Suspended sediment fluxes in the large river basins of Brazil

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Abstract In Brazil, measurements of suspended sediment transport have been undertaken regularly since 1970 at a number of stations located on the main rivers. The database resulting from those measurements now makes it possible to study the sediment loads of the largest river basins. The primary objective of this paper is to present a preliminary study of the suspended sediment loads of Brazil's largest river basins, namely the Amazon, Tocantins, São Francisco and Paraná rivers. In view of the available data and the importance of information on sediment loads, this analysis has also been extended to other important basins of the country. The sediment balance along each river was assessed by comparing the mean suspended sediment load of successive measuring stations. Values of mean annual suspended sediment concentration and discharge have been calculated for each station. The total suspended sediment production from the territory of Brazil has been estimated to be 610×10^6 t year^{-1}.

Key words Brazilian rivers; sediment loads; suspended sediment flux; water management; water quality

INTRODUCTION

Knowledge of the sediment load of a river basin is of fundamental importance for devising appropriate water resource management strategies and developing economic activities that depend on such resources. Brazil is a country of continental dimensions, characterized by a large range of geophysical, biological and climatic conditions. Because of this diversity, the hydrological and sediment transport regimes of Brazilian basins are highly variable and require specific studies. In spite of the importance of sediment load data, the size of the country and the high operational costs involved in maintaining and gathering information from a large network of discharge and sediment monitoring stations have inhibited the development of sediment transport studies in Brazil.

The hydrological and sediment load database, named "Hidro", which is based on the measurements that have been made since the 1970s at the stations of the Brazilian Hydrometric Basic Network, contains a large mass of data, but for some rivers only a few measurements are available, mainly during flood periods. This database contains about 20 000 records, but most of them have never been fully analysed.

The objectives of the study reported in this paper were twofold:

(a) to present the results of the analysis that has been undertaken in Brazil on the sediment loads of some of its large river basins;
(b) to undertake a preliminary analysis of other data and information, in order to estimate the suspended sediment flux from the entire territory of Brazil.

MATERIAL AND METHODS

The Hidro database used for this study (Hidroweb, 2004) contains all the data collected from each station in the Brazilian Hydrometric Basic Network, and is operated under the responsibility of the Brazilian National Water Agency—ANA. All the hydrological and sediment data for the São Francisco and the Araguaia-Tocantins basins has already been recently analysed and published (Lima *et al*., 2001, 2003). For the other basins, the approach was to analyse the data from the stations located near the estuary of each river. In the case of the Paraná River, which is a tributary of the Prata River, the stations considered were those located furthest downstream, but still inside the Brazilian borders. For each large basin, some additional stations from tributary rivers were also included, in order to provide information on the sediment balanced along the basin.

The suspended sediment load values from each measurement were derived as:

$$Qss = 0.0864 Q \cdot Css \tag{1}$$

where Qss is the suspended sediment discharge (t year^{-1}); Q is the water discharge (m^3 s^{-1}); and Css is the suspended sediment concentration (mg l^{-1}). After having calculated the suspended sediment discharge for each measurement, the sediment rating curve for each station was then established using the methodology presented by Carvalho *et al*. (2000). The rating curves generally have the following form:

$$Qss = a \cdot Q^b \tag{2}$$

in which a and b are fitted parameters.

To evaluate the sediment rating curve quality, two criteria were used: the first was that the r^2 value must be higher than 60%; and the second involved a visual assessment of how closely the exponential form of the generated curve followed the measured points. Based on the sediment rating curves, the daily water discharge series from each station were transformed into the corresponding suspended sediment discharge daily series.

RESULTS AND DISCUSSION

The hydrological/sediment monitoring stations used in the study and their summary data are presented in Table 1.

The Amazon River basin

The sediment studies undertaken to date on this river have produced divergent estimates of the total amount of sediment discharged to the Atlantic Ocean. According

Table 1 Summary of the main characteristics of the water and sediment fluxes for the individual monitoring stations included in the study.

