Sediment Budgets I (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 291, 2005.

The role of flood plains in the hydrology and sediment dynamics of the Amazon River, Brazil.

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Abstract Flood plains can act as important sinks of sediment and associated heavy metals, such as mercury. In this study, we present an estimate of the role of an Amazonian flood plain in sediment storage. The Curuai flood plain is located on the right bank of the Amazon River, 900 km upstream of the mouth. It is a complex system of more than 30 interconnected lakes, with a maximum inundated area of 2300 km^2, representing 0.8% of the total flooded area of the Central Amazon basin. For the period 2000–2003, a mean average sediment deposition of 380 000 (±7.82%) t year^{-1} was determined using a box model calibrated using a network of gauging, meteorological and sediment monitoring stations operated over a 4 year period and analysis of multi-temporal remote sensing images. This storage represents approximately 0.6% of the total annual sediment flux transported by the Amazon River. The associated mean specific sedimentation rate approaches 165 t km^{-2} year^{-1} if only the flooded area is considered.

Key words Amazon River; flood plain; flood plain storage; sediment deposition; suspended sediment

INTRODUCTION

Flood plains play a major role in the hydrology and sediment dynamics of the Amazon River. They store water during the rising stage (from December to June) and release it when the river level is decreasing (from July to November). This results in a smoothing of the annual hydrograph and explains why the maximum discharge at Obidos (280 000 m^3 s^{-1}) is only four times the minimum value (70 000 m^3 s^{-1}). Geomorphologically, the Amazon flood plain is highly complex (Mertes *et al.*, 1996). Along the Solimões River, it is dominated by scroll-bar topography and hundreds of narrow lakes. Downstream, as far as the confluence with the Madeira River, the flood plain is narrower. From the Madeira confluence to Obidos, the relatively low and incomplete levee system, breached by large distributary channels, results in the inundation of a wide flood plain, containing hundreds of lakes of irregular outline that appear to be due to subsidence of compacting sediment (Dunne *et al.*, 1998).

In this paper, we present the results of a study aimed at measurement and modelling of the sediment dynamics of a mid-Amazon flood plain lakes and channels system. The resulting improved understanding of flood plain behaviour permits a more general assessment of the contemporary role of the Amazon flood plain.

STUDY AREA

Climate and hydrology

The Amazon basin is the largest drainage basin in the world, covering about 6×10^6 km^2 and generating a mean annual flow of 163 000 m^3 s^{-1}, at Obidos, 900 km upstream of its mouth (Callède *et al.*, 2002). The Obidos gauging station (01°56′S, 55°30′W) (Fig. 1) has a catchment area of 4 677 000 km^2, and is the only gauging station on the Amazon River with reliable and long-term water level records (over 30 years). It is the lowest gauging station on the river above the estuary and the tidal effect does not influence mean daily water level by more than 10 cm, during the low water stage (Callède *et al.*, 2004), which corresponds to a standard deviation of the discharge measurements of only ±2%. At this location, the maximum rainfall is observed between February and April (Fig. 2) and the mean annual precipitation for the 1971–1998 period is 1820 mm. In this region, the rainfall is influenced by the activity and position of the Inter Tropical Convergence Zone (ITCZ) over the tropical Atlantic Ocean (Ronchail *et al.*, 2002). During the rising water stage, excess floodwaters temporarily fill huge wetland areas connected to the main channel of the river, inundating an estimated area of about 300 000 km^2 (Junk, 1982). The flood plains constitute a very heterogeneous system, composed of thousands of temporary or permanent lakes, forming hundreds of sub-systems of interconnected lakes. Lake hydrology is characterized by large variations of the water level, which can be up to 15 m in the Manaus region.

In this study, we present an estimate of the importance of the Amazon flood plain in the transport and accumulation of sediment by studying one specific site (Fig. 1), the “Lago Grande de Curuai” flood plain located on the right bank of the Amazon River, opposite the city of Óbidos.

