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# The Significance of Suspended Sediment Transport Determination on the Amazonian Hydrological Scenario

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## 1. Introduction

Rivers play an important role in continental erosion as they are the primary agents of transferring erosion products to the ocean. Understanding rivers and their transport pathways will improve the perception of many processes of global significance, such as biogeochemical cycling of pollutants and nutrients, atmospheric $CO_2$ drawdown, soil formation and their erosion, crust evolution- in short the interaction between the atmospheric and the lithospheric compartment of the Earth´s system (Allen, 2008). This interaction is characterised by the relative proportions of mechanical degradation vs. chemical weathering, whose products are, in dissolved or solid form, transported by rivers. The sediment load of rivers is thereby controlled by catchment relief, the channel slope and its connectivity to the hill slope, but also by climatic factors such as precipitation. The latter, together with temperature, exert control over chemical weathering that is dependent on physical erosion to a degree that is yet unknown (Anderson et al., 2002; Gaillardet et al., 1999; Riebe et al., 2001). Both mechanical erosion and chemical weathering, are, however, governed by tectonic activity, which drives processes of landscape rejuvenation and preconditions the fluvial transport regime (von Blanckenburg et al., 2004). On the shorter time scale, humans may act as geomorphic agents by constructing dams and reservoirs, and changing land use by deforestation and mining (Hooke, 2000; Syvitski et al., 2005; Wilkinson and McElroy, 2007).

In tropical regions around the globe, large river basins are especially concentrated, and their behaviour plays an important role in river sediment transport (Latrubesse et al., 2005). For example, the tropics represent 25% of the total continental lands and contain 57% of the world's fresh water, and associated catchments contribute 50% and 38% to solids and dissolved solid input into the oceans, respectively ( Milliman and Meade,1983, Guyot, 1993 and Latrubesse et al,2005). Large river basins often display mixed river channel forms, as they usually constitute a rapidly eroding sediment source area and an associated depositional area in the lowlands (Latrubesse et al., 2005). Among the highest erosion rates worldwide are found in mountainous areas of the tropics (Pinet & Souriau, 1988; Milliman & Syvitzki, 1992; Summerfield & Hulton, 1994), of which the Amazon basin is an excellent example. Here, most of the sediment that is transported in the main Amazon channel is derived from the Andes, but is also intermittently stored for at least several thousands of years in the floodplain (Meade, 2007). This chapter discuss some factors about suspended sediment transport determination and its importance into the Amazon Basin hydrological scenario. The text is divided in sections. After introduction, section 2 presents the Amazon basin and some topics concerning sediments and hydrology. Section 3 presents a brief review about the works done about Amazon River suspended sediment discharge into the Ocean. Section 4 shows the importance of the suspended sediment discharge values, into the Amazonian hydrological scenario, especially at central portion of the basin. Section 5 presents some information about new techniques contributions to study that scenario. Finally, Section 6 summarizes the chapter and concludes it with some comments about the use of suspended sediment data to help water resource management.

## 2. The Amazon Basin

The Amazon Basin (Figure 1) is the biggest river basin in the world. It has more than 6 million km$^2$ in area. This area corresponds to almost 5% of the total global continental land. This basin flows into the Atlantic Ocean at approximately 6.6 $10^{12}$ m$^3$ yr$^{-1}$, and this volume is approximately 16% of the world's fresh water (Molinier et al., 1995 and 1996). The Andean mountains take up around 12% of the Amazonian land. Most of the sediment transported by the region's rivers originates from these mountains as a result of rapid erosion processes (Sioli, 1950, 1964; Gibbs, 1967; Meade et al., 1985; Guyot et al., 1994; Filizola, 1999; Wittmann et al., 2011). The most important rivers, in terms of contributing sediment to the main river, are the Rio Solimoes (draining the Peruvian Andes and forming the main tributary of the Amazon in Brazil upstream of the Rio Negro confluence) and the Madeira River that drains in part the Andes, and in part the cratonic Brazilian Shields.

The Rio Amazonas crosses a huge flood plain surrounded by two pre-Cambrian shields (the Guiana shield to the north and the Brazilian shield to the south). Compared to the Rio Madeira and the main channel, rivers with their headwater sources in the shields and those that cross them do not contribute much to the Rio Amazonas in terms of transporting suspended sediment. The flood plain landscape is characterised by areas where deposition and re-suspension occur (Meade et al. 1985). Additionally, extreme climate events, such as El Niño/Southern Oscillation (ENSO), have been identified as important agents for landscape construction. As described by Aalto at al. (2003), episodic sediment accumulation on the Amazonian flood plains is influenced by ENSO. An important correlation was also established between sediment deposition and La Niña occurrences. With a very wet climate, the majority of the Amazon Basin receives 2400 mm yr$^{-1}$, with extremes that can vary from 100 mm yr$^{-1}$ to 6000 mm yr$^{-1}$. The Amazon Rain forest covers more than 70% of the basin area, but there are also small areas of tundra (high altitude), desert and savannah.

