Suspended Sediment Load in the Amazon Basin: An Overview

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ABSTRACT: In this report the state of knowledge of sediment transport by rivers of the Amazon drainage basin is reviewed. On an annual basis the Amazon river transports about $1200 \times 10^6$ tons of sediment from the South American continent to the ocean, which puts it among the world’s largest rivers in this respect. The main source of sediment is erosion in the Andes mountains and this material is progressively diluted with sediment poor runoff from lowland draining tributaries. Almost half of the Amazon river transport is attributable to one tributary, the Rio Madeira ($488 \times 10^6$ t/y). The Rio Negro, which drains the N cristalline shield, has a comparable water discharge to the Rio Madeira, but only contributes $7 \times 10^6$ t/y. In general the sediments in transport are about 1% organic carbon by weight and this results in an annual particulate carbon to the oceans of $13 \times 10^6$ t/y. Total carbon transport, particulate plus dissolved, is about twice this amount.

Introduction

The Amazon river accounts for nearly 20% of the world freshwater discharge to the oceans, and is the third largest river in terms of sediment transport, carrying approximately $1200 \times 10^6$ tons/y suspended sediments (Meade et al. 1985). Such large volumes of water and sediments influence the global water and nutrient balances (Meybeck and Carbonnel 1975; Meybeck 1982; Gibbs 1965). Additionally, the highly dynamic exchange of sediment and organic matter between the floodplain and the main channel via an erosion-deposition transport mechanism plays a key role in regional carbon cycling (Richey et al. in press).

Although it is presently known that the great majority of Amazon river sediment transported to the ocean is derived from Andean erosion processes (Gibbs 1965), the alarming rate of change in land use pattern in the region may, in the future, alter the quantity and dynamics of sediment transport in several of its major tributaries. Recent estimates have shown that approximately 8% of the Brazilian Amazon is already deforested, and critical areas such as Rondônia have lost more than 20% of their forest cover (Fearnside, in press). Despite the potential anthropogenic impact, sediment studies in the Amazon basin are still relatively few (Gibbs 1965; Meade 1985; Brinkmann 1986). Systematic efforts to describe the sediment distribution in the Amazon river mainstem and major tributaries were only initiated in 1982 as part of the CAMREX (Carbon in the Amazon River Experiment) and Polonoroeste projects.

The central objective of this report is to summarize the available sediment and transport data for the Amazon river and its major tributaries and to present some previously unpublished data. Among the tributaries, the Rio Madeira and several of its affluent in the region of the Brazilian state of Rondônia are of particular interest due to the current development and deforestation in the area.
The Amazon River System

Hydrology

The Amazon basin encompasses five morphostructural regions differing mainly in altitude and geological substrate. The highest region is the Cordilheira dos Andes, followed, in an easterly direction, by the Sub-Andean region and the Amazon depression. The Brazilian and Guianas Pre-Cambrian crystalline shields are located at the S and N borders of the basin respectively.

With an enormous watershed (6 million km²), and an average yearly rainfall of 2200 mm (Salati 1986), the rivers in the region have high freshwater discharges. Measured at Obidos, about 600 km from the mouth, the Amazon river water discharge ranged from an average minimum of 100,000 m³/s to an average maximum of 220,000 m³/s (Richey et al. 1986). The Rio Madeira and Rio Negro are the largest tributaries of the Amazon river proper. Both have similar averaged discharges of approximately 30,000 m³/s, which, if they were not tributaries of the Amazon, would place them among the top 5 rivers of the world (Holland 1978). Other tributaries and their averaged discharges include the rios Jutai (1,500 m³/s), Jurua (3,000 m³/s), Iça (7,500 m³/s), Purús (11,000 m³/s) and Japurá (14,000 m³/s).

