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ASSESSMENT OF WASH LOAD TRANSPORT IN THE ARAGUAIA RIVER (ARUANÃ GAUGE STATION), CENTRAL BRAZIL

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Abstract: With an area close to 377,000 km^2 and a mean annual discharge of ~ 6,420 m^3 s^{-1} the Araguaia River is the main river draining the central highlands of Brazil. The Araguaia Rivers is a particularly sandy anabranching system that has been suffering geomorphologic and sedimentary changes because of the effect of high rates of deforestation during the last decades. Little is known, however, on the amount of wash load transport. We will present the first relatively systematic results on wash load transport for the Araguaia River at the Aruanã gauge station. The drainage area at Aruanã is 77,000 km^2 and the mean annual discharge is ~1,200 m^3 s^{-1}. A total of 140 samples from 20 field surveys were analyzed and the wash load transport was estimated. We calculated that from 2001-2007 the average annual transport oscillated between 8 Mt yr^{-1} and 6 Mt yr^{-1}. An interesting aspect that makes the Araguaia unique when compared to other large alluvial rivers of Brazil is the relation between sandy load and wash load. The Araguaia at Aruanã carries up to ~57% of the total sediment load as sandy load. We can now conclude that wash load just represents near 43 to 49% of the total sediment load in this system. Our results demonstrate that previous works overestimated the total wash load transported by the Araguaia. Taking into account that these are the first systematic results on wash load transport in the Araguaia, proposed human interventions in this system affecting sediment flows such as dams can be extremely harmful for the fluvial system. A more systematic analysis of sediment transport and an integrated and multidisciplinary plan of basin management must be done so that the detrimental effects of these human interventions will be understood.

Resumen: Con un área de drenaje de ~377.000 km^2 y un caudal medio anual de ~ 6.420 m^3 s^{-1} el Río Araguaia es el principal río que drena el Brasil Central y el Bioma Cerrado. El Rio Araguaia es un sistema anabranching de tipo arenoso que ha sufrido importantes cambios geomorfológicos y sedimentológicos como consecuencia de las altas tasas de deforestación sufridas por su cuenca durante las últimas décadas. Sin embargo, poco se conoce sobre el transporte de sedimentos de lavado (limo y arcilla) en este sistema. Aquí se presentan los primeros datos sistemáticos de la carga de lavado del Río Araguaia en la estación hidrométrica Aruaná. Se colectaron y analizaron en total 140 muestras obtenidas en 20 trabajos de campo. Se estimó que el transporte de sedimentos de lavado entre 2001 y 2007 osciló entre aproximadamente 8 Mt año^{-1} y 6 Mt año^{-1}. Un aspecto interesante que hace del Araguaia un sistema particular cuando comparado a otros grandes sistemas aluviales de Brasil, es que la relación entre la carga de lavado y la carga arenosa o carga "de fondo" (bedload) es muy alta. El Araguaia transporta hasta 57% del total de sedimentos como carga arenosa y la carga de sedimentos de lavado representa

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entre 43 y 49% de la carga total del sistema. Nuestros resultados muestran que trabajos previos sobrestimaron el total de carga de lavado transportado por el Araguaia. Teniendo en cuenta que estos son los primeros resultados sistemáticos sobre carga de lavado, consideramos que las intervenciones humanas/ingenieriles propuestas en el Araguaia, en particular las represas, pueden ser extremamente perjudiciales para el sistema. Un análisis más sistemático de transporte de sedimentos y un plan integrado multidisciplinar de manejo son fundamentales para estimar y entender la verdadera dimensión del daño que esas obras pueden generar en el ambiente.

Keywords: wash load, deforestation, sediment transport, Araguaia, Central Brazil.
Palabras clave: sedimentos de lavado, deforestación, transporte de sedimentos, Araguaia, Brasil central.

INTRODUCTION

The Araguaia-Tocantins fluvial basin is relatively poorly known when compared to the major fluvial systems such as the Amazon, the Paraná and other rivers such as the São Francisco, which is frequently mentioned in the international literature as a typical example of river with a wave dominated delta. However, spreading on near 780,000 km^2, the Araguaia-Tocantins basin is the fourth largest basin of South America (Latrubesse and Stevaux, 2002) and the 13th largest tropical river of the world (Latrubesse *et al.*, 2005). The basin is formed by two major rivers: the Tocantins and the Araguaia. Although the Araguaia is considered from the cartographic point of view to be a tributary of the Tocantins, it is geomorphologically and hydrologically the main system of the Tocantins basin.