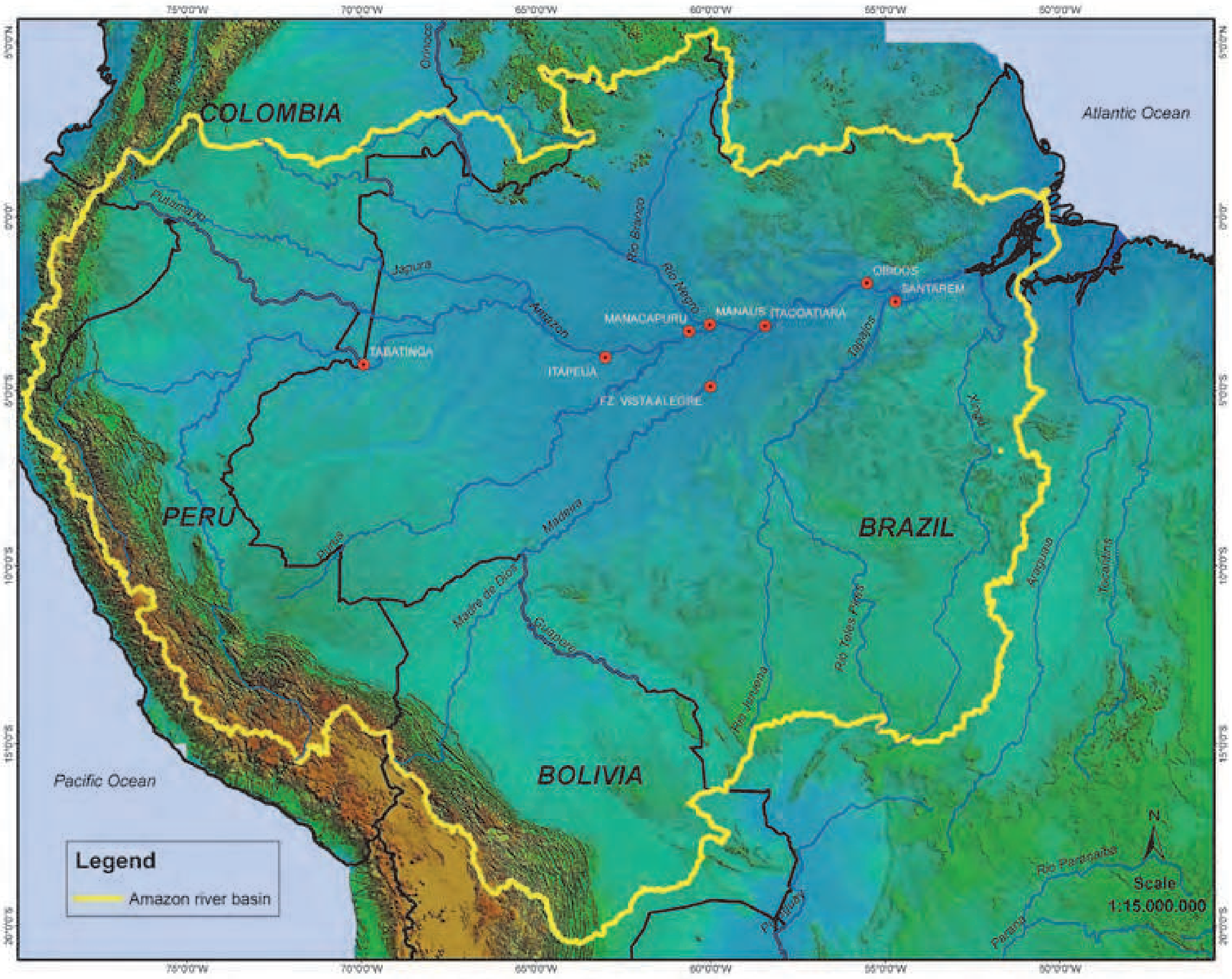

Fig. 1. The Amazon Basin with sites indicated in the text.

## 3. Amazon Basin suspended sediment discharge into the ocean, a brief review

Since the 1960s, the Amazon ecosystem had been an important subject for systematic science. Initial results, conclusions and also new scientific questions have emerged from those studies, which motivated the emergence of new research groups. Interdisciplinary themes were proposed, and important scientific publications summarised the advancement of this period of knowledge: *The Amazon* (Sioli, 1984); *Key Environments: Amazon* (Prance & Lovejoy, 1985); *Biogeography and Quaternary history in Tropical Americas* (Whitmore & Prance, 1987). The impact of those publications was observed as new environmental policies emerged for sustaining the Amazon region.

Concerning suspended sediment, Sioli (1950, 1957, 1984) classified Amazonian rivers based on their physical and chemical characteristics and partly based on the suspended solid concentrations. Gibbs (1967) investigated the factors that controlled the amount and composition of the suspended load found in the Amazon River. During high and low water periods, Gibbs collected a total of 74 samples. He estimated the Rio Amazonas suspended load to be approximately ~500 $10^6$ t $yr^{-1}$ or 79 t $km^{-2}$ $yr^{-1}$. Gibbs also demonstrated that 82% of the total suspended sediment load discharged by the Amazon comes from only 12% of the total area of the basin, which comprises the mountainous environment (the Andes).

For the Óbidos station (~800 km from the Rio Amazonas mouth), Oltman (1968) reported concentration variability from 300 to 340 mg $l^{-1}$ near the stream bed to 50-70 mg $l^{-1}$ near the water surface. He estimated, using a few data points, that the suspended sediment input from the Amazon River into the ocean was 1.5 $10^6$ t $day^{-1}$ or ~600 $10^6$ t $yr^{-1}$. Oltman also indicated the important influence of the black and white water rivers on the proportion of the total water flow contribution at Óbidos.

After that, Schmidt (1972) determined the annual variability of the suspended sediment concentrations. He only reported the suspended sediment concentration (SSC), and no estimations were made as to the suspended sediment discharge. Meade et al. (1979), in the course of the Alpha Helix Project, estimated a mean total suspended sediment (TSS) discharge from Óbidos of approximately 900 $10^6$ t $yr^{-1}$. Using that data, Meade (1985) provided the first description of the vertical and lateral variation of suspended sediment in the Amazon River. The result were derived from more than 300 samples collected during two field cruises conducted during the high water periods of 1976 and 1977.

The CAMREX Project, during the 1980s, measured water discharge and collected a series of suspended sediment samples from the Amazon (Richey et al., 1986). In this project, more than 200 new samples were collected during several field cruises, mainly between 1982 and 1985. The samples were collected at a single cross section as depth-integrated composites. As indicated by Meade et al. (1985), a new estimate of 1100 to 1300 $10^6$ t $yr^{-1}$ suspended sediment discharge from the Amazon into the ocean was made. The CAMREX Project also estimated bank erosion contributions to total suspended sediment discharge (Dunne et al., 1998).

After that, Bordas et al. (1988) and Bordas (1991) used almost 200 samples from both the Brazilian national dataset (managed by the Brazilian National Water Authority) and from several Brazilian companies and obtained results very similar to those reported by Meade et al. (1979). Again similar results were obtained by Guyot et al. (1988 and 1996), especially for the Madeira Basin (250-300 $10^6$ t $yr^{-1}$). From this river, Martinelli et al. (1989; 1993) and Ferreira et al. (1988) estimated a somewhat higher suspended sediment discharge of approximately 550 $10^6$ t $yr^{-1}$.

The Amazon Shelf SEDiment Study (AmasSeds) group, working with a 190 CTD Probe profiles at the continental shelf, indicated a total flux between 550 and 1,000 $10^6$ t $yr^{-1}$ from the Amazon River into the ocean (Nittrouer et al., 1986a and 1995).

In the scope of the HiBAm (Hydrology and Geochemistry of the Amazon Basin) Project until 2001 when it was completed and after that until today with the ORE/HYBAM (Environmental Research Observatory on Amazon Basin Hydrology, Geochemistry and Geodynamics) Program, Guyot et al. (1996), Filizola (1999), Filizola (2003), Filizola and Guyot (2004), Guyot et al. (2005) and Filizola & Guyot (2009) calculated the contributions from tributaries to the main stream during several cruises (HiBAm and ORE/HYBAM data) and using data from the Brazilian National Data set (from Brazilian Agência Nacional de Águas). They tested different kinds of sampling, data sources and calculation procedures. The results from their multiple approaches, using more than 5000 samples, were quite similar. They indicated imprecision concerning some data from the Brazilian National Data Set (data at www.ana.gov.br) but also validated it with data from several field cruises made between 1995 and 2001 (with the HiBAM Project) and afterwards with the ORE/HYBAM Programme. With the ORE/HYBAM data set Laraque et al. (2005) tried to characterise the spatial distribution of sediment yields and sediment transfer processes in the Brazilian

Amazon basin between 1998 and 2003. These authors established a relationship between the surface concentration and the mean suspended sediment concentration for the whole cross section at each ORE/HYBAM station. Using the same data set, but beginning from 1995, Guyot et al. (2005) highlighted a marked seasonality in the sediment flux, which did not correspond to the discharge variation at Óbidos. From those ensemble of works the results indicated TSS discharge values between 600 and 900 $10^6$ t $yr^{-1}$.