Basin / Code no.	Station	River	A. Drain. (km²)	Q ($m^3 s^{-1}$)	Q *sp.* ($l s^{-1}.km^{-2}$)	*Qss* ($t.year^{-1}$)	*Qss sp.* ($t km^{-2} year^{-1}$)	*Css* ($mg l^{-1}$)
Amazon River Basin								
15400000	Porto Velho	Madeira	954 285	19 274.0	20.2	242 529 461	254.1	399.01
15860000	Faz.Vista Alegre	Madeira	1 324 727	30 614.9	23.1	237 868 139	179.6	246.38
11400000	São Paulo de Olivença	Solimões	990 781	47 239.4	47.7	342 590 825	345.8	229.97
14100000	Manacapuru	Solimões	2 147 736	101 588.4	47.3	452 368 441	210.6	141.20
17050001	Óbidos	Amazonas	4 680 000	181 430.8	38.8	567 400 818	121.2	99.17
18850000	Altamira	Xingu	446 203	7 752.6	17.4	3 435 161	7.7	14.05
Parnaíba River Basin								
34690000	Teresina	Parnaíba	232 000	577.1	2.5	3 469 847	15.0	190.67
34879500	Luzilândia	Parnaíba	300 000	694.8	2.3	6 060 804	20.2	276.59
Paraná River Basin								
64843000	Guaíra (Porto Guaíra)	Paraná	802 150	9 381.2	11.7	8 275 827	10.3	27.97
65986000	Estreito do Iguaçu -Novo	Iguaçu	63 236	1 767.9	28.0	2 230 218	35.3	40.00
66070004	Caceres	Paraguai	32 774	532.7	16.3	1 261 128	38.5	75.06
Uruguai River Basin								
73010000	Marcelino Ramos	Uruguai	41 267	895.6	21.7	1 027 680	24.9	36.39
77150000	Uruguaiana	Uruguai	163 547	4 687.8	28.7	3 593 591	22.0	24.31
Doce River Basin								
56425000	Faz, Cachoeira D'Antas	Doce	10 080	161.1	16.0	1 003 896	99.6	197.58
56920000	Tumiritinga	Doce	55 425	717.2	12.9	6 210 942	112.1	274.60
56948005	Resplendor-Jus	Doce	61 610	638.5	10.4	6 280 788	101.9	311.92
56994500	Colatina	Doce	75 800	921.0	12.2	11 219 000	148.0	386.25
Paraíba do Sul River Basin								
58183000	Pindamonhangaba	Paraíba do Sul	9 576	154.6	16.1	215 794	22.5	44.25
58321000	Barra do Piraí	Paraíba do Sul	17 639	273.3	15.5	1 381 672	78.3	160.33
58974000	Campos-Ponte Municipal	Paraíba do Sul	55 500	791.4	14.3	4 354 574	78.5	174.47

A.Drain: drainage area; Q: water discharge; Q *sp.*: specific water discharge; *Qss*: suspended-sediment discharge; *Qss sp.*: specific suspended sediment discharge; *Css*: concentration of suspended sediment.

to Gibbs (1967), the average sediment discharge from this basin to the ocean is about 500×10^6 t year^{-1}. However, the samples used to estimate the suspended sediment concentration were obtained near the water surface, and this may have caused the actual values to be underestimated. Meade *et al.* (1979) estimated the average sediment flux to the ocean to be between 800×10^6 to 900×10^6 t year^{-1}, also using samples collected from the surface. Meade *et al.* (1985) used 10 measurements to produce a revised estimate in the range 1100×10^6 to 1300×10^6 t year^{-1}. In this case, even though the estimates are based on a small set of measurements, the concentration data used were obtained using a more adequate sampling scheme. Filizola (1999), using a database from the Brazilian Hydrometric Basic Network, concluded that the average

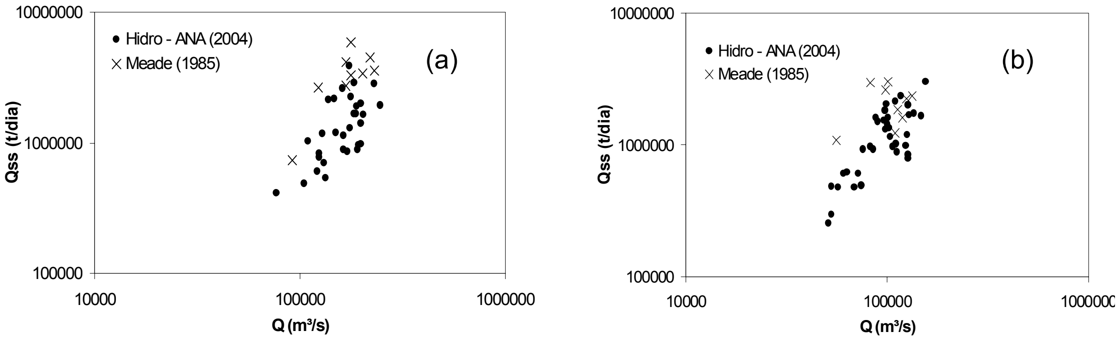

Fig. 1 A comparison between the sediment data collected from both the Óbidos (a) and Manacapuru (b) stations on the Amazon River and currently included in the Hidro database from ANA, with the measurements reported by Meade (1985).