With an area close to 377,000 km^2 and a mean annual discharge of ~6,420 m^3 s^{-1} the Araguaia River is the main river draining the central highlands of Brazil. The basin is covered by the Brazilian savanna (Cerrado), with a small part of the lower basin being within the Amazon rainforest. The annual precipitation varies between 1,300 mm in the upper basin, rising to more than 2,000 mm in the lower. The degradation of the Cerrado and their water resources by deforestation and land use changes has been significantly larger than those on the tropical rainforest. From the original 2,000,000 km^2 of Cerrado, more than 50% has been converted and fragmented by deforestation and expansion of the agriculture frontier (Klink and Machado, 2005; Sano *et al.*, 2008). No other biome in the world has been destroyed so quickly and thoroughly in human history.

The Araguaia River was not separated from this dramatic environmental reality. From the 120,000 km^2 watershed of the upper and middle Araguaia basin, located mainly in the Goias state, only 38.5% of the basin is still preserved, while the other 61.5% present some kind of environmental disturbance and approximately 44% of the area covered by riparian vegetation is already unprotected (Ferreira *et al.*, 2008).

The Araguaia suffered strong geomorphologic and sedimentary changes during the last decades and has been considered the most spectacular example in human history of geomorphologic and sedimentary response of a large river, free of engineering, due to extreme deforestation (Latrubesse *et al.*, 2009). It was estimated that more than 230 Mt of sediments, mainly sandy materials, were stored along the floodplain since the 1970's (Latrubesse *et al.*, 2009) along a 570 km length reach of the channel-floodplain area in the Middle Araguaia.

The Araguaia is a very unusual system that carries a huge amount of sandy sediments. Estimation of sandy sediment transport was assessed in the middle Araguaia, exactly at the Aruanã gauge station reach (Fig. 1). Nevertheless remarkable advances were obtained on the themes mentioned above, but the information on wash load transport is still poorly understood. For that reason, our main objective is to present new information on wash load sediment transport in the Araguaia River. Wash load and suspended load have different meaning for engineers and geomorphologists but both refer to the transport of fine sediments (silt and clay). In this study we will use indistinctively the terms wash load and suspended load as synonymous, representing fine sediment transport.

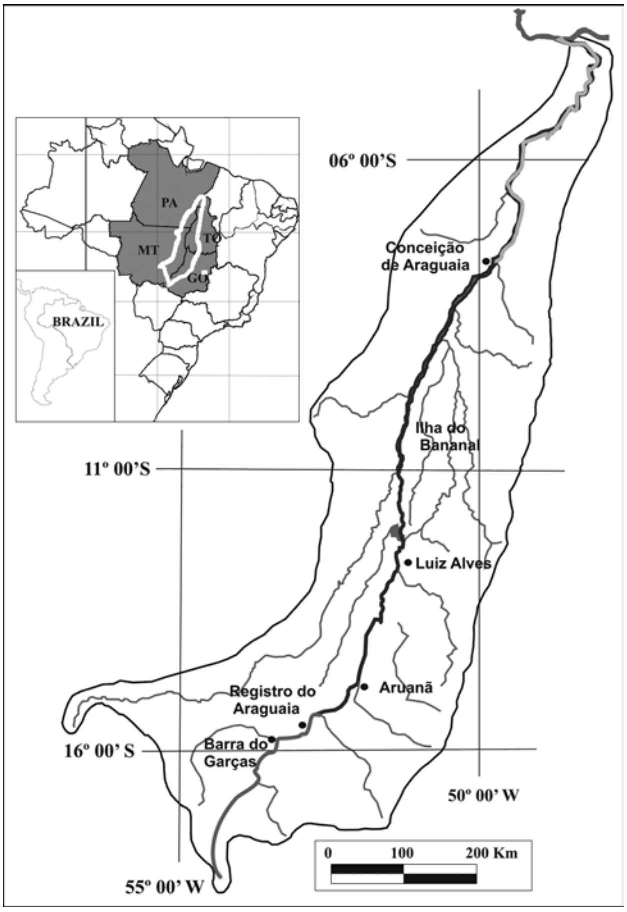

Figure 1. Location of the study area.

middle course increasing significantly the drainage area up to 320,290 km^2 draining dominantly Precambrian rocks and Tertiary-Quaternary deposits of the Bananal plain.

The lower Araguaia starts downstream of the Bananal plain, close to Conceição do Araguaia. The river flows for 500 km up to its confluence with the Tocantins (Fig. 1) dominantly on an area of crystalline Precambrian rocks where the alluvial plain practically disappears.