The HiBAm Project and ORE/HYBAM Programme are research initiatives involving several Amazonian countries (Brazil, Peru, Colombia, Equator, Bolivia and Venezuela) and France. Especially ORE/HYBAM is a long-term programme to evaluate the process of matter transport in the Amazon Basin. From this project, data points were acquired daily for hydrology, every ten days for suspended sediment and monthly for geochemistry and physical-chemistry at fifteen gauging stations mainly on the larger rivers of the Amazon basin. The aim of this network was to investigate the piedmont areas, the flood plain tributaries, the tributaries that originate in the Andes and those that drain into the Brazilian and Guiana shields (Cochonneau et al., 2006). The ORE/HYBAM initiative is operated today in cooperation with research institutions and national agencies, creating an independent data set. The main interests are focused on mass transfer within the Amazon basin and towards the Atlantic Ocean, the sensitivity of mass transfer to climatic variability and anthropogenic activities, and the key role of the wetlands in mass transfer. The data acquired with standardised collection and analysis methods are freely available at http://www.ore-hybam.org.

Martinez et al. (2009) used a combined approach of both the HiBAm and ORE/HYBAM data where they also introduced remote sensing data from MODIS spaceborne sensors to estimate the suspended sediment discharge at the Óbidos to be near 800 $10^6$ t $yr^{-1}$. They also showed an increase in the suspended sediment discharge of the Amazon River between 1996 and 2007 (see Section 5.1).

Recently, using a completely different approach from those cited above, namely by using cosmogenic nuclide-produced $^{10}$Be [1], Wittmann at al. (2011) obtained an estimation of the Rio Amazonas total sediment discharge of approximately 610 $10^6$ t $yr^{-1}$ (see Section 5.2). This estimation integrates over several thousands of years and thus provides a long-term estimate on the total sediment load.

Finally, Guyot et al. (2011) showed that the whole ORE/HYBAM data set, with more than eight years of data, can be used to give a more complete picture of the Amazon Basin between the Andean region and the portion near Óbidos. The estimated contribution from the basin to the ocean remains within the range of 600 to 900 $10^6$ t $yr^{-1}$ as found by other authors. With those data the best estimation of sediment discharge at Óbidos is 862 $10^6$ t $yr^{-1}$. If other tributaries contributions, downstream Óbidos (Rivers like Tapajós, Xingu, Paru and Jari), are included in the sediment discharge value, the TSS discharge increases to 872 $10^6$ t $yr^{-1}$.

## 4. The significance of suspended sediment discharge values to the actual Amazonian hydrologic scenario

Determining the Rio Amazonas suspended sediment discharge into the Ocean is not a simple task. The presented results (as showed in Table 1) sometimes differ in their methods

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[1] This method is described later in the text.

| QS ($10^6$ t yr-1) | Source |
|---|---|
| 500 | (Gibbs, 1967) |
| 600 | (Oltman, 1968) |
| 900 | (Meade et al., 1979) |
| 1,100 – 1,300 | (Meade et al., 1985) |
| 550 – 1,000 | (Nittrouer et al., 1995 and Nittrouer et al., 1986a) |
| 600 - 700 | (Bordas 1988; Filizola,1999)* |
| 600 - 800 | (Filizola 2003), Guyot et al., 2005 and Filizola and Guyot ,2009)* |
| 800 | (Martinez et al., 2009)* |
| 610 | (Wittmann et al., 2011)* |
| 872 | (Guyot et al., 2011) |

Table 1. Shows a summary (by author) of the determined values of suspended sediment discharged (QS) by the Amazon River (*)at Óbidos or at its mouth.

and approaches used, and different periods of measurement different measurement periods of measurement could explain some of the variability. Wittmann et al. (2011) give a summary of measurement periods for TSS monitoring in their table 2. Further, discrepancies could be attributed to variability in hydrological behaviour, sampling methods, sediment discharge calculation, and others topics discussed further in this section.

In the following, we will review the hydrological behaviour of Amazon Basin tributaries, which will aid understanding sediment transport. When single gauging stations or regions are considered, water discharge appears to behave regular and stable over time, but nevertheless, the system as a whole can be quite complex. Some authors (Meade et al., 1991; Molinier et al., 1996; Dunne et al., 1998) have described some of these complexities (backwater effect, flood effects combinations, river channel morphology, etc.), which must be considered during suspended sediment analysis.

### 4.1 Water discharge and suspended sediment concentration variability

Molinier et al. (1996) demonstrated the importance of taking into account that the Rio Negro, Rio Madeira and Rio Solimões (see Figure 1) are the most important discharge contributors to the total amount of water discharged from the Amazon Basin into the ocean. The Madeira basin represents 23% of the total Amazon basin area and 15% of total Amazon water discharge into the ocean. The Rio Negro basin represents only 11% of the total Amazon basin area but contributes 14% in terms of water discharge. These values are correlated to areas receiving most rainfall, which are predominantly located in the northwest area of the basin (Espinoza et al. 2008). Despite these water discharge values, the Rio Negro does not transport as much suspended solids compared to the Madeira (Filizola and Guyot, 2009). This difference is attributed to the different sediment source areas (low-erosion cratonic Shields vs. high-erosion Andes) and the lowlands traversed by the rivers.

The high and low water periods of the above cited rivers have special characteristics that display interesting behaviours. The Rio Madeira's high water period takes place between March and April with the average maximum occurring in April, and the minimum value occurring in the end of September. The Rio Solimões' high water period occurs between May and July with the average maximum occurring in June. Additionally, the Rio Amazonas high water period at the Óbidos station takes place between May and June, and the average maximum value occurs at the end of May. Thus, the downstream peak at the

Rio Amazonas at Óbidos occurs before the upstream peak at the Rio Solimões[2] at Manacapuru. This behaviour, as reported by Molinier et al. (1996), is, in fact, the result of the influence of the Rio Madeira high water period, whose maximum occurs two months (on average) in advance of the maximum from the Rio Solimões. This event also causes an advance in the Rio Amazonas discharge peak at the Óbidos gauging station.