Much of the deforestation in the Amazon basin is occurring in Rondônia along the middle reaches of the Rio Madeira. The main tributaries of the Rio Madeira in this region are the Jiparaná and Jamari rivers, both of which run in a S-N direction through Rondônia, over areas that have been severely deforested. These two tributaries of the Rio Madeira drain mainly the crystalline shields of the Brazilian plateau and the Amazonian depression, and thus have characteristically low electrolyte concentrations (Martinelli et al. 1987). For the Rio Jiparaná, discharge measurements done at the town of Jiparaná (approximately half the way up the river), during the period 1970 to 1983, resulted in an average value of 70 m³/s. Two additional measurements done at the mouth during high water resulted in discharges of 1700 m³/s (April 1984) and 2700 m³/s (January 1986) (Martinelli et al. 1988). For the Rio Jamari, similar measurements resulted in averaged discharges of 170 m³/s at its mid course and 900 m³/s (April 1984) and 1100 m³/s (January 1986) at its mouth during high water (Martinelli et al. 1988). The Rio Aripuaná, a tributary joining the Rio Madeira about 780 km downriver from Porto Velho, is the largest tributary to the Madeira main channel, with an averaged discharge of 8500 m³/s (Martinelli et al. 1988).

Sediment Sources

The major sediment source to the Amazon rivers and its major tributaries, especially the Rio Madeira, is weathering in the Andean Cordilheira. In this area, steep topography combined with rainfall rates of up to 5000 mm/y (Salati 1986) are the driving forces of erosional processes that produce the large amounts of sediment (Gibbs 1965). For Amazonian rivers in general, the suspended sediment concentration in a river is determined by the geographical extent of the drainage basin that lies in the Andes. Therefore, rivers like the Rio Madeira that have a large fraction of their headwaters drainages in the Andes always have high suspended sediment and nutrient concentrations (Martinelli et al. in press; Ferreira et al. 1988). On the other hand, rivers like the Rio Jutai and Rio Negro that drain exclusively the Amazon depression have the lowest sediment and nutrient concentrations (Richey et al. 1986; Brinkmann 1986; Martinelli et al. 1988). In between these extremes are the rivers with headwaters in the Sub-Andean region (Purus and Jurua) or rivers with headwaters in the Andean region but draining extensive lowland areas (Iça and Japurá).

Methods

Sampling Locations

The CAMREX project has been measuring water flow, sediment and chemical concentrations at various different points along the Amazon mainstem between Vargem Grande and Obidos and at sampling stations located on major tributaries about 30 km upstream of their respective confluences with the mainstem (Fig 1). Results for Vargem Grande, Obidos, and the major tributaries that were obtained on 8 sampling cruises conducted at different stages of the hydrograph between 1982 and 1985 will be used in this paper (Fig 1 and Fig 2).

The Rio Madeirae basin rivers were sampled as part of the Polonoroeste project. Two types of sampling expeditions were performed; river cruises and terrestrial excursions. The river cruises sampled the Rio Madeira main channel between Porto Velho and Urucurituba. During these cruise five main channel and three tributaries sampling stations were occupied (Martinelli et al. in press). The tributary sampling stations (Rios Jamari, Jiparaná and Aripuaná) were located between 30 to 50 km upstream from confluence with the Rio Madeira (Fig 1). In total, two cruises were performed, one in April 1984 and one in January 1986, both during high water periods.

During the river cruises samples were obtained using the Amazon Equal Transit Rate (ETR) method because it yields depth integrated and discharge normalized samples. Detailed information about the sampling methodology used on the river cruises can be found in Meade (1985) and Richey et al. (1986). Briefly, at each sampling station the river was vertically sampled at 8 to 18 locations (depending on the cross section width) equally spaced across the river. Samples were collected
in collapsible plastic bags coupled to a hydraulic winch sampler. A Price AA current meter was also attached to the sampling array for concurrent measurements of river discharge. Half of the samples were used for analysis of suspended sediments and half for chemical analysis. For the sediment samples, the water volume collected at each profile was measured and the sample was sieved through a 63 μm sieve to separate the coarse sediment fraction. Sieved samples from all the profiles were then combined into a composite sample, from which subsamples were filtered through dried and pre-weighed Millipore filters (0.45 μm pore diameter) for fine sediment measurements.