This study concentrates on the Aruanã gauge station which is located in the middle Araguaia basin. Drainage area at Aruanã is 77,700 km^2 and the mean annual discharge is ~1,200 m^3 s^{-1}. Several factors make the Aruanã gauge station an interesting point of control and monitoring. There is available through the gauging station a good record of stages and discharges, as well as the drainage area at this point collecting all the runoff produced by the Upper basin and by the upper reach tributaries of the middle basin coming from the east side (Goiás State territory). The sediment input is relatively representative from the amount of sediment coming from the upper basin and transported across the initial reaches of the middle basin where the alluvial plane starts to develop.

STUDY AREA

The Araguaia River has been divided in three units: upper, middle and lower Araguaia (Latrubesse and Stevaux, 2002). The upper Araguaia extends from the source to Registro do Araguaia along 450 km draining an area of 36,400 km^2 (Fig.1). The geology of the upper basin is mainly composed of Paleozoic, Mesozoic and Precambrian rocks. This is a hilly area that rises up to 1,000 m a.s.l. Paleozoic and Mesozoic sedimentary and basaltic rocks form a table landscape. The river flows through a V-shaped valley, controlled by lithologic and structural Precambrian lineaments.

The middle course, extending from Registro do Araguaia to Conceição do Araguaia through 1,160 km (Fig. 1), is characterized by having a well developed alluvial plain. The middle Araguaia is a low sinuosity anabranching river with a tendency towards braiding (Latrubesse, 2008). Single meanders are scarce and are just present in a few reaches. Major tributaries such as the das Mortes River, Vermelho River, Crixas and others tributaries joint the Araguaia in the

METHODS

The Aruanã gauge station started to operate in October 1969. The historical temporal series of discharges is available at the ANA (Brazilian National Water of Agency) data base. The data are collected by the Geological Survey of Brazil (CPRM) and transferred to ANA. The gauge station is located on the right bank of the Araguaia River, approximately one kilometer downstream the confluence with the Vermelho River. In general terms the historical record is complete. The only interruptions of the record happened from March to May 1970 because the ruler was destroyed by bank erosion. The geological survey considers that the discharge data are reliable and the station works well telemetrically.

Field work and samples collection has gone on continuously since 2001 and samples are still being collected. The results, however, concentrate on the period 2000-2007 because hydrological data are not available yet from ANA for the years 2008 and 2009.

Suspended sediment sampling was carried out by boat along the transverse section of the gauge station using a Van Door bottle in at least three verticals (right, middle and left side of the channel) with two samples each to 20 and 60% depth and 3 samples in the deepest part. The samples were stored and duplicated in one-liter plastic bottles and stored in a refrigerated environment to avoid algae development. The CPRM makes in the gauge station four field surveys per year to measure discharge and the transverse section. Occasionally during sampling field work, we additionally surveyed some transverse sections with a Furuno echo-sound GP 1560-F/DF (50-200 kHz) coupled to a GPS and measured discharge with an acoustic doppler current profiler (ADCP Rio Grande of 600 kHz). The bathymetric data were processed in the Fugawy software and transferred for processing to a Surfer software environment. When comparing similar daily records, the discharge measurements that were obtained with ADCP are in agreement with the discharge estimations obtained by the CPRM.

Concentrations of fine sediments were produced in the laboratory by filtration of a determined amount of water (250 ml) with a vacuum pump in a Millipore filter system (Pore size = 45μ and diameter of 47 mm) and weighting the mass of sediment retained by the filters. A total of 140 samples from 20 field surveys were analyzed.

In addition there were also included in the record two sets of suspended concentration data from field sampling from the Geological Survey of Brazil-ANA.

The bed sediments were sampled with a modified Petersen dredge and conic samplers. Twenty samples were processed by sieving and using a Mastersizer 2000 particle size analyzer.

RESULTS

The hydrological regime of the Araguaia is that of a savanna environment with high discharges during the rainy season and lower discharges during the dry season (Fig. 2). The mean annual discharge (Q_{mean}) is approximately 1,200 m^3 s^{-1}. The transverse section of the Araguaia's channel at Aruanã gauge station is shown in figure 3. The mean channel width is ~360 m, the mean depth at mean annual discharge is 4.3 m, the width/depth ratio (w/d) at bankfull stage is 64, the slope at the same stage was estimated in 15 cm km^{-1}, and the specific stream power in 12.3 W m^{-2}. The mean grain size for each reach is presented in figure 2. The bed is formed by coarse and medium sand.

The collected suspended sediment data spread on a variety of discharges from lower to higher (Fig. 2). Recorded concentrations of wash load (C_{ss}) vary from a minimum of 21.7 mg l^{-1} to a maximum of 181.4 mg l^{-1}.