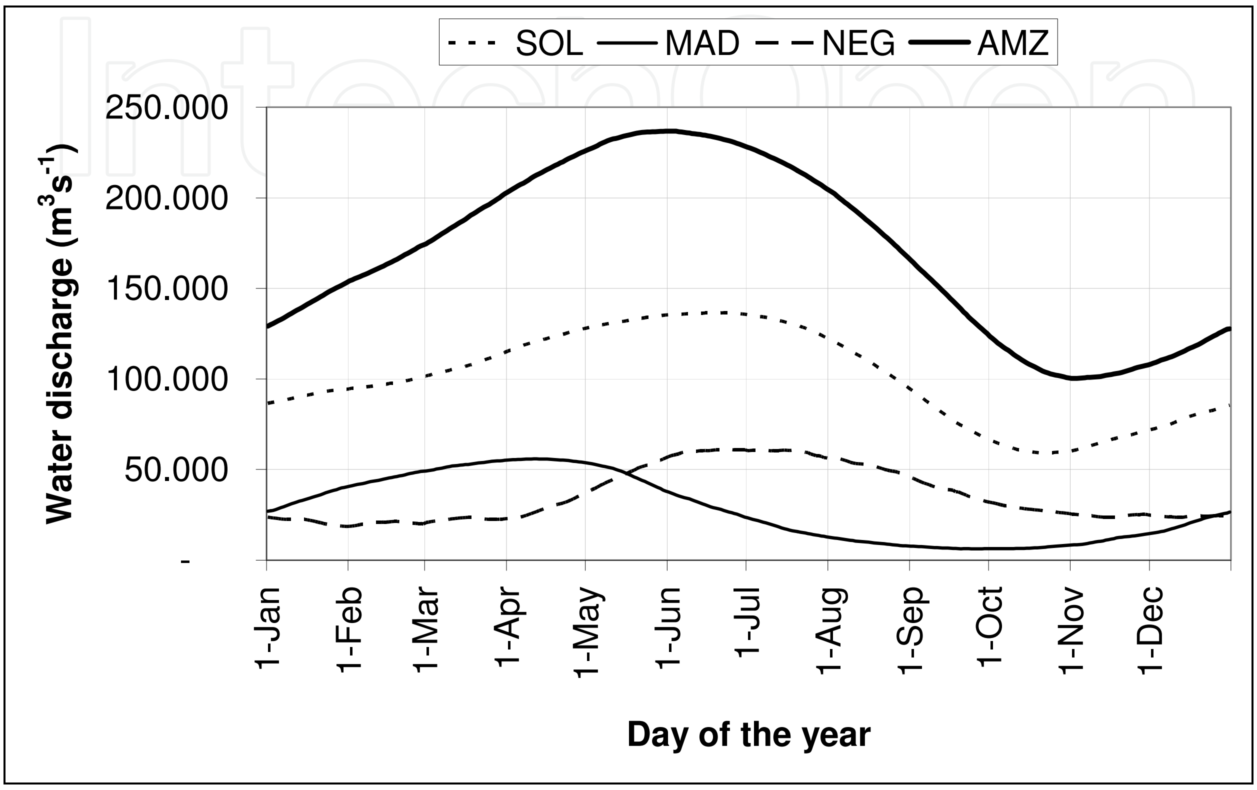

Fig. 2. Average hydrograms of the Rio Amazonas (AMZ) at Óbidos, the Rio Negro (NEG) at Manaus, the Rio Solimões (SOL) at Manacapuru and the Rio Madeira at Fazenda Vista Alegre for the years 1978 to 2008. The data source is the Brazilian National Water Agency dataset (http://www.ana.gov.br). The discharge of the Rio Negro at Manaus was calculated by discharge transposition using upstream to downstream stations correlated with HYBAM Doppler discharge data (http://www.ore-hybam.org) to eliminate the backwater effect.

From Figure 2 and Table 2, we can observe that the Rio Solimões dominates the water flow to the Rio Amazonas at Óbidos; however, from February to May, the Rio Madeira flow controls the variability, and between June and September, the flow of the Rio Negro waters have a greater influence. From October until January, the power of the flow of Rio Solimões is superimposed over the other two large rivers.

Some authors, such as Filizola (2003), Guyot et al. (2005), Bourgoin et al. (2007) and Martinez et al. (2009), showed graphs with the surface and total suspended sediment concentrations at Óbidos as a function of the Amazon River water discharge. The suspended sediment

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[2] Rio Solimões and Rio Amazonas are, in fact, the same river; the difference in names comes from the importance of the Rio Negro to local culture and tourism (meeting of the black and white waters respectively from the Negro and the Solimões). Thus, before the mouth of the Rio Negro, the main river is called Solimões, and the name Amazonas (in Brazil) is used downstream of their confluence.

| | High Period | Max | Low Period | Min |
|---|---|---|---|---|
| R. Solimões | May – Jul | mid Jun | Oct - Nov | mid Oct |
| R. Negro | Jun - Jul | mid Jun | Jan - Feb | end Jan |
| R. Madeira | Mar - Apr | mid Apr | Sept - Oct | end Sept |
| R. Amazonas | May - Jun | end May | Oct - Nov | early Nov |

Table 2. Summary of the hydrological behaviour of the most important rivers within central Amazonia showing periods for high and low water discharge. Also shown are the months in which the average maximum and minimum values are observed (using data series from 1978 to 2008).

concentration measurements used were collected on a 10-day basis since 1995 at Óbidos and other important sites within the Amazon Basin by the HiBAm project and by ORE/HYBAM after 2003. From this data, Bourgoin et al. (2007) obtained three different equations to calculate QS from water discharge relations over three different periods of time, which were used to develop different scenarios for the temporal dynamics of water and sediment exchanges between the Curuai floodplain (Várzea) and the Rio Amazonas in front of Óbidos. The resulting figures shown by those authors clearly show a non-linear behaviour between water discharge and suspended sediment concentrations as well as three distinct temporal situations that enable distinguishing between the discharge modulation of the Rio Amazonas at Óbidos from that of the Rio Madeira and Rio Negro (see Figure 3). These three characteristic temporal situations are interpreted as follows. The first one, on the left side of the figure, represents a moment in the cycle corresponding to September, October and November and correlates well to the low period of all three rivers (Negro, Madeira and Solimões). The second situation (the highest clockwise) is the result of samples collected between February and April. This period coincides with the highest period of water discharge and sediment input from the Rio Madeira. The third area (on the right) corresponds to the period from May to July, which correlates to the highest period of water discharge from the Rio Negro. The samples collected between December and January (shown on the left side of the figure) are concurrent with the rising period of the Rio Madeira. The same conclusion can be drawn for the Rio Negro when looking at the right side of the figure. It follows that, between March and May, the Rio Negro is rising, with very low SSC, and the flow of Madeira is decreasing. Finally, the base of the figure can be attributed to the period between August and September when the flow of all three rivers is decreasing. Thus, the process described above indicates an SSC multi-control system for the Rio Amazonas at Óbidos. This system is highly dependent on the sediment contributions from the Rio Madeira during a certain period of time and also on absent sediment contributions from the Rio Negro during another period of time.

From the above presented data and Figure 3, it clearly follows that at Óbidos, sediment discharge is not a linear function of discharge.. If linear functions would be applied to estimate suspended sediment discharge from the Rio Amazonas to the Ocean, these would be seriously compromised and probably overestimated. This data provides important information on water and sediment interaction within the Amazon Basin. The water discharge and SSC behaviour demonstrated above shows the key to explaining some of the differences in the suspended sediment values presented at Table 1. It can indicate a kind of "teleconexion" among the upward areas of Rio Madeira and the Rio Amazonas downward region. With dams reservoirs now under constructions at the Rio Madeira this behaviour assumes an important role. If the new Madeira Hydropower Plants reservoirs will reduce sediment discharge it can also will cause impacts at the lower Rio Amazonas region. Stressed here is the significance of the Rio Madeira sediments to support the large Várzea (seasonal humid/flooded plains) areas, situated near of Óbidos, in terms of floodplain fertilization that is of great importance to the local farming and grazing economy.