The Lago Grande de Curuai flood plain

The “Lago Grande de Curuai” flood plain (*várzea* in Portuguese) is a complex system of more than 30 interconnected lakes, linked to the Amazon River by nine channels, two of them with permanent flow, located on the eastern side (Fig. 3). Located at 01°50′S, 55°43′W, it drains a total area of 3610 km^2, which in the south is covered by dense forest, located on elevated ground, which never floods. The Óbidos flood plain is typical of the western Amazon flood plains, being very extensive and flat and occupied during the low water season by savannah, low vegetation and alluvial forest (RADAMBRASIL 1976). The banks, delimiting the river from the lakes, constitute the northern limit of the várzea and are characterized by large patches of forest, whose trees rarely reach more than 20 m, bordered by pioneer communities.

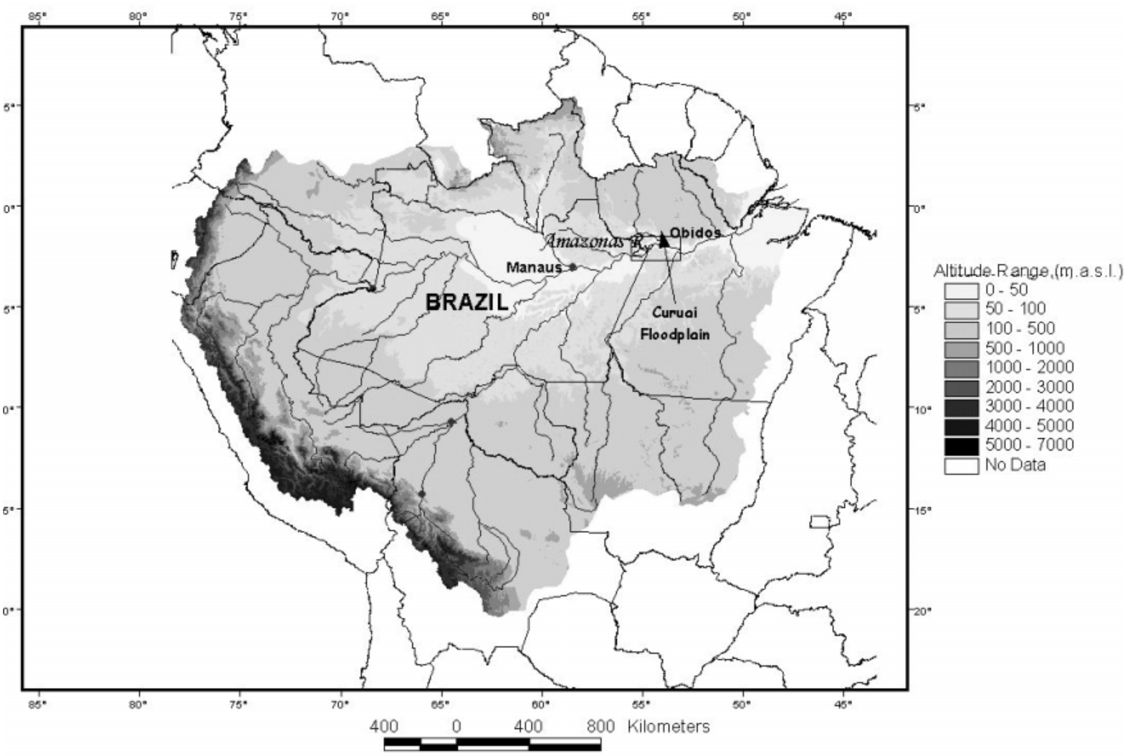

Fig. 1 The location of the Obidos station and the Curuai flood plain on the Amazon River. The relief map of the whole Amazon basin shows the highest altitudes (500–7000 m a.s.l.) corresponding to the Andean cordillera, and at the lowest elevations, the extended foreland basin characterised by sediment deposition.