During the terrestrial excursions to the Rio Madeira basin, the rivers were sampled alongside highways. In total, five different excursions were done covering five different stages of the hydrograph; November 1984, September 1985, March 1986, March 1987 and July 1987 (Fig 3). Sampling was concentrated in the Jiparaná and Jamari river basins. Surface water samples were collected with a USH-59 type collector, at the middle of the channel. Two to three samples were collected at each point. Sample processing after collection was similar to that used for the river cruises.

Sediment flux was calculated as the product of concentration (g/m³) and discharge (m³/s). Wherever data permitted, a discharge versus sediment flux rating curve was derived and used for long-range predictions of sediment loads. Details of this procedure may be found in Martinelli et al. (1988). Errors involved in sample collection and processing do not exceed 10% for the river cruises (Meade 1985). This error is small enough to permit the study of changes in the dynamics of sediments and sediment transport. Interpretation of the terrestrial excursion data is complicated by the fact that they were not depth-integrated. Errors were not estimated in this case, but maximum differences between replicates were also 10%.

Results

Sediment Concentration

Detailed sediment concentration data for the river cruises may be found in Meade (1985) and Martinelli.
et al. (in press). In this paper only the averages extracted from those data are presented (Tab 1). Data for the terrestrial excursions are presented in Tab 2.

For the Amazon river main channel, averaged sediment concentration decreased from 456 mg/l at the uppermost sampling station (Vargem Grande) to 176 mg/l at Obidos, almost 2000 km downriver. The downriver decrease in sediment concentration observed in the Amazon river mainstem was primarily due to dilution by the sediment-poor tributaries along the way (Meade 1985; Gibbs 1965). The slope of the fitted line shows a decrease of approximately 17 mg/l every 100 km (see Meade 1985).

Among the major tributaries to the Amazon river, the highest observed average concentration was 627 mg/l at the mouth of the Rio Madeira; the Rio Juruá had concentrations similar to the lower mainstem, 194 mg/l, while in the Rios Içá and Purús values were much lower than the mainstem, 85 and 74 mg/l, respectively. Concentrations in the Rio Japurá were slightly lower, 54 mg/l. The lowest suspended sediment concentrations were observed in the black-water tributaries, the Rios Jutai, 16 mg/l, and Negro, 7 mg/l.

As in the Amazon river, sediment concentration in the Rio Madeira decreased downstream over the 600 km between Porto Velho and Manicoré. However, unlike the Amazon river the concentration then increased slightly over the 400 km between Manicoré and Uricurituba. The rate of decrease in concentration in the upper section, 66 mg/l per 100 km was significantly greater than that seen in the Amazon river mainstem. The rate of increase below Manicoré was 18 mg/l per 100 km. The decrease in concentration was expected due to the dilution with sediment-poor waters from the lowland tributaries and the high rate observed has been attributed to higher sediment deposition in the floodplain during the particular portion of the hydrograph (Martinelli et al. in press). It is important to note here that direct comparison with the Amazon river is difficult because the Rio Madeira data were taken only at the high water stage of the hydrograph.

Average concentrations for the Rios Candeias, Jaru and Jamari, sampled during the terrestrial cruises to Rondônia area of the Madeira basin were very low and similar to the concentrations found for the Rios Negro and Jutâi in the Amazon drainage. While the rivers Pimenta Bueno, Comemoração and Jiparaná had somewhat higher values, about 25 mg/l, overall, these were sediment poor rivers also (Tab 2).