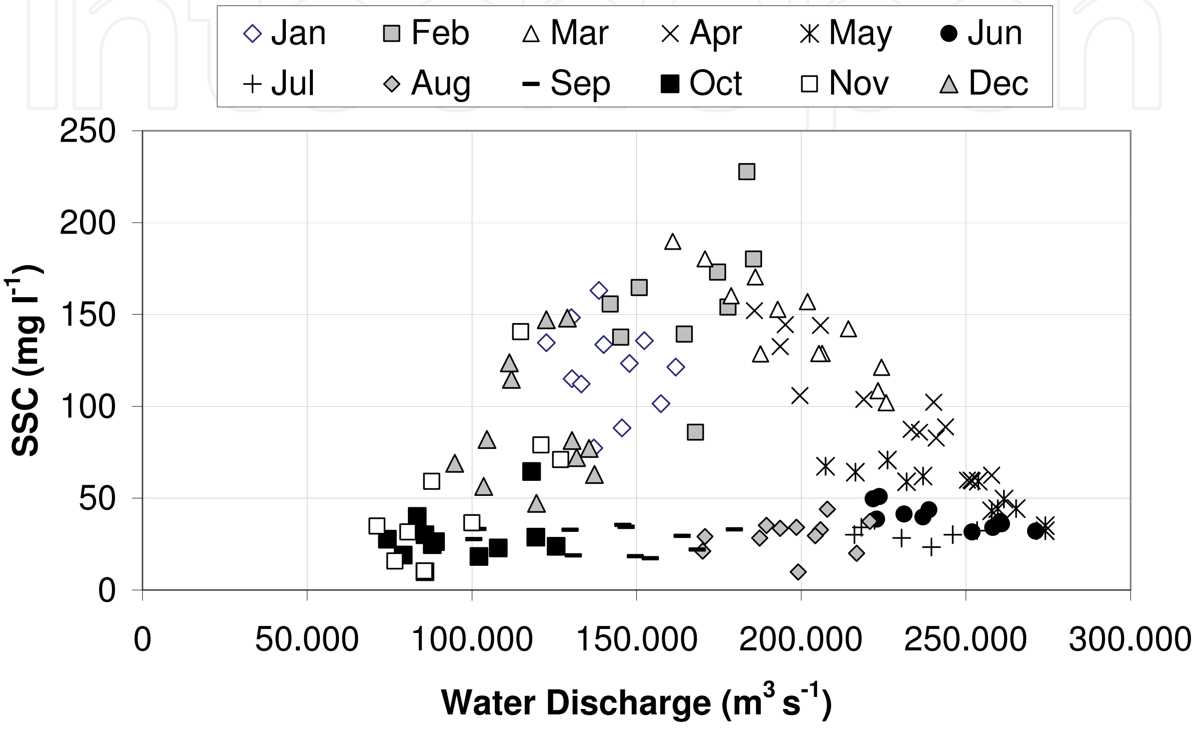

Fig. 3. Suspended Sediment Concentration versus the water discharge data for Rio Amazonas at Óbidos. The graph also shows the distribution of samples collected between 1995 and 1998 according to the month the samples were collected. For details see text. Figure modified from Guyot et al. (2005) using ORE/HYBAM data (http://www.ore-hybam.org).

**4.2 Suspended sediment concentration variability (in deep and at the water surface)**

Suspended sediment transport and the actual Amazon hydrology scenario can be changed by the new infrastructure construction (e.g., hydropower plants, roads and new agriculture frontier), climate change impacts and land use policies. Monitoring those factors and its variability is an important issue. In the Amazonian Hydrographical Region Book (Brasil, 2006), the Brazilian National Water Resources Management Plan describes the sustainable development of hydropower plant reservoirs and new agriculture frontiers as two of the most important goals to be achieved. Both are affected by sediment transported by rivers within the Amazon region. With a large sediment source such as the Andes to the west and its low general slope (especially from the piedmont to the flood plains) of about 2 cm $km^{-1}$ (Molinier et al. 1996), reservoirs will act as trapping areas, which will increase deposition processes. These trapping areas can reduce, for example, the amount of sediment deposited from Rio Madeira into the main stream (lower Amazon stretch), leading to a diminished fertilisation of the flood plain. However, in other areas, the intensive agricultural land use and deforestation can have the opposite effect. These areas are more susceptible to erosion. Additionally, erosion occurs as a consequence of rain intensification derived from more frequent climatic variations. Thus, monitoring sediment transport in this kind of scenario must consider analyses over both space and time.

Some sampling methods and calculations were evaluated by Filizola and Guyot (2004) for the Óbidos station and for other stations in the basin by Filizola and Guyot in 2009, with the aim to reconcile the different methods and approaches used. For the test conducted at Óbidos, Filizola and Guyot used three types of depth samplers: one 8-liter collapsible bag depth integrator, a Brazilian model of the US P-63 adapted to the Amazonian rivers conditions (deep sections, high water velocities and discharge), and a 12-liter point horizontal oceanographic sampler, also adapted to the Amazonian rivers conditions. Surface sediments were sampled using a simple bucket, and a Doppler device was used for water discharge determination, and to test its use to determine suspended sediment discharge. Sampling surface sediments was carried out to test whether they represent the total suspended sediment discharge. Using the different samplers, the results showed a very small difference between all samplers when using the same QS calculation procedures. The relationship between the surface and total suspended solids was found to be, on average, 28%. It means that, in average, the SSC of a sample obtained in Óbidos at the water surface represents 72% of the total suspended sediment concentration. However, this relationship cannot be extended over the whole hydrological year, because it varies seasonally.

Another important question to be answered is that of the SSC variability with depth. Filizola (2003) showed that increasing SSC with depth does not always correspond to an increase in vertical SSC discharge (qS). Using Doppler data combined with SSC data, Figure 4 was created as an example from the Rio Madeira at Fazenda Vista Alegre. It can be seen that SSC values increase with depth, but qS values do not follow suit. The qS value seems to be influenced by the water velocity component. Filizola (2003) also demonstrated that this heterogeneous behaviour with depth has a seasonal variation, and is smoothed during the low water period.