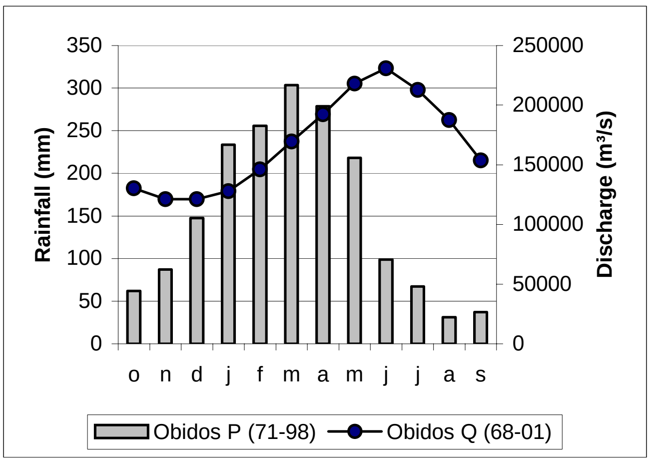

Fig. 2 Mean monthly precipitation (P) and discharge (Q) at Obidos station on the Amazon River, for the 1971–1998 and 1968–2001 periods respectively. (Data from the Water National Agency (ANA) and from the HyBAm Project, in cooperation between France (IRD) and Brazil (CNPq)).

The inundated area of the flood plain varies from 700 km^2 during the dry season to 2300 km^2 at the time of the maximum flood (Martinez *et al.*, 2003), representing 0.8% of the total flooded area of the Central Amazon basin. The difference in height of the water surface between the two extremities of the *várzea* (separated by 150 km along the Amazon river) is 0.5 m during low water and 2 m during high water (Kosuth, 2002). Low water stage usually occurs in November and the water levels rise from December to May–June. The lowest and highest water levels recorded at the Curuai gauging station during the 1982-2003 period are 4.12 m and 10.73 m, respectively, giving a maximum variation of 6.61 m.

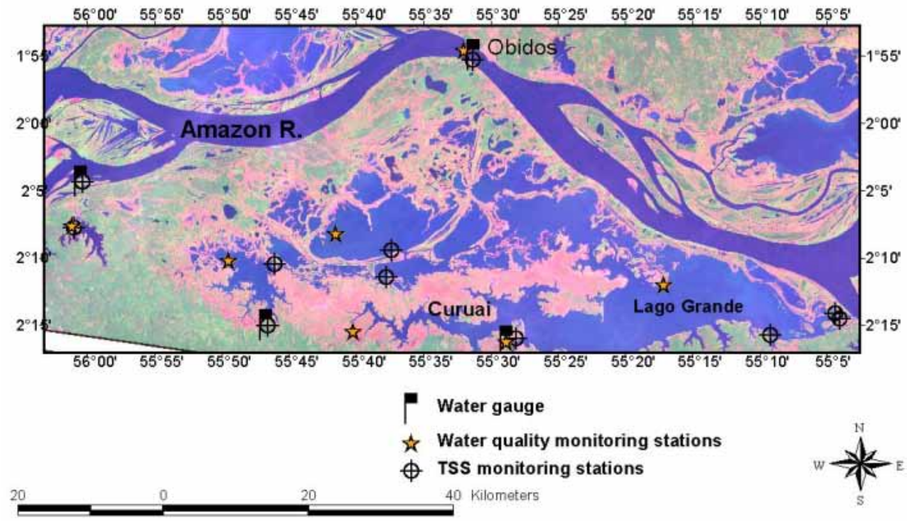

Fig. 3 The Curuai flood plain, showing the location of the four gauging stations (daily record). The stars represent the water quality monitoring stations (monthly sampling) and the circles, the TSS monitoring stations (sampled every 10 days).

The main lakes shown on Fig. 3 never dry out, but most of these are very shallow during November and December, with depths of about 50 cm. The main exchange of water and sediment between the flood plain system and the Amazon mainstream occurs at the eastern extremity of the Lago Grande lake through two channels. These are about 30 m wide and 3 km long during the low water stage and they never dry out. As the river level rises, several other channels progressively connect different parts of the flood plain to the river. Ground observations show that the flood plain lakes are fed by seven main channels. These are about 15 to 30 m wide and they vary significantly in length, with the longer channels extending over 40 km. Satellite image analysis and ground observations suggest that there is also massive overbank spilling during the peak inundation phase on the western part of the flood plain (Martinez *et al.*, submitted).

MATERIAL AND METHODS

The results presented were derived from a monitoring network operated between 1999 and 2003; seven field campaigns undertaken between 2001 and 2003; multi-temporal remote sensing images; and a numerical model applied to the Curuai flood plain.