The total wash load transport for each day was also estimated applying the equation:

$$Q_{ss} = 0{,}0864 \times Q_{md} \times C_{ss} = (t\ d^{-1}) \quad (1)$$

where, Q_{md} = mean daily water discharge in m^3 s^{-1}, C_{ss} = suspended sediment (wash load) concentration in mg l^{-1}, and 0.0864 = a constant derived from time and mass unit conversions. The mean daily wash load transport at Aruanã for each sampling date is presented in table 1. The daily wash load transport oscillated for the recorded data between 697 t d^{-1} to 22,042 t d^{-1} (Table 1).

Table 2 shows the transport of sediments obtained from the four concentration values provided by ANA-CPRM Goias.

Annual Transport:

We calculate the rating curve of wash load correlating mean daily discharge (Qmd) and wash load concentration (C_{ss}) (Fig. 4). After that, we estimated the main daily transport in tons per day.

Where

$$C_{ss} = 0.0939\ Q_{md}^{1{,}0194} \quad (2)$$

Applying eq. (2) to the hydrological historical record it is possible to estimate the annual transport of wash load at Aruanã gauge station (Table 3).

However, suspended sediment concentration (Css) is higher during rising stage through the rainy season than during falling stages (through the dry season) showing a clock loop hysteresis. To improve the differentiation between both periods, two curves were plotted being for rising and dropping stages respectively.

$$C_{ss} = 0.6256 Q_{md}^{0.7714} \quad (3)$$

for rising stage and

$$C_{ss} = 0.1227 Q_{md}^{0.9461} \quad (4)$$

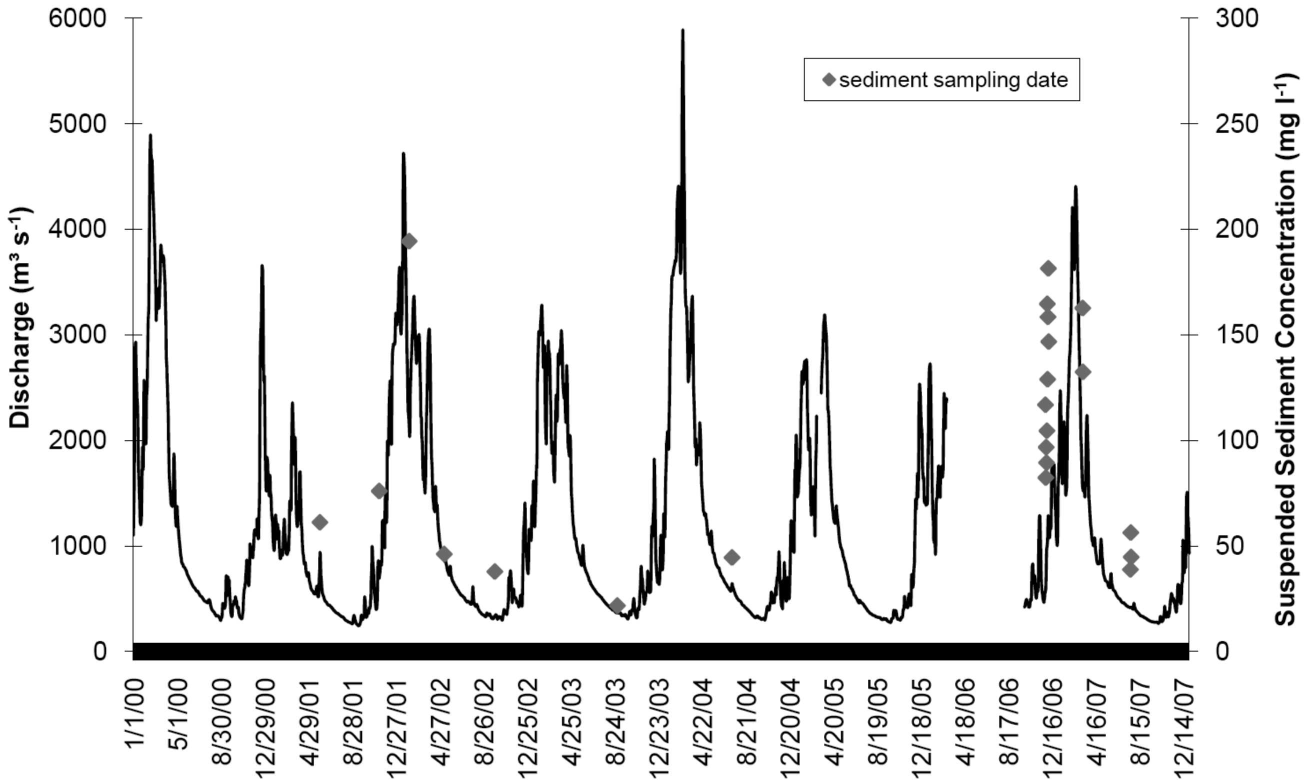

Figure 2. Daily hydrograph at Aruanã gauge station and date of wash load sampling. Triangles indicates the values of suspended sediment (wash load) concentration.

for dropping stage (Fig. 5).

