Seasonal links between the Amazon corridor and its flood plain: the case of the várzea of Curuaí

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Abstract Due the large extent (about 600 000 km^2) of the Amazonian flood plain it is expected to greatly influence the Amazon River dynamics, in terms of suspended solids and chemical fluxes. However, up to now, fluxes and exchanges between the main stream and its flood plain are poorly known and it is still difficult to precisely quantify to what extent the flood plain may play a significant role. For several years, in the framework of the HyBAm (Hydrology and Geochemistry of the Amazonian Basin, IRD-CNPq) research programme, *in situ* hydrological and geochemical conditions have been investigated in a flood plain located in the lowest part of the river course. This data set enabled development of a model describing fluxes exchanged between the flooded area and the Amazon River. The model—in a relatively simple form—was in good agreement with the data. The results show that the flood plain is a source of water and of redox sensitive elements, such as arsenic, for the Amazon River.

Key words Amazon River; flood plain; modelling

INTRODUCTION

The Amazon basin drains a surface area of around 6 000 000 km^2, constituting ~5% of the Earth's terrestrial surface. In the middle and lower part of their courses, the Amazon River and its large tributaries are accompanied by large flooded areas named "várzeas" in Brazil. These systems cover a total area of about 300 000 km^2 (Junk, 1997), including 110 000 km^2 along the main stream (Melack & Fisher, 1990) and are composed of permanent and temporary lakes which increase in size and become connected to each other during periods of high water level stage. Due to their large extent, these areas are expected to play a significant role in the river dynamics (Junk *et al.*, 1989; Sparks *et al.*, 1990), such as enabling damping of the hydrograph with efficiency, depending on their storage capacity. Based on a Muskingum formula, Richey *et al.* (1989) indirectly estimated that 30% of the Amazon River flow is routed through the flood plain along a 2000 km reach between Sao Paulo de Olivença and Óbidos. However, the role of the flood plain in fluxes of suspended solids and the biogeochemistry dynamics of the Amazon River is still not yet well quantified.

The major part of the suspended solids in the Amazon River originate from the Andean chain; the particles are strongly altered by deposition/re-suspension cycles in channels and flood plain (Quay *et al*., 1992). More than 80% of the suspended solids entering the várzeas are deposited (Mertes *et al.*, 1996; Dunne *et al.*, 1998), but the storage in the flood plain is temporary. Dunne *et al*. (1998) estimate that on an annual timescale roughly 2 billion tons of suspended solids enter the flood plain, while 1.5 billion tons are exported from these systems due to re-suspension processes, wind action or erosion. Similarly, flood plains are expected to play a significant role in the carbon cycle. A high primary production takes place in the flood plain (estimated to 115 t C ha^{-1} $year^{-1}$; Junk, 1985) of which 73% is due to phytoplankton and macrophytes. Part of the organic carbon produced in the flood plain is exported and sustains heterotrophic activity in the Amazon River (Quay *et al.*, 1992). Redox conditions present in the flood plain sediment and eventually in the water column may induce dissolution of oxide and hydroxide minerals. A recent study of geochemistry of the Amazon River has shown that some trace elements, such as Mn or Fe, show a concentration maxima a few weeks after the discharge maxima. This was interpreted as the influence of dissolved substances fluxes exported from the várzea in which biochemical processes were favourable to dissolution or desorption (Seyler & Boaventura, 2001, 2003).

In this study, we aim to quantify the exchanged water fluxes as well as the fluxes of some dissolved substances between the Amazon River and a particular várzea. Our approach is based on a relatively simple model which takes advantage of an extensive database.

STUDY SITE AND AVAILABLE DATA

The study site is the várzea of Lago Grande de Curuaí (between 56.10°W and 55.00°W from upstream to downstream, and 2.3°S and 1.9°S) located in the lowest part of the Amazon River near Óbidos (Para state, Brazil), the last gauging station before the estuary (Fig. 1). This várzea has a flood area varying between 1340 and 2000 km^2 (Kosuth, 2002) according to water level stage. Its watershed covers 3660 km^2 including open waters.

This várzea is formed by several white-water lakes (waters characterized by high suspended sediment loads) and black-water lakes (waters characterized by high concentrations of dissolved humic acids and low concentrations of suspended sediment) interconnected with each other and permanently connected to the Amazon mainstream by small channels.

Since 1999, daily water level was recorded at several locations in the várzea. Discharge, using an ADCP (Acoustic Doppler Current Profiler), was estimated in the main connecting channels between the Amazon River and the várzea. Samples for determination of suspended solids and major and trace elements concentrations were taken three times per month and monthly, respectively. Precipitation was recorded daily at Curuaí.