The flood plain hydrology is controlled by the main river regime and is influenced by the flood plain geometry (water elevation slope, bathymetry, sinuosity, …), the local climate regime (rainfall, wind and sunshine), the watershed hydrology (runoff to the flood plain) and many other related processes (infiltration, runoff, evaporation, channel flow, lake storage, etc.). The hydrology and sediment dynamics of the Curuai flood plain have been monitored since March 1999 as part of the HYBAM Project

("Hydrogeodynamics of the Amazon basin at the present time"), coordinated by the IRD in cooperation with the Brazilian National Water Agency (ANA)), through records of rainfall, water level and total suspended solids (TSS) concentrations in the main river and in the major lakes.

Three stage recorders provide daily records of water levels within the flood plain. These records extend back 20 years for the recorder at Curuai, located on the biggest lake of the *várzea*, and 5 years for the recorders installed at Ponto Seguro and Tabatinga do Sale, located in the western part of the várzea (Fig. 3). Another gauging station has been in operation at Óbidos on the Amazon river for 33 years. Due to the exceptionally low topographic gradient, the three records are highly correlated (R = 0.99 over one annual cycle) and consequently only the records from the Curuai station have been used to assess water levels fluctuations across the entire flood plain. Water samples have been collected every ten days from 13 stations for total suspended solids (TSS) analysis. Seven field measurement campaigns have been organized at various stages of the annual hydrological cycle to measure liquid and solid discharges in the main stream and all the connecting channels, and to study the spatial heterogeneity of the water geochemistry.

MODELLING OF THE HYDROLOGICAL DYNAMICS OF THE LAGO GRANDE DE CURUAI FLOOD PLAIN SYSTEM

A simple box model of the Curuai flood plain was developed (Martinez *et al.*, 2005) and refined in this study. The different water inputs are: the Amazon River, direct rainfall (P), and surface runoff from the surrounding watershed. The outputs modelled are: the infiltration (I) and the evaporation (EV). Calibration was based on measured channel and mainstream discharges. The model was run for the 2000–2003 period and provided time series of simulated water flux between the Amazon mainstream and the Curuai flood plain lakes. The field measurements and hydrological modelling have permitted estimation of the daily water fluxes and the volumes of river water entering and leaving the flood plain during three complete annual cycles.

At the daily step time (Δt) the water exchange or flux between the main river and the flood plain (ΔQ) is represented by the following equation:

$$\Delta Q = (\Delta V/\Delta t) + EV - P + I \qquad (1)$$

where: ΔV is the volume of water stored (or lost) during the period between the calculation step time and the equivalent time the previous day over the entire Curuai flood plain. ΔV is determined by interpretation of radar images between the low water stage and a given lake stage corresponding to a water level h (Martinez *et al.*, 2003; Martinez & Le Toan, 2004).

$$\Delta V = \int_{h_{etiage}}^{h'} S(h)dh = \int_{h_{etiage}}^{h'} (ah^3 + bh^2 + ch + d)dh \qquad (2)$$

where: $S(h)$ is a third order polynomial fitted to the flooded surface–lake stage relationship based on the levels recorded at the Curuai station; h' is the water level at the Curuai gauge station; h_{etiage} is the water level at the Curuai station during the lowest water stage.

$S(h)$ has been determined using the total flooded area calculated from radar images for 10 different water levels (Martinez *et al.*, 2005). Twenty one J-ERS scenes available for the test site from 1993 to 1997 were acquired. The J-ERS sensor uses L-band (21 cm wavelength) and has a spatial resolution of 12.5 m. As the *várzea* extends over 100 km, two J-ERS scenes were necessary to cover the entire flood plain area. The range of water level fluctuation is well covered, extending from 4.16 m to 10.56 m. All the images were carefully co-registered, and then geo-referenced using 20 ground control points for each frame, based on GPS measurements undertaken during the field campaigns on the flood plain.

