ACKNOWLEDGEMENTS

Most of what I have written in this paper was learned in the context of several multidisciplinary projects. Field work in the Amazon was supported first (1976–77) by the U.S. National Science Foundation (NSF) Grant OCE 77-27148 to the Massachusetts Institute of Technology (J.M. Edmond, Principal Investigator) and later (1982–84) by NSF Grant DEB-8017522 to the University of Washington (J.E. Richey, Principal Investigator). Field work in the Orinoco basin (1981–83) was organized and funded mostly by Proyecto Orinoco-Apure of the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovable and by Electrificacion del Caroné. For the opportunities to work in so many parts of the Orinoco basin, I thank especially Abel Mejía B., José M. Sainz, Guillermo Colmenares Finol, Carmen Delgado and Herman Roo G. I enjoyed the collaboration and comradeship of Carl Nordin, Bob Stallard, Bill Curtis, Clare Cranston and John Edmond in both river basins; Tom Dunne, Bruce Forsberg, John Hedges, Allan Devol, Leal Mentes and Jeff Richey in the Amazon, and David Pérez Hernández, Lois Koehneken and Franz Weibezaehn in the Orinoco. After having worked so closely with such stimulating colleagues for so many years, I find it impossible to remember who was the first to make each key observation or articulate each seminal insight. If these people (and others I have not named) find their observations and ideas used without attribution in this paper, I hope they will have the grace to look on my lapses as acts of inadvertent admiration rather than of intentional larceny.

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