suspended sediment flux at the mouth of the Amazon is approximately 600×10^6 t year^{-1}. The database used in the present study is the same as that utilized by Filizola (1999), except for the inclusion of additional data up to the year 2002. The results presented in Table 1 show that the estimated suspended sediment discharge at Óbidos is consistent with the values estimated by Filizola (1999), at about 570×10^6 t year^{-1}.

The above discrepancies in the estimates of the sediment discharge at the mouth of the Amazon probably reflect the differences in sampling techniques used in the different studies. Figure 1 shows the data used in this study, collected from both Óbidos and Manacapuru stations, as currently recorded in the Hidro database, in comparison with the same information used by Meade (1985).

As it can be seen in Fig. 1, there is a detectable difference between the values of suspended sediment discharge (*Qss*) obtained from the measurements undertaken by Meade (1985) and those recorded in the Brazilian Hydrometric Basic Network. The results from Meade (1985) show a tendency to yield a larger value of *Qss* for a given water discharge (*Q*), when compared with the corresponding values used in this study.

According to the instruction manual for operating the Brazilian Hydrometric Basic Network, the method utilized for sampling suspended sediment employs a depth-integrating sampler, with the sampling points within a given cross section of the river selected using the equal-width-increment method. Doubts necessarily remain as to how close this procedure has been followed by the various bodies contracted to operate the hydrometric network in the Amazon Basin.

Figure 2 presents one example of the measurement scheme implemented to collect data for the Óbidos station within the HiBAm (Hydrology and Geochemistry of

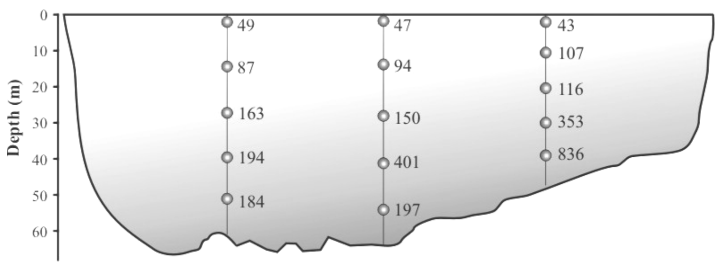

Fig. 2 The variation of suspended sediment concentrations (mg l^{-1}) within the cross-section of the Óbidos station on the Amazon River, 19 October 2001.

the Amazon Basin) project, using a point sampler, as described by Lima *et al*. (2003). In Fig. 2, there is clear evidence that sediment concentrations increase down the profile, indicating that if the samples were only collected close to the water surface, the total sediment discharge in this cross section would be underestimated. This emphasizes the importance of taking account of both vertical and lateral variations in sediment concentration within the river cross-section, when estimating the total suspended sediment flux of the river.

Araguaia-Tocantins River basin

Lima *et al*. (2003) have analysed all the sediment data recorded in the database maintained by ANA and have identified the main limitations of these data, not only in relation to the number of measurements, but also their quality. They used these data to establish the sediment fluxes in the Araguaia-Tocantins River Basin. The results of this work are presented in Fig. 3. These show that there is considerable deposition of sediment at the confluence of the Araguaia and Tocantins rivers, in the region known as “Bico do Papagaio”, and also in the reservoir of the Tucurui hydropower plant, near the mouth of the Tocantins River.