The evaporation (*EV*) has been modeled from mean monthly data published by the RADAMBRASIL Project (1976) for the Obidos region (Table 1). The mean annual evaporation reaches 1610 mm. The rainfall (P) distribution over the study area is characterized by considerable heterogeneity, with differences in mean annual precipitation between the two main regions, the south (*terra firme* forest) and the north (lakes), reaching 26% (during the last 12 years). To take account of this heterogeneity, two areas have been considered in the model, namely, the lakes located in the north of the site, with a mean annual rainfall of 2028 mm (Juruti station) and the area of the drainage basin located in the south which one part is never flooded, and affected by the orographic effect, with a mean annual rainfall of 2566 mm (Curuai station). For each step time, a 10-day moving mean was applied in order to smooth the rainfall distribution all over the study area. It was assumed that 30% of the rainfall infiltrates directly into the soil and reaches the water table and the remaining 70%, less the water volume lost by evaporation, is applied to the system over a period of 3 days, in order to take into account the soil saturation process during the rainy season.

Calculations were undertaken for three hydrological years (November 2000–October 2003). This model was validated using field measurements of discharge along the mainstream and in the channels connecting the river with the flood plain lakes made over 7 or 8 hours and averaged over a tidal cycle (Fig. 4). The water flux is positive when the Amazon waters are filling the flood plain lakes and negative during the outflow. As the rainfall and the evaporation processes are modelled using a measured dataset, the accuracy of the model is mainly controlled by the accuracy of the estimates of the volume of water stored in the system. This accuracy is relatively high as it reaches 88%.

Table 1 Mean annual water and sediment fluxes between the Amazon R. and the Curuai flood plain for the 1999–2003 hydrological years, and corresponding water and sediment balances.

Hydrological year	Water flux entering (km^3)	Water flux outflowing (km^3)	Water balance (km^3)	Sediment flux entering (t)	Sediment flux outflowing (t)	Sediment balance (t)	Standard deviation (%)
1999–2000	5.97	–10.43	–4.46				
2000–2001	6.27	–11.08	–4.81	848 848	–496 265	352 583	7
2001–2002	8.27	–9.78	–1.51	879 221	–504 529	374 692	21*
2002–2003	7.03	–9.35	–2.32	909 459	–498 270	411 189	3

*On 2 hypothesis of calculation instead of 4

MODELLING THE SEDIMENT DYNAMICS OF THE LAGO GRANDE DE CURUAI FLOOD PLAIN SYSTEM

The sediment inputs to the flood plain lakes were calculated by multiplying the positive daily water discharges by the daily total suspended solids (TSS) in the main river at the Obidos station. Daily TSS concentrations were estimated by linear interpolation