The time span of the data available is not sufficient to permit any conclusion about temporal variations in sediment concentration in either the Amazon or Madeira basin.
Tab 2
Suspended sediment concentration of the Madeira basin rivers sampled during the terrestrial excursions of the Polonoroeste project

<table>
<thead>
<tr>
<th>River station</th>
<th>Jamari</th>
<th>Jiparana</th>
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<tbody>
<tr>
<td></td>
<td>Aiquemes*</td>
<td>Samuel*</td>
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<tr>
<td>Date</td>
<td>Concentration (mg/l)</td>
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</tr>
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<td>3.0</td>
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<tr>
<td>Aug. 85</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Mar. 86</td>
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<td>10.7</td>
</tr>
<tr>
<td>Mar. 87</td>
<td>16.0</td>
<td>17.7</td>
</tr>
<tr>
<td>Jul. 87</td>
<td>25.0</td>
<td>17.3</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td>22.1</td>
</tr>
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<table>
<thead>
<tr>
<th>River</th>
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<th>Candeias*</th>
<th>P. Bueno</th>
<th>Comemoração</th>
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<tbody>
<tr>
<td>Date</td>
<td>Concentration (mg/l)</td>
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<td></td>
<td></td>
</tr>
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<td>2.0</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
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<td>2.7</td>
<td>2.3</td>
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<td>25.6</td>
<td>17.3</td>
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<tr>
<td><strong>Average</strong></td>
<td>11.0</td>
<td>6.6</td>
<td>-</td>
<td>11.1</td>
</tr>
</tbody>
</table>

* averages for those stations were not discharge weighed.

river drainage systems. Meade (1985), however, analyzing a longer data time series obtained from the Amazon river mainstem at Ilha de Marchantaria (near Manaus), observed that the highest sediment concentrations were found in December or January, during the rising-water stage, or 6 months after the peak of the river hydrograph. Minimum sediment concentrations were observed in September or October, two months after the lowest stage of the hydrograph.

Sediment Load

Water discharge and sediment flux values for the Amazon drainage basin are presented in Tab 3 (upper panel). With the exception of the Rio Madeira, the values were extracted from Forsberg et al. (in prep.) and are based on the 8 CAMREX cruises. The value for the Rio Madeira includes the 8 CAMREX cruises plus the 2 Madeira cruises done during the Polonoroeste project.

For the Amazon river the highest flux was obtained at Obidos, with an averaged value of $1156 \times 10^6$ tons per year, which is of the same order of magnitude as the other major sediment transporting rivers in the world; e.g., the Ganges/Brahmaputra and Hoangho rivers (Milliman and Meade 1983). The sediment flux at Vargem Grande was only half that observed at Obidos but, nevertheless, it was still the second highest in the basin. Although sediment flux doubled in the Vargem Grande-Obidos reach, water discharge tripled. Similarly, for the same period, the flux of dissolved substances was also only 1.4 times greater at Obidos than at Vargem Grande (Martinelli et al., in prep.). This clearly shows that the Amazon depression is a supplier of nutrient depleted, sediment poor waters and that the Andean region is the major supplier of nutrients and sediment for the basin.

Among the tributaries, the highest sediment flux was observed for the Rio Madeira, with $488 \times 10^6$ tons per year. The Rio Negro, with discharge values similar to the Madeira, but with headwaters in the crystalline shield, showed a sediment load 100 times lower. The fluxes for the Rios Iça, Japurá, Jurua, and Purús were similar, with values ranging from $20 \times 10^6$ to $30 \times 10^6$ tons per year. The lowest sediment flux, of about $2 \times 10^6$ million tons per year, was observed in the Rio Jutai, which also has the smallest drainage basin.

For the Madeira basin, the fluxes could only be calculated for the two Polonoroeste cruises (Tab 3, lower panel). Sediment fluxes are, therefore, presented on a per day basis and can not be directly compared to the Amazon basin fluxes. However, the annual value for the Rio Madeira given in the upper part of Tab 3 has been recalculated on a daily basis and listed as Uruçurituba (annual) in the lower part of Tab 3. Also, the difference between average discharge at the mouth, $29 \times 10^6$ m$^3$/s (Tab 3, upper) and high water discharge at the mouth, $51 \times 10^6$ m$^3$/s, should be noted.