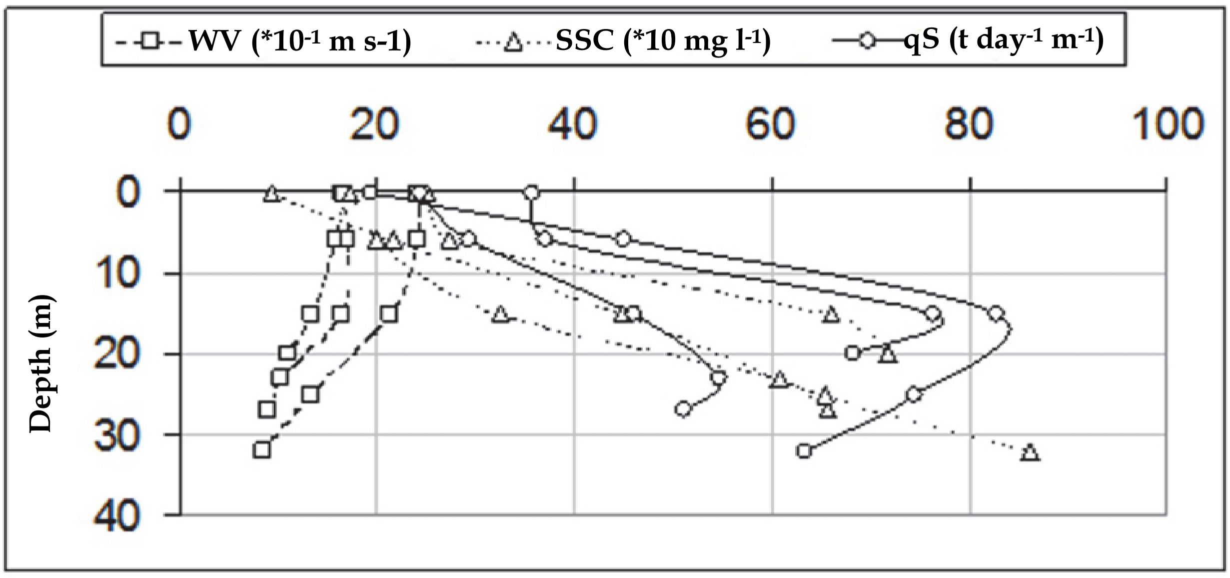

Fig. 4. Rio Madeira at Fazenda Vista Alegre on 22/05/1997 showing the variations with depth of water velocity (WV), suspended sediment concentration (SSC) and the discharge of suspended sediment (qS) for three vertical sampling profiles. Source: Filizola, 2003.

Another important point stems from the idea that stable river sections are good for water discharge determinations are good for TSS discharge determination as well. An interesting case about it has been presented by Filizola et al. (2009) at Manacapuru (Rio Solimões), a station used by Brazilian Agencies as a school site to conduct a yearly training course on large river water discharge measurement methods. Additionally, this site is also an SSC collection point. The authors showed that, at Manacapuru, geological structures, as described by Latrubesse et al. (2002), continue into the river channel and create bottom irregularities that influence the water movement. This movement causes heterogeneous behaviour of the surface SSC compared to that on the bottom. The surface results can be viewed by satellite images with "in situ" data confirming the image impressions (Figure 5). The resulting plume of suspended sediment from the phenomenon varies seasonally (Filizola et al. 2009).

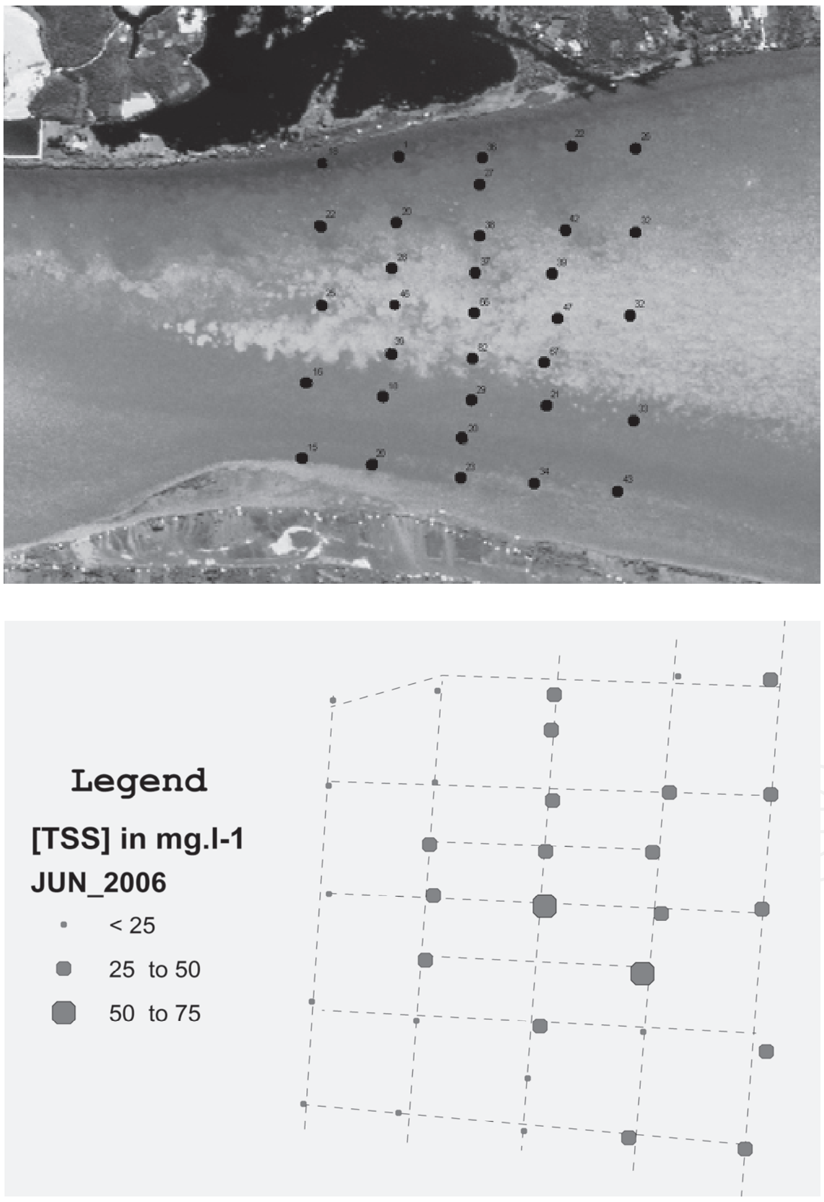

Fig. 5. A satellite image with the plume marked by Filizola et al. (2009) with the "in situ" results from the total suspended sediment collected at the water surface.

Regarding not only the suspended sediment transport, but also the bedload transport, important work was performed by Strasser (2008). He quantified the geometry, sediment transport and dynamics associated with the riverbed configuration of the main course of the Rio Solimões/Amazonas. He reported that, in the Brazilian Amazon territory, dunes are the prevailing bedform along the fluvial reach of the Rio Amazonas with heights that ranged from 0.2 to 12.0 meters and wavelengths of up to 400 meters. The main characteristics of the dune geometry (height and wavelength) remains practically unaltered throughout the year. Using dune geometry and migration measured in different stretches of the river, Strasser (2008) estimated the bedload transport to be $4\ 10^6$ to $5\ 10^6$t $yr^{-1}$ between the Iracema, near the city of Itacoatiara at the Rio Amazonas a few kilometres before the mouth of Rio Madeira, and the Óbidos stations, which represents less than 1% of the total sediment transport of the Rio Amazonas.

All of the numbers produced in terms of suspended sediment concentration and discharge as well as all of the related phenomena seem to indicate that additional research still needs to be conducted with more emphasis on the processes and factors that control the transport of suspended sediment through the Amazonian rivers. Knowledge of the processes will provide a better understanding not only of the Amazonas contributions to the ocean, but will also aid to understanding the importance of tributaries..