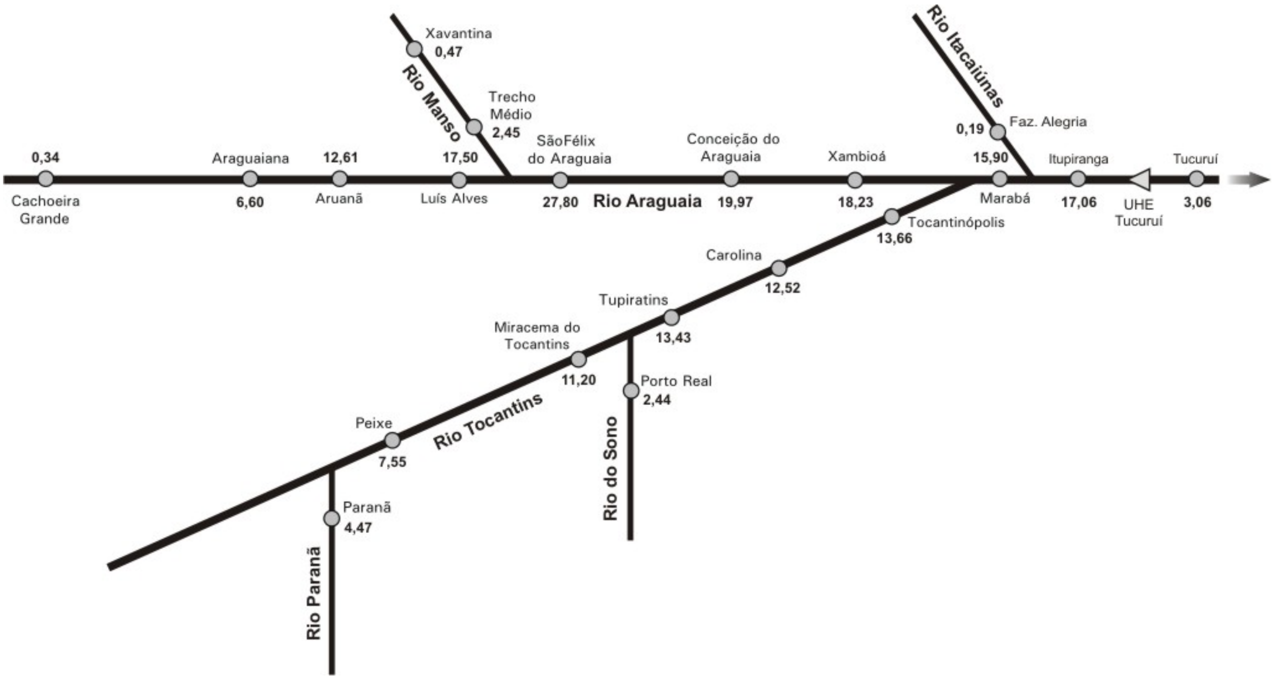

Fig. 3 The spatial distribution of the estimates of suspended sediment flux (10^6 t year^{-1}) obtained for measuring stations on the Araguaia-Tocantins Basin (Lima *et al*., 2003).

San Francisco River basin

There are several large dams along the San Francisco River, which have been constructed with the main objective of generating hydropower, and the resulting

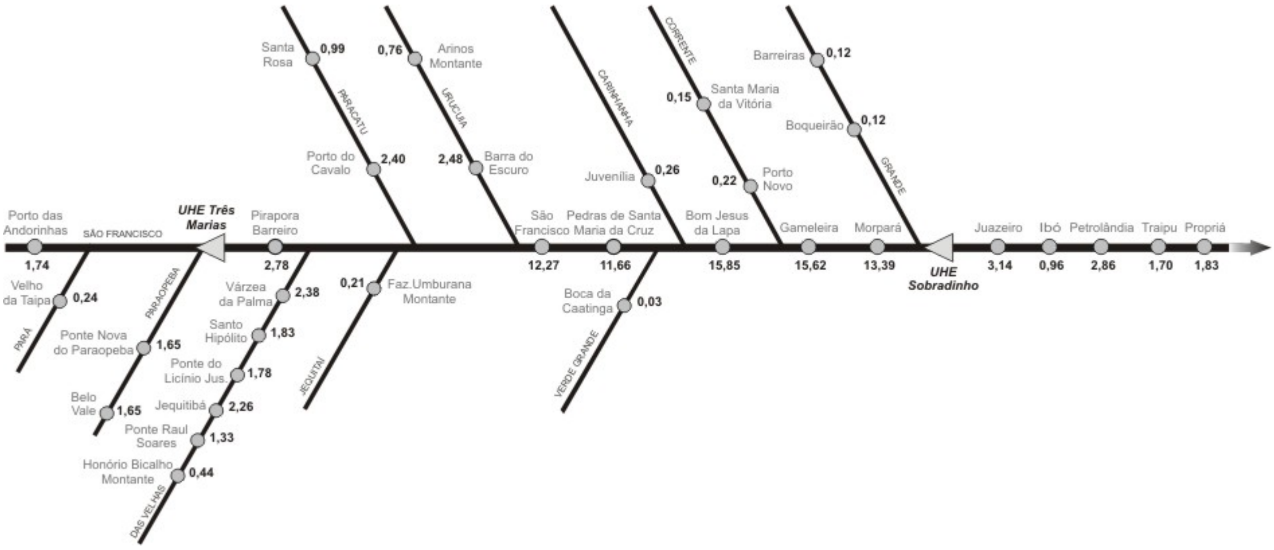

Fig. 4 The spatial distribution of the estimates of suspended sediment flux (10^6 t year^{-1}) obtained for stations on the San Francisco River (based on Lima *et al.*, 2001).