Total daily wash load sediment transport was calculated applying eq. (3) and eq. (4), and with each daily transport value we obtained the annual wash load transport (Table 3, RFF).

Although both methods seem to be appropriate, there is a substantial difference when applying both equations. Equation (2) estimated a higher transport with an average for the period 2001-2007 of 7.3 Mt yr^{-1} while the combined eq. 3 and 4 provided a mean annual transport of 6.2 Mt yr^{-1} (Table 3). Although results from eq. (3+4) looks more realistic, we have

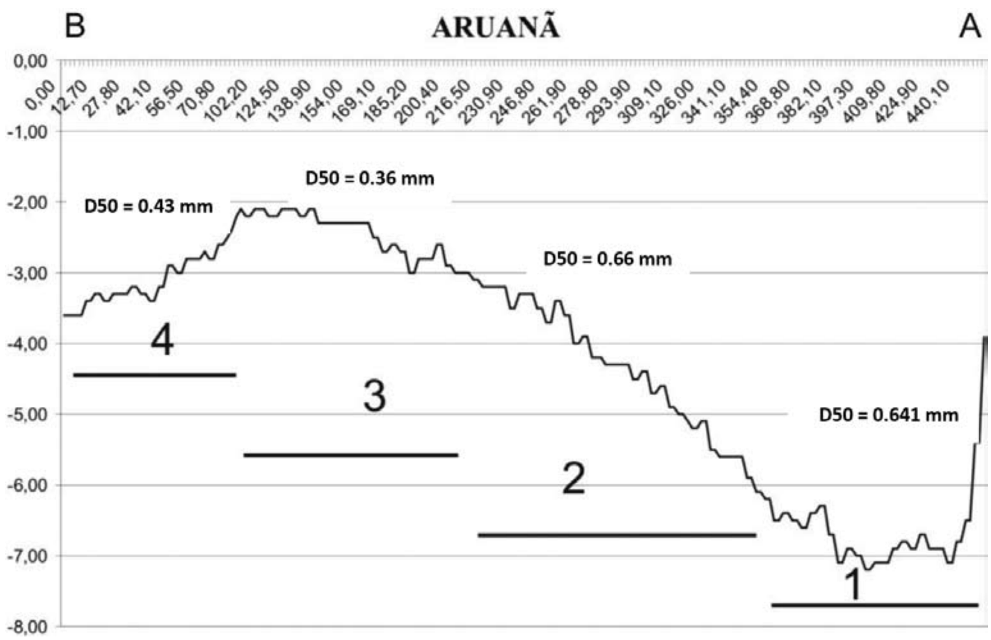

Figure 3. Mean bed grain size (D50) through the Aruanã gauge station transverse section. The transverse section was sampled and divided in four reaches. A= right bank, B= left bank. Horizontal distances and depth are in meters.

Date	Q_{md} Daily discharge ($m^3 s^{-1}$)	Raising Flow Wash load concentration ($mg l^{-1}$)	Falling Flow Wash load concentration ($mg l^{-1}$)	Q_{ssd} Daily sediment transport (t)
31/05/2001	941		61.1	4,972
11/11/2001	692	75.9		4,541
10/05/2002	794		46.2	3,167
01/09/2003	371		21.7	697
14/07/2004	642		44.5	2,468
28/11/2006	557	116.8		5,621
29/11/2006	589	82.3		4,188
30/11/2006	703	96.7		5,873
01/12/2006	877	89.4		6,774
02/12/2006	970	104.5		8,758
03/12/2006	1,014	164.6		14,421
04/12/2006	1,048	128.9		11,672
05/12/2006	1,186	158.4		16,231
06/12/2006	1,288	181.4		20,187
07/12/2006	1,206		146.7	15,286
11/03/2007	1,569		162.6	22,042
12/03/2007	1,530		132.4	17,498
21/07/2007	413		38.8	1,385
22/07/2007	416		56.3	2,024
23/07/2007	420		44.7	1,622

Table 1. Wash load sediment concentration (C_{ss}) and daily wash load transport (Q_{ssd}) at Aruanã gauge station.

not enough data from flood discharges to identify with precision the depletion between sediments and discharge.