## 5. New technique contributions

In situ networks with stations systematically collecting samples on suspended sediment concentrations and also non-systematic field cruisers performing detailed surveys will continue to be useful and important tools. However, new techniques can contribute, in terms of improving the capacities of remote analysis (in time and space), or estimating a more long-term average of sediment load transportation in the Amazon Basin by using cosmogenic nuclides.

### 5.1 Satellite approach, an example using MODIS sensors

Using satellite techniques, reflectance of the inland water turbidity can be useful to suspended sediment transport studies. A reflectance wavelength of 700 to 800 nm agrees with SSC in turbid inland waters as described by Martinez et al. (2009). These authors successfully tested this correlation and spaceborne sensors, such as MODIS, which are promising methods to monitor inland water, in the Amazon basin. These sensors offer spatial resolution and spatial coverage that is compatible with the dimensions of Amazonian River system and allow for fine temporal resolution.

The methodology proposed by Martinez et al. (2009) used five atmospherically corrected surface reflectance products from the Terra and Aqua MODIS spaceborne sensors. They used composite images with the following considerations: i) the 8-day composite is compatible with the 10-day field measurement sampling frequency (the ORE/HYBAM data set); ii) the amount of data to be analysed is reduced because a large number of daily images cannot be taken due to persistent cloud cover; and iii) the directional reflectance effects and atmospheric artefacts are significantly reduced. For each date, the composites from Terra and Aqua were automatically scanned, and the image with the lowest cloud coverage was selected. When both composites exhibited low cloud coverage, the composite acquired with the lowest satellite viewing angle was preferred. A pixel-based river mask covering nearly 10,000 pixels was manually outlined over the tested station (Óbidos) to automatically extract the reflectance in each MODIS image.

The surface reflectance data appeared to be robustly linked to the suspended sediment concentration at the river surface over a large range of concentrations and for several consecutive hydrological cycles (Martinez et al. 2009). Thus, MODIS data can be useful as an operational tool to provide more observations in a poorly gauged basin, especially the large rivers, by combining excellent temporal resolution and fine calibration quality. This technique can also be used to map SSC superficial dispersion in the main stream and to observe the impact of tributaries. However, the authors emphasise that the quest for a universal algorithm for suspended sediment retrieval from satellite data is never likely to succeed. This is because the scattering efficiency of suspended particles is very much a function of the average particle size and is quite variable from one catchment to another. Thus, the local calibration of satellite data would have to be developed and tested for each river basin.

### 5.2 Cosmogenic nuclide-produced $^{10}$Be used to derive long-term sediment loads

The cosmogenic nuclide-produced method to derive denudation (or erosion) rates is a useful tool for estimating long-term sediment loads. $^{10}$Beryllium ($T_{1/2}$ = 1.39 Myr) is the most widely used cosmogenic nuclide for studying the processes that shape the Earth's surface despite the fact that very low nuclide abundance requires time-consuming chemical $^{10}$Be enrichment and costly accelerator mass spectrometer (AMS) analysis. $^{10}$Be is produced in situ within mineral lattices (e.g., quartz) through the interaction of cosmic rays, and its production is altitude-dependent (Lal, 1991). In situ-produced $^{10}$Be accumulates in near-surface deposits over time such that the concentration of the nuclide is related to both the age and stability of the surface (Lal, 1991). The accumulation rate of $^{10}$Be is thereby inversely proportional to the erosion rate of the surface, if the erosion process has been taking place for a period that is long compared to the erosion time scale $z^*/\varepsilon$ (see Figure 6A). This time scale is equivalent to the time it takes to erode ~60 cm of silicate rocks, which is a depth where the intensity of cosmic irradiation is reduced by a factor of $1/e$ through interaction with the material. In this case, the production of nuclides equals the removal of nuclides at the surface by erosion ("cosmogenic steady-state") and a basin-wide rate (i.e., the total rate of chemical and physical removal from the surface) can be calculated. At the same time, this basin-wide rate integrates over all spatially variable erosion rates within a single basin following the concept of "Let nature do the averaging" (see Figure. 6A). More comprehensive synopses of cosmogenic nuclides and their applications are given by Gosse and Phillips (2001), Bierman and Nichols (2004), von Blanckenburg (2005), and Granger and Riebe (2007).

Basin-wide erosion rates from cosmogenic nuclide concentrations are normally derived from actively eroding hillslope settings, where no storage occurs. Long-term sediment storage in large depositional basins might violate the assumption of cosmogenic steady state, and may result in (i) additional nuclide production when exposed to cosmic rays or (ii) the loss of nuclides during decay when sediment is prone to deep burial and shielding from cosmic rays. However, under certain prerequisites, it is possible to correct cosmogenic nuclide-derived erosion rates in lowland basins to yield rates that are not affected by low elevation, depositional areas. This concept is summarised in Figure 6 where production rates of nuclides are altitude-dependent. Thus, the average basin-wide production rate decreases with increasing lowland (low-elevation) area. Additionally, the modeling of cosmogenic nuclide concentrations in lowland areas (Wittmann and von Blanckenburg,