reservoirs have caused profound changes in the natural water and sediment flow regime. Lima *et al.* (2001) used the Hidro database to estimate the impacts of these reservoirs on the sediment discharge along the river, by applying a sediment mass balance approach (Fig. 4).

Lima *et al.* (2001) found that the largest concentrations of suspended sediments come from the tributary basins known as Paraopeba and das Velhas rivers, with an average value ranging between 250 and 1000 mg l^{-1}. In Fig. 4, only the hydroelectric power (UHE) reservoirs of Sobradinho and Três Marias are represented. However, downstream of the Sobradinho Dam, there are also four other large dams, all of which affect the flux of sediments along the river.

The data presented in Fig. 4 show that the Sobradinho dam reduces the suspended sediment flux from 13.39×10^6 t year^{-1} to 3.14×10^6 t year^{-1}. Other relevant information derived from this study include the fact that the amount of suspended sediment that reaches the mouth of the São Francisco River is quite small, around 1.83×10^6 t year^{-1}, with an average water discharge of 2200 m^3 s^{-1} and a mean daily suspended sediment concentration of only 25 mg l^{-1}. It is expected that this clean water discharge to the ocean may produce environmental problems related to the stability of this river estuary.

Paraná River basin

This Brazilian river basin is highly affected by a wide range of human activities. The presence of large cities, the intensive agricultural land use, the several existing reservoirs found along this river, and its principal tributaries make this basin an important laboratory for studying sediment loads. The Paraná River basin constitutes the portion of the Prata River basin located in Brazil. The river then passes through other South American countries to reach its estuary, which discharges into the Atlantic Ocean. In this study, the suspended sediment flux across the Brazilian border to the

Prata River was estimated. The amount of suspended sediment generated within the Brazilian portion of this river basin is about 10.50×10^6 t $year^{-1}$, but it is important to note that a large proportion of this load is trapped by the Itaipu dam.

Paraguay River basin

It should be emphasized that in Table 1, only the data from the Cáceres station were analysed to estimate the suspended sediment flux from this basin. The amount of data available in the Hidro database for the Porto Murtinho and Porto Conceição stations is insufficient for meaningful analysis. There are several tributary rivers in the upper reaches of this basin that are characterized by high suspended sediment concentrations. After reaching the Pantanal region, which has a low natural slope, the flow velocities are reduced and significant flooding occurs for a relatively long period during the year. As a result, there is considerable deposition of sediment, clogging the river's course (Oliveira & Calheiros, 2002).

Parnaíba River basin

According to the results presented in Table 1, the suspended sediment flux at the lowest monitoring station on the Parnaíba River is approximately 6.06×10^6 t $year^{-1}$. However, it should be recognized that there is a region of intense sediment deposition further downstream close to the ocean, in the area known as the "Delta do Parnaíba".

Uruguay River basin

The suspended-sediment flux at the lowest measuring station on the Uruguay River, which is a tributary of the Prata Basin, was estimated to be 3.59×10^6 t $year^{-1}$.

Doce River basin

Even though this basin does not have a drainage area as large as that of the other rivers included in this study, it is well known for its high sediment load, which causes problems for the hydropower plants constructed along the river. The high suspended sediment concentrations associated with the main monitoring stations (see Table 1) result in a total sediment load at the basin outlet of 11.22×10^6 t $year^{-1}$, which is considerably greater than those of other larger basins.