DISCUSSION

The wash load transport in the Araguaia-Tocantins basin was estimated by Werneck Lima *et al.* (2003) for the Brazilian National Agency of Water-ANA. The scarcity and the sporadic nature of the data, however, were a problem faced by those authors. At Aruanã gauge stations, for example, Werneck Lima *et al.* (2003) mentioned that just four mean daily concentration data samples were used to estimate the transport rating curve. The equation of the sediment rating curve proposed by Werneck Lima *et al.* (2003) is a power function that relates in a direct way discharge and wash load transport.

$$Q_{ss} = 0.0123 Q_{md}^{2.017} \text{ and, } R^2 = 0.9946 \quad (5)$$

Date	Q_{md} Daily discharge ($m^3 s^{-1}$)	Raising Flow Wash load concentration ($mg l^{-1}$)	Falling Flow Wash load concentration ($mg l^{-1}$)	Q_{ssd} Daily sediment transport (t)
02/02/2002	2,103	194.2		35,302
27/09/2002	333		37.8	1,088

Table 2. Wash load sediment concentration (C_{ss}) data from ANA and daily wash load transport (Q_{ssd}) at Aruanã gauge station.

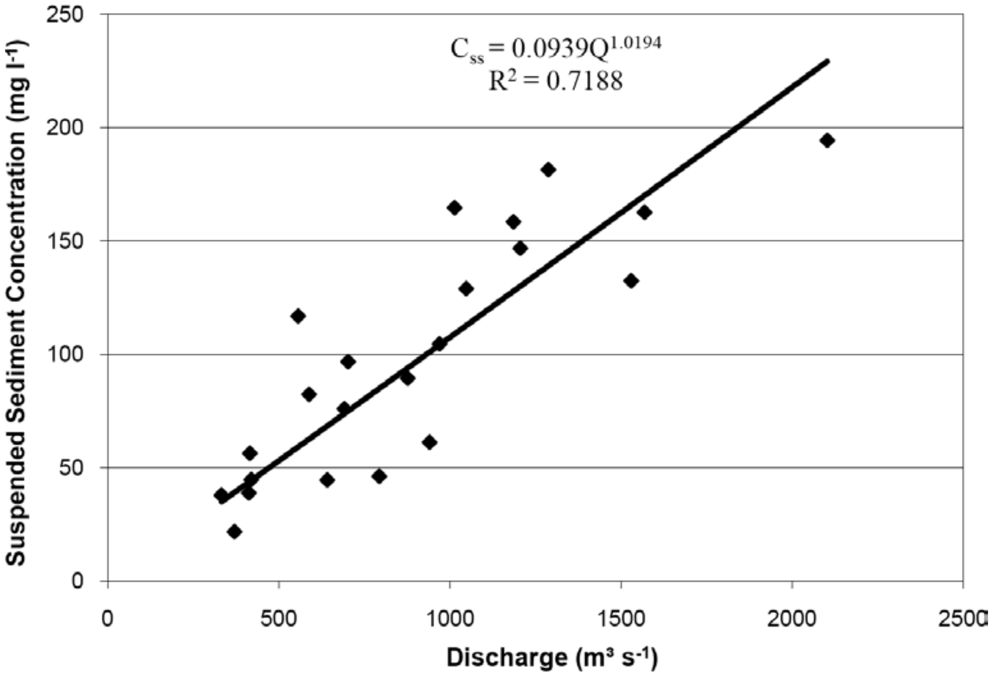

Figure 4. Relation between wash load concentration of sediments and water discharge (mean daily discharge- Q_{md}) -eq. (2)-, at Aruanã gauge station.

They remark that they found some inconsistencies correlating discharge and concentration. Werneck Lima *et al.* (2003) calculated sediment transport by using mean monthly discharges, as opposed to this research that used the mean daily discharges. They do not mention the day of the data collection and for that reason it was not possible to identify when the samples were collected. For the period 1981-1998 Werneck Lima *et al.* (2003) estimated that the annual average wash load transport (Q_{ss}) at Aruanã gauge station was 12.6 Mt yr^{-1} while our results indicate a range of wash load transport from 6.2 to 7.3 Mt yr^{-1}.