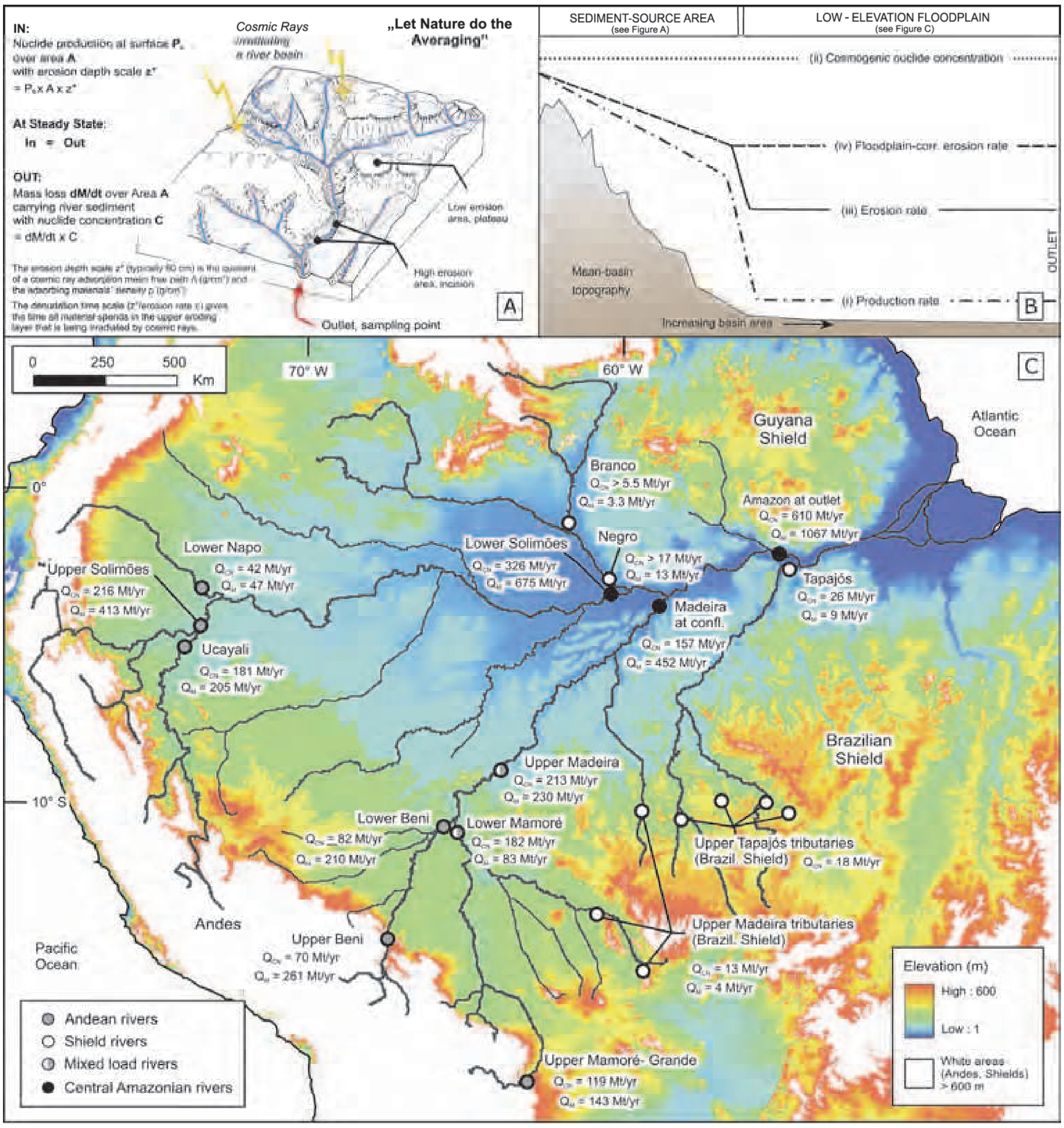

Fig. 6. (A): Illustration of the "Let Nature do the Averaging" concept for cosmogenic nuclide-derived basin-wide erosion rates; modified from von Blanckenburg (2005); (B): Concept of correction applied to cosmogenic nuclide-derived erosion rates in lowland basins; modified from Wittmann et al. (2011); and (C): Sediment loads (Mt/yr) in the Amazon basin calculated from cosmogenic nuclide-derived erosion rates (QCN) compared to published modern loads from gauging (QM); modified from Wittmann et al. (2011). For QM-related references, the reader is referred to Wittmann et al., 2011.

2009) and the testing of the model in a large Amazonian tributary (Wittmann et al., 2009) have shown that the concentration of long-lived nuclides (e.g., $^{10}$Be) contained in headwater sediment is not prone to change due to storage in depositional areas of the basin. Thus, uniform nuclide concentrations from the sediment source area to the floodplain are expected. As a result of decreasing production rates, uniform nuclide concentrations translate into decreasing basin-wide erosion rates. As this effect is only caused by decreasing production rates, erosion rates may be corrected using the production rate of the sediment source area only (i.e., to be "floodplain-corrected"). A prerequisite for this correction is that the cosmogenic signal of the sediment-producing area is preserved in the floodplain, which is the case when sediment storage is shorter than the nuclides half-life (Wittmann and von Blanckenburg, 2009).

In the central Amazonian lowlands, cosmogenic nuclide concentrations resemble those measured in the sediment source areas (Andes, cratonic Shields). Thus, erosion rates for the entire basin may be calculated, which integrate over the time it takes the sediment to be transported through the basins, i.e., 5-15 kyr (Dosseto et al., 2006; Mertes and Dunne, 2007). These erosion rates can be converted to loads using the sediment density and can then be compared to decade-scale, gauging-derived sediment loads (see Figure 6). This comparison yields an average factor of ~2 agreements between QCN and QM, which could be due to stable erosion rates in the sediment source areas over the last 5-15 kyr until today, despite changes in climate. Additionally, the slightly better overall agreement between QCN and QM in central Amazonia in comparison to the source areas could be caused by the buffering capability of the large Amazon floodplain (Métivier and Gaudemer, 1999). Changes in Amazon River sediment output fluxes, as measured by long-term cosmogenic nuclides or short-term gauging, could have been stabilised over the last millennia by a persistent, accommodation-dominated floodplain.

## 6. Conclusions

Sediment transport is part of natural processes undergoing in river basins, and the rivers are the natural ways to transport suspended sediments from the continent to the ocean. This chapter showed that since 1950 the Amazon basin suspended sediment transport has been studied by several scientific groups. Therefore, different results have been presented. These results were obtained from different data sets, sampling and calculation methods. They came not only from several multidisciplinary scientific projects, which operates since the 1970, but also from local hydrometric networks providing long-term data. Now, with the help of all these previous works, it is possible to indicate with more certitude that the suspended sediment flux from the Amazonas to the Ocean is lower than 900 $10^6$ ton.yr$^{-1}$.

The value cited above was indicated thanks to the progressive evolution of scientific works and also by an intensive and more frequent sampling procedure, especially done since the year 2000. These data permit a more efficient evaluation about hydrology scenario and its importance to the sediment discharge variability, especially at central Amazonian region. This scenario marks the importance of the biggest Amazon tributaries (Rio Negro and Rio Madeira) to modulate the Rio Amazonas SSC flux at Óbidos (~ 700km to the mouth). New techniques, using satellite data or cosmogenic nuclide, helps to reinforce these results, open other perspectives to the theme and also reinforce that the huge distance between the Amazon River sources in the Andes and its mouth in the Atlantic Ocean makes possible the co-existence of erosion, deposition and re-suspension processes at different scales in time and space.

The transport of suspended sediment is a product of erosion, and erosion and deposition processes within a basin depend heavily on factors such as climate and relief. In Amazonia, the western landscape acts as an important driving mechanism of climate, and the gradient relief has an important effect on the erosion and deposition processes between the highlands and the exit of the basin. However, anthropogenic factors also play an important role in those processes. Within this context, Allen (2008) suggested that the sum of physical, chemical and biological processes that shape the Earth's surface and drive its mass fluxes, affecting suspended sediment transport; need to be investigated over the so-called human timescale. Additionally, integration over larger spatial and temporal scales needs to be performed. More complexity is thereby added by human actions, when aiming at studying the processes that shape our Earth's surface, and thus an increasing need arises for new monitoring systems and new techniques. In today's Amazonia, the environmental scenario reflects challenges especially concerning to water resource management, with integration techniques studies under development. To do so, the suspended sediment transport by rivers is an important issue to be included on that kind of integration.

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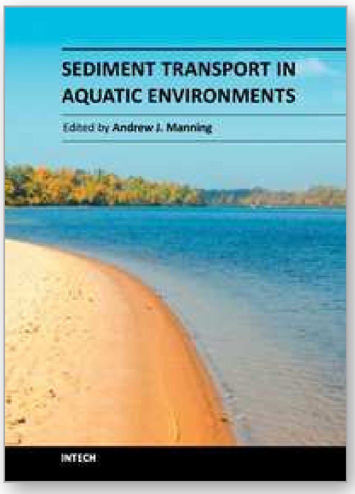

**Sediment Transport in Aquatic Environments**

Edited by Dr. Andrew Manning

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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

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