Paraíba do Sul River basin

Covering parts of the most developed states of Brazil, such as São Paulo, Rio de Janeiro, and Minas Gerais, the Paraíba do Sul basin has been impacted by the intense human

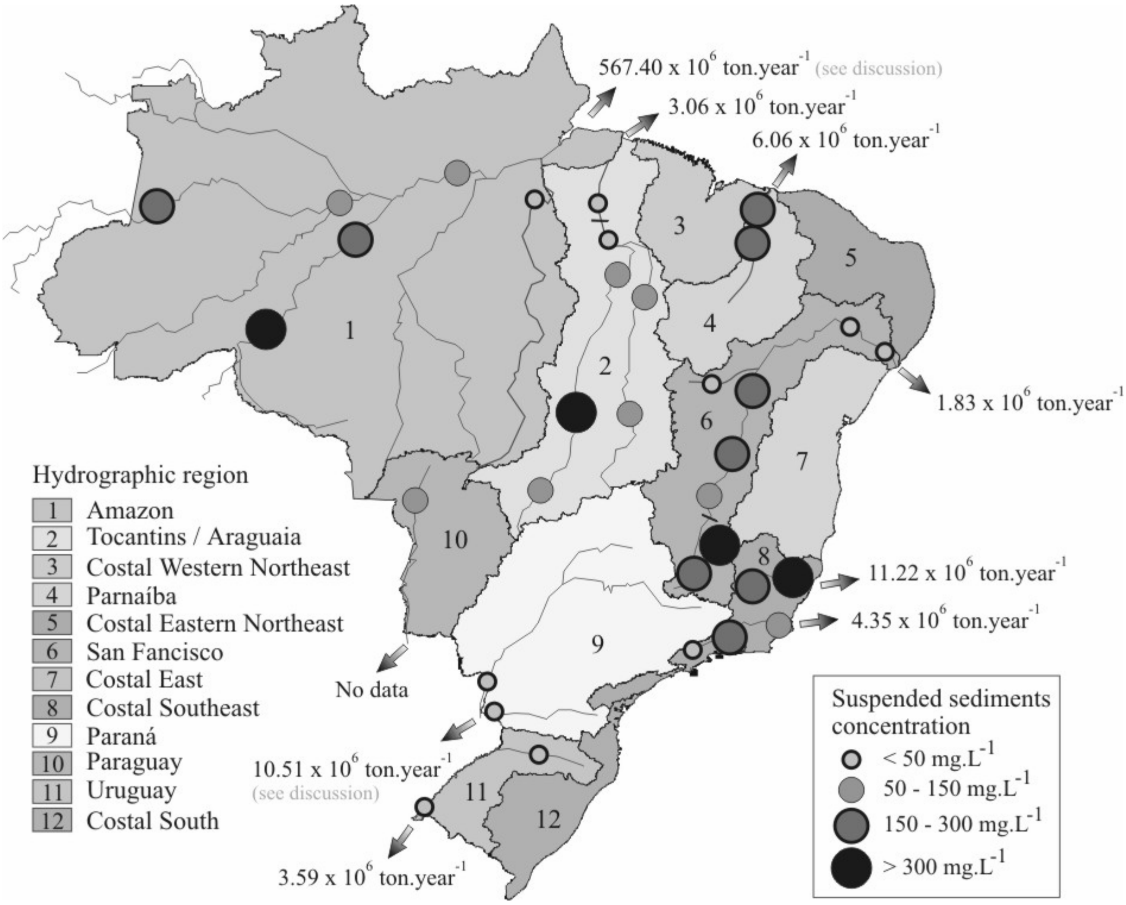

Fig. 5 A summary of the sediment flux data obtained for the main river basins of Brazil.

activity along its course, including the presence of several cities, industries, agricultural projects and various dams. All of these have exerted an important influence on the flux of suspended sediment from the basin. The data presented in Table 1 indicate that the sediment flux at the lowest measuring station at Campos-Ponte Municipal is approximately 4.35×10^6 t year^{-1}, a value quite close to the 4.40×10^6 t year^{-1} reported by Hora (1998).

Suspended sediment fluxes in Brazil

Figure 5 presents a schematic representation of the sediment fluxes at the mouths of the Brazilian rivers included in this study and the magnitude of the sediment concentrations found along their courses. By summing the suspended sediment fluxes for the individual river basins, the total suspended sediment flux from the territory of Brazil is estimated to be about 610×10^6 t year^{-1}.

CONCLUSIONS

As identified in this contribution, there is still considerable divergence between the available estimates of the suspended sediment flux from the Amazon Basin. The difference between the individual estimates is as much as twofold. While some studies have reported estimates of approx. 600×10^6 t year^{-1}, others have produced values as high as 1200×10^6 t year^{-1}, indicating the necessity to undertake further data collection in the Amazon basin, in order to refine these estimates.

With the exception of the data presented for the São Francisco and Araguaia-Tocantins basins that were recently analysed in an integrated form, all the other sediment load estimates presented in Table 1 should be viewed as preliminary and requiring further refinement.

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