As with the Amazon river mainstem, sediment fluxes increased less in the downstream direction than discharge. Between Porto Velho and Uruçurituba the sediment flux increased by a factor of 1.2, from $2950 \times 10^3$ t/d to $3430 \times 10^6$ t/d, while water discharge increased by a
Denudation Rates

Due to the different water volumes generated in each subbasin, which are in turn proportional to basin areas (Forsberg et al. 1988), it is difficult to interpret directly the sediment flux behavior. A better way to analyze such data is through the so-called denudation rate (DR), which is the sediment flux from each subbasin expressed per unit area of the sub-basin. Strictly speaking, however, the total denudation rate (Σ DR) includes not only the suspended sediment flux component (DRs) but also the dissolved flux (DRd).

In general (DRs) is higher than the (DRd) and this difference is enhanced in the Andean tributaries (Tab 5). As the lowland area of the basin is expanded, the ratio of DRs to DRd decreases (Gibbs 1965; Stallard and Edmond 1983) as is shown in the plot of DRs versus this ratio. With the exception of Vargem Grande, all the other points can be fitted to a straight line ($r^2 = 83\%$, $P > 0.001$). The extreme observed values were the Rio Madeira and the Rio Negro, with DRs/DRd ratio equal to 12 and 1.4 respectively. The ratio DRs/DRd is small for the rivers of Rondonia rivers. In some cases, DRs is even smaller than DRd; e.g. the Rio Jaru (Tab 5). It should be noted that alkalinity was not determined for these rivers, but alkalinity in them is generally low, and underestimation in this case should not be substantial (J. R. Ferreira, personal communication).

As expected from previous work (Gibbs 1965: Stallard and Edmond 1983; Ferreira et al. 1988) the highest denudation rates were obtained for rivers of Andean origin. Thus, the highest calculated Σ DR was that from Vargem Grande, with approximately 732 t km⁻² y⁻¹, followed by the Rio Madeira, with a value of 384 t km⁻² y⁻¹. Values for the Rios Iça and Juruá rivers were similar and approximately 140 t km⁻² y⁻¹, while the Rios Japura and Purus showed values of approximately 100 t km⁻² y⁻¹. Although the Rios Iça and Japura are both Andean in origin, the latter drains a much larger area of the central basin than the former. The same observation is valid for the Rios Juruá and Purus, both sub-Andean in origin but draining different areas of the central basin. For this reason the Rios Iça and Juruá have higher Σ DR values than their lowland draining counterparts. As expected, tributaries draining solely lowland areas, the Rios Jutaí and Negro showed the lowest Σ DR, with values of 23 and 8 t km⁻² y⁻¹, respectively.

Finally, it is interesting to compare the Rio Madeira tributaries with the Amazon basin rivers. The three tributaries are located in the state of Rondônia and drain the southern crystalline shield. All these rivers had very low Σ DR values similar to the Rios Negro and Jutaí. The smallest rate was for the Rio Jaru, approximately 19 t km⁻² y⁻¹, most of which is due to export of dissolved substances (Martinelli et al. 1988b). The Σ DR for the Rio Jiparaná was equal to the Rio Jutaí, while the value for the Rio Pimenta Bueno was intermediate.
Sediment Composition

Organic Composition

The transport of particulate organic carbon (POC) is a function of the physical processes that regulate sediment dynamics, as well as the biological and chemical processes that produce and process the organic materials. In the Amazon drainage basin the mass of organic carbon transported in relation to the mass of sediment transported is relatively constant, therefore sediment distribution in the basin reflects the organic carbon distribution (Richey et al., in press). Richey et al. (in press) calculated that the Amazon river exports about $13 \times 10^6$ t of POC per year, or about 3 t/km² of the basin per year, which accounts for about 1% of the total suspended sediment in the basin. POC constituted 42% of the total organic carbon (TOC=POC+DOC) transported, 37% in the form of fine POC (< 63 μm), and the remaining 5% in the form of coarse POC.