Werneck Lima *et al.* (2003) considered a mean annual water discharge of 1,258 m^3 s^{-1}, and a mean daily wash load transport Q_{ssd} = 34,555 t d^{-1} estimating a mean concentration of 310 mg l^{-1}. The largest transport was recorded from January to March and minimum transport was recorded from August to October. Although they classified the Araguaia basin as a basin with "moderate" transport, they mention as well that the Araguaia basin at Aruanã gauge station should be classified as "high" transport

Year	Q_m Mean Annual Discharge (m^3 s^{-1})	Annual wash load transport Eq. (2) (t)	Raising Flows Eq. (3) (t)	Percent %	Falling Flows Eq. (4) (t)	Percent %	Annual wash load transport. Raising (Eq. 3) + Falling (Eq. 4) (total wash load transport) = RFF (t)	Difference between RFF and Eq. (2) (%)
2001	915	4,436,040	2,248,461	57.30	1,675,508	42.70	3,923,969	<11.54
2002	1,189	8,877,306	2,314,512	33.03	4,692,263	66.97	7,006,775	<21.07
2003	1,150	7,173,534	2,102,934	35.60	3,804,253	64.40	5,907,187	<17.65
2004	1,315	11,219,959	5,614,046	60.87	3,609,475	39.13	9,223,521	<17.79
2005	1,060	5,952,221	4,205,731	75.90	1,335,297	24.10	5,541,028	<6.91
2006	1,207	DNA	1,377,711	DNA	DNA	DNA	DNA	DNA
2007	1,010	6,664,392	3,620,370	63.15	2,112,697	36.85	5,733,067	<13.97
Average	1,121	7,387,242	3,069,109	54.31	2,871,582	45.69	6,222,591	<14.82

Table 3. Annual wash load transport (Q_{ss}) at Aruanã. Results from eq. (2) and eq. (3+4). (DNA= no data available).

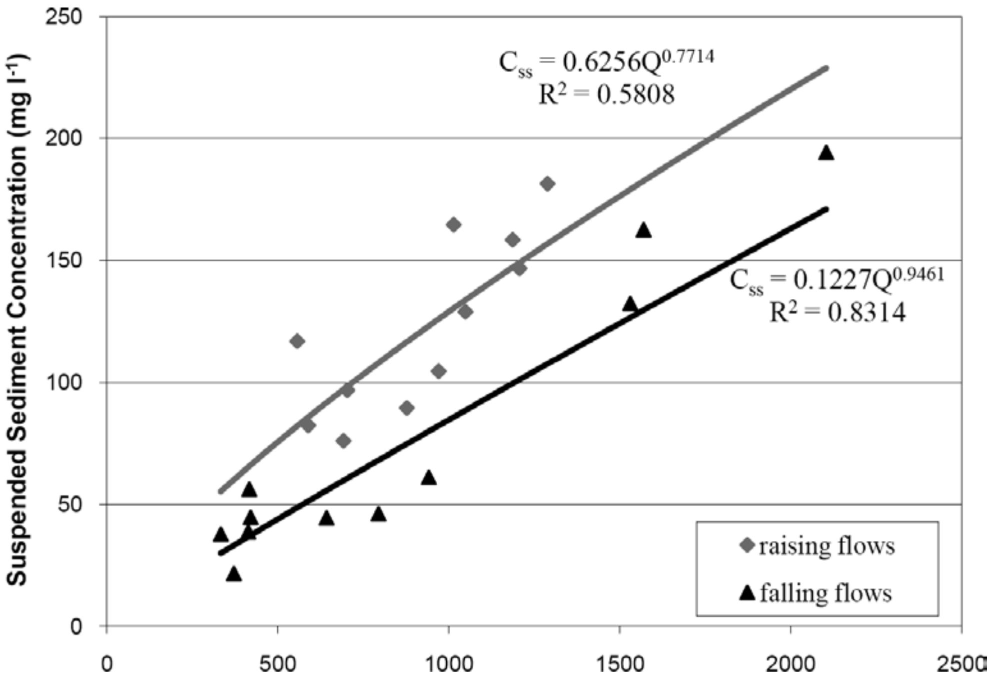

Figure 5. Relation of wash load concentration and mean daily discharge (Qmd) for rising and falling stages -eq. (3) and (4)- at Aruanã gauge station.

because their estimations of a yield of 164 t km yr^{-1}.

Several problems are detected when analyzing the data by Werneck Lima *et al.* (2003). First of all, the data obtained for our study through several years of field work never reached values of suspended sediment concentration higher than 185 mg l^{-1}. The data available at the data base of ANA are, as well, not higher than 195 mg l^{-1}. In general the samples collected for us during high discharges show values oscillating typically between 100 and 200 mg l^{-1}. During lower river stages the concentration of suspended sediments, drop significantly to values as low as ~20-60 mg l^{-1} from May to September (Table 1).