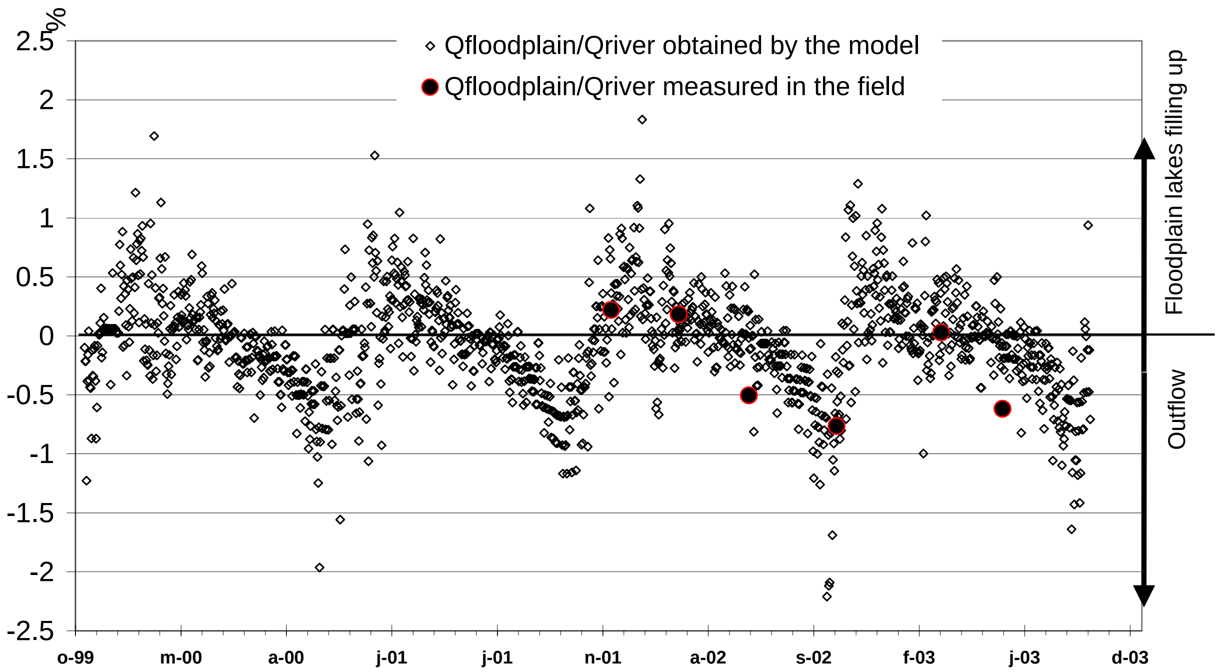

Fig. 4 Water fluxes between the Amazon mainstream and the flood plain system normalized by the Amazon discharge for the 2000–2003 hydrological years. A comparison between modelled (diamonds) and measured (circles) values is provided.

of the TSS concentrations measured in the surface water every 10 days, based on three periods during each hydrological year. These three periods were defined according to the variation of TSS with the water discharge measured at the same station, namely:

(a) from November to February, during the rising water stage, characterised by a net increase in the TSS concentration with discharge, due to the Madeira and Solimões River floods;

(b) from February to May, around the flood peak, characterised by decreasing TSS concentrations during the Amazon flood, due to the input of water with low TSS concentrations, during the Negro River flood; and

(c) the low water stage, from June to October, with low TSS concentrations.

These calculations were made for each of the modelled years.

The solid fluxes flowing out of the flood plain system were calculated by multiplying the negative water discharges by the TSS measured in the two eastern channels of the system, where the highest water and sediment fluxes were observed and measured. Four hypotheses were tested to check the sensitivity of the model to the TSS concentration data, by applying at each calculation step: (a) the TSS measured at Foz Norte in the eastern channel; (b) the TSS measured at Foz Sul; (c) the mean TSS concentrations averaged for both channels; and (d) the lowest TSS concentration measured in the two channels, during the flood period (reflecting sedimentation) and the highest TSS concentration during the low water stage (reflecting resuspension of bottom sediment in shallow water by the wind). Standard deviations range from 3 to 7% of the average, except for 2002, when very high TSS concentrations were measured in the northern channel of the Grande lake mouth during the low water stage, in October.

RESULTS AND DISCUSSION

At the scale of the annual hydrological cycle, the filling phase of an Amazon flood plain lasts about 7 months, from November to May. Outflow from the *várzea* begins at the

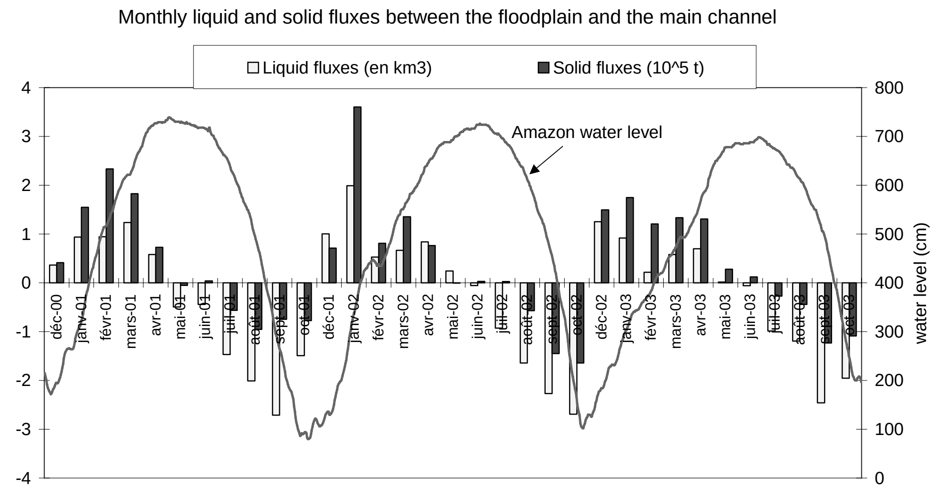

Fig. 5 Monthly water and solid fluxes between the Amazon mainstream and the flood plain system, for the 2000–2003 hydrological years. A comparison with the Amazon River water level (Obidos station) is provided. Fluxes are positive during the filling of the flood plain lakes and negative during the outflow.