Hedges et al. (1986) showed that the organic composition of the sediment fine fraction (< 63 μm) is mainly very old and refractory soil derived organic matter. The coarse fraction organic composition, on the other hand, was distinctively different, consisting mainly of leaf (80%) and wood (20%) debris of more recent origin, Brinkmann 1986; Hedges et al. 1986). Nevertheless, although organic substances different in both origin and dynamics are being concurrently transported, nearly 90% of the total suspended sediment is in the fine fraction; thus, the refractory soil derived matter is the major organic form transported by the river. Being refractory, this POC is not prone to biological changes, and is therefore controlled by physical processes that regulate sediment transport.

Mineralogical Composition

Gibbs (1965), using sediment samples at the river surface, showed that the dominant clay minerals were
montmorillonite and kaolinite, and that the clay composition did not change spatially. On the other hand, Irion (1976) and Martinelli (1986) observed downstream decreases in Ca and Mg concentrations, both in the exchangeable and total forms. Thus, although the physical structure of the clay minerals is not changed during transport, they appear to become progressively depleted in basic cations, mainly due to addition by nutrient-poor waters of the tributaries.

Tributaries draining predominantly the lowland Amazon depression had sediment mineralogical composition dominated by kaolinite, with the Rio Negro being the extreme case (Brinkmann 1986; 1989). That was also the case for the Rios Tapajós and Xingü, which drain the S crystalline shield (Brazilian Plateau). The Rio Içá, though dominated by kaolinite, showed significant concentrations of montmorillonite. Although a kaolinite dominance was also to be expected for the Rio Jutai, montmorillonite concentrations were surprisingly similar to kaolinite concentrations for this river. Montmorillonite was the dominant clay mineral for the Rios Juruá and Purús. The Rio Madeira had a distinct mineralogical composition, dominated by Ilite with smaller proportions of kaolinite (Irion 1984).

Changes in Land Use and Sediment Loads

Deforestation in the Amazon has been increasing progressively since 1970. Estimates of deforestation rates are variable, ranging from 17,000 km²/year (INPE 1989) to 80,000 km²/year (Setzer and Pereira in press). It is, however, generally agreed that the area most presently affected is Rondônia, where nearly 20% of the area of the state is estimated to be already deforested (Mahar 1989). Much of the deforestation in Rondônia has been to establish pastures, which is generally recognized as one of the patterns of land use change that most enhances erosion, particularly in tropical areas (Salati and Vose 1984).

The water and sediment loads of many of the rivers in the Amazon region is to be are high under natural conditions than it would be difficult to use them as monitors of erosion losses due to changes in land use in their basins (i.e., the signal-to-noise problem). The Madeira tributaries of Rondônia, with generally low sediment concentrations, could be used as indicators of land use changes in their basins. The major difficulties for such a program are associated with the topography of the region and the necessity of intensive sampling of the rivers. Graham (1986), showed that the increase in sediment load in the Rio Jamari coincided with soil erosion losses. The delivery ratios (soil erosion losses/river sediment load) were, however, highly variable, and longer time studies are necessary to definitely ascertain such tendencies. Erosion-derived sediment could well be temporarily stored in accumulation zones in the basin, masking the results.

Conclusions

Sediment and sediment transport data for the Amazon region are still scarce, despite the effort of several groups currently working in the region. The data are, however, sufficient to indicate areas were research efforts should be preferentially directed. Such is the case for the state of Rondônia, where changes in land use are occurring at alarming rates. This does not preclude continuation of studies of the Amazon main channel, for a trustworthy baseline of data is necessary for assessment of future changes.

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