We conclude that a suspended sediment mean annual concentration of 310 mg l^{-1} in the Araguaia at Aruanã gauge station as proposed by Werneck Lima *et al.* (2003) is incorrect and unrealistic because the typical suspended sediment concentrations values in the system range from 20 to near 200 mg l^{-1} (Table 1).

The average transport for the period 2000-2007 obtained in this study was 7.3 Mt yr^{-1} for eq. (2) and 6.7 Mt yr^{-1} for eq. (3) and (4). Our calculations demonstrate that, when the mean annual sediment transport of the Araguaia River at Aruanã station is near 42% less than that estimated by Werneck Lima *et al.* (2003),when we use eq. (2) and 50% less when we apply eq. (3) and (4).

We are not able to discuss at some level of confidence the transport before our recorded period that time in particular because the Araguaia River had been suffering deep impacts affecting bed load transport since 1970's and the effects of deforestation on the suspended load transport still unknown. From the 1970's to the 1980's a strong increase in bed load sandy transport was suffered by the Araguaia River as consequence of extreme rates of deforestation (Latrubesse *et al.*, 2009). At Aruanã gauge station the transport of sand increased from 1970's to 1980's from 6.6 to 8.5 Mt yr^{-1} remaining stable at near 8.6 Mt during the 1990's and 2000's (Latrubesse *et al.*, 2009). It is possible that because of land uses changes, the transport of wash load also increased by some amount. The available data from ANA from 1970's to the 2000's are too scarce to allow the identification of sediment transport changes and trends or for applying our equations to the data.

An interesting aspect that makes the Araguaia unique when compared to other large alluvial rivers of Brazil is the relation between sandy load and wash load. For example, the Paraná River in Brazil and Argentina carry near 18% to 25% of the total sediment load as sandy load (Amsler and Prendes, 2000, Orfeo and Stevaux, 2002, Ramonell *et al.*, 2000, 2002). A good part of the Amazonian rivers such as the Solimões-Amazonas, Madeira, Japura, Purus and Jurua rivers transport less than 5% of sandy load and more than 95% of wash load (Latrubesse, 2008). The Araguaia is different than the rivers above because it transports just ~55 to 43% of the total load as wash load and carries an extremely abundant sandy load (up to ~57% of the total sediment load). From the total sand, more than 80% enters in temporary and episodic suspension while ~10% moves as typical bed load with sandy dunes moving up to a velocity of 7 to 10 m d^{-1} (Latrubesse *et al.*, 2009).

The Middle Araguaia floodplain sustains a rich mosaic of aquatic ecosystems and alluvial vegetation of high diversity (Latrubesse and Stevaux, 2006, Prado *et al.*, 2008). The importance of the floodplain and its lakes in the mechanisms of water saturation and flood transmission have been considered a main element in sustaining the high diversity of aquatic environments (Prado *et al.*, 2005, Aquino *et al.*, 2008). Fine sediments provide nutrients to the floodplain, favoring the development of alluvial soils and sustaining biodiversity in tropical environments. Although fine sediments are a main environmental component, the role of wash load and the geomorphic mechanisms of transferences/distribution and rates of sedimentation of wash load from the channel to the floodplain in the Araguaia had been not yet estimated.

CONCLUSIONS AND RECOMMENDATIONS

The Araguaia Rivers at Aruanã is an unusual anabranching system that carries up to ~57% of the total sediment load as sandy load. Now it can be concluded that wash load just represents in average near 43 to 49% of the total sediment load in this system. The results demonstrate that previous works overestimated the transport of wash load in the Araguaia.

Nevertheless, the Araguaia suffered tremendous impact by deforestation since the 1970's, increasing the transport of the sandy bed load (Latrubesse *et al.*, 2009). It is not possible, with the available information, to estimate changes or trends in wash load (clay and silt) transport during the last decades. The Araguaia is an endangered system, and waterways and dam construction are planned or proposed by some governmental organizations such as the Ministry of Transport and Ministry of Energy. Others such as the Goias State Environmental Agency and the Ministry of the Environment-IBAMA claim that the basin is one of the last environmental frontiers of the Cerrado that deserve preservation and implementation of sustainable policies and uses (Latrubesse and Stevaux, 2002). The Araguaia floodplain sustains a complex and diverse mosaic of aquatic ecosystems and alluvial forest that are highly dependent of the relatively small amount of clayey-silty sediment load that is transferred from the channel to the floodplain environment.

While taking account that these are relatively early systematic results on wash load transport in the Araguaia, it should still be taken into consideration that human interventions in this system affecting sediment flows can be extremely dangerous and harmful for the fluvial system without a more systematic analysis of sediment transport and an integrated and multidisciplinary plan of basin management.

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