flood peak of the Amazon River, in June, due to the filling of the lakes by local rainfall (Fig. 5). Because of the intensity and the timing of the local rainfall, the output of water from the flood plain is greater than the input of Amazon water to the system (Table. 1). The net annual input of water from the Curuai flood plain into the Amazon River varies from 1.5 km^3 to 4.8 km^3, depending on both the local and the regional mean annual rainfall. The highest output fluxes are observed between October and December, during the low water stage of the mainstream river.

The net sediment balance is always negative, confirming that this Amazonian flood plain acts as a sediment trap. The mean annual sediment fluxes entering the modelled area of the Amazon flood plain at Curuai do not vary significantly from year to year and reach 879 176 t ± 3.45%. In contrast, the variability of the annual volume of sediment trapped in the flood plain system is higher, with a mean annual value of 379 421 t ± 7.82%. The different hypotheses employed for the sediment flux calculations do not have a major effect on the results, and the annual mass of sediment trapped in the flood plain lakes varied between 352 583 t in 2000–01 and 411 189 t in 2002–2003 with a standard deviation of less than 8% (Table 1). Very high TSS concentrations were measured during 2001–2002 in one of the main channels connecting the mainstream river with the flood plain mainstream, in October. TSS concentrations measured in the northern and southern channels of the Lago Grande were frequently characterized by considerable variability due to tidal effects, such that within the space of one hour, the time required for the observer to collect the two samples, the direction of the current flow can change and consequently affect the TSS concentrations. This effect was particularly detectable in the field during low water stages. A high level of temporal variability of the monitored TSS was also observed for the lakes and channels. High sedimentation rates are expected in major side channels of the Amazon River, but sedimentation rates are much lower within the *várzea.* Depositional processes in lakes can be disrupted by the re-suspension of sediment by wind waves, as is regularly observed in white water lakes during the low water stage. Suspended sediment concentrations in threes lakes ranged from 4 mg l^{-1} during the flood peak, to very high values during the dry season (1600 mg l^{-1}), more than six times the maximum TSS concentration measured in the Amazon mainstream during the same period.

During the flood peak, from May to July, sediment exchanges between the flood plain and the mainstream seemed to equilibrate. In contrast, high sediment deposition was observed during the first months of the low water stage, from September to December, leading to a negative balance. Although the suspended sediments inputs associated with the flux of Amazon waters into the flood plain move through the 10 different channels located around the system, the suspended sediment outputs from the *varzea* into the mainstream river mainly take place via the two widest channels located on the eastern side of the Lago Grande, which can reach widths of about 5 km in June and July.

CONCLUSION

To refine these preliminary findings, it would be interesting to devote more attention to modelling the re-suspension processes associated with wind effects that affect the bottom sediment in the connecting channels during low water stage, when the highest sediment fluxes are observed.

The area of flood plain investigated represents 0.8% of the total inundated area of the main Amazon River including the Negro and Solimões basins. The initial estimate of the mean sediment storage in the Curuai flood plain of about 380 000 t $year^{-1}$ (±7.82%) represents approximately 0.5 to 0.6% of the total annual sediment flux of the Amazon River at Óbidos, 600 to 800 10^6 t $year^{-1}$ estimated by Filizola *et al.* (2003). The associated mean specific sedimentation rate approaches 165 t km^{-2} $year^{-1}$, if only the maximum floodable area is considered. This is far less than the deposition rate of 2400 t km^{-2} $year^{-1}$ reported for the Beni River flood plain in an upstream foreland basin in Bolivia by Maurice-Bourgoin *et al.* (2002). These results underscore the key role of channel-flood plain sediment interchange in regulating the transport and accumulation of sediments and any heavy metals associated with fine particles.

Acknowledgements This research was funded by the HyBAm Program of IRD, the French Research Institute for Development, and the ANA (Brazilian Water Agency), in the framework of the cooperation agreement between IRD and CNPq (Brazil). The authors are grateful to the Brazilian observers who undertook the regular sampling of surface waters and to the crews who accompanied them during the surveys.

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