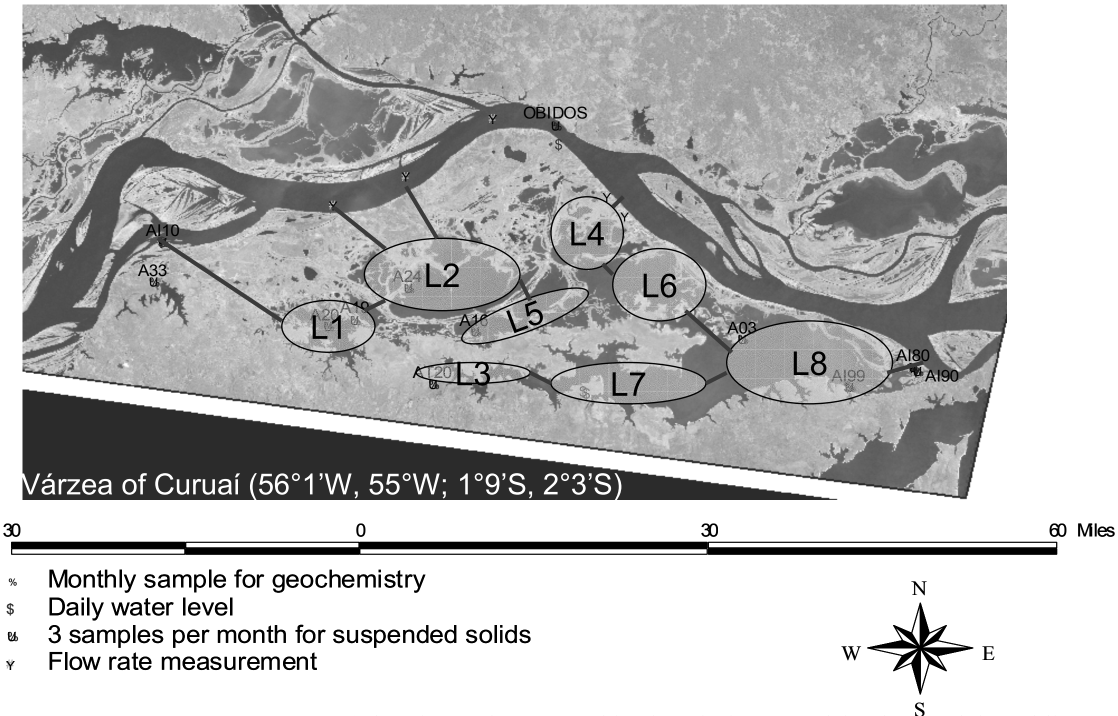

Fig. 1 Map of the site and topographic descriptions used in the model enabling an optimal use of the *in situ* data.

MODEL PRINCIPLE

The objectives of the modelling approach are to quantify the flux of water and some dissolved substances fluxes exchanged between the Amazon River and its flood plain and to determine water renewal time within the different parts of the várzea. The hydrological model is based on three governing equations allowing the description of the water mass balance of the different lakes constituting the várzea. Resolution is achieved using an implicit scheme in time and an upstream scheme in space.

At each time step t:
flow rate Q_{ij}^{t+1} (m^3 s^{-1}) in channel ij linking lake i and j (or Amazon River connecting point i and lake j) is computed by a Strickler-Manning formulation assuming depth $H << L$, where L is the channel width (m).

$$Q_{ij}^{t+1} = K_s \sqrt{p_{ij}^{t+1}}\, L {H_{ij}^{t+1}}^{5/3} \tag{1}$$

with K_s the roughness coefficient, $p_{ij}^{t+1} = \dfrac{\left|Z_i^{t+1} - Z_j^{t+1}\right|}{l}$ is the bottom slope (m m^{-1}) assumed equal to the water slope between upstream points Z_i^{t+1} and Z_j^{t+1}. l (m) is the channel length. Flow direction is deduced from the sign of p. $H_{ij}^{t+1} = \dfrac{Z_i^{t+1} + Z_j^{t+1}}{2}$ is the mean depth of the channel.

The water mass balance of each lake B_i (m^3 s^{-1}) is computed as follows:

$$B_i^{t+1} = \left(\sum_{ij} Q_{ij}^{t+1} \right) + Q_{p_i}^{t+1} + Q_{BV_i}^{t+1} \tag{2}$$

where $\sum_{ij} Q_{ij}^{t+1}$ is the algebraic sum of flow rates in ingoing (positive) or outgoing (negative) channels for lake i (m^3 s^{-1}), $Q_{p_i}^{t+1}$ (m^3 s^{-1}) is the flow rate linked to precipitation on S_i^{t+1}, the open water area, whereas $Q_{BV_i}^{t+1}$ (m^3 s^{-1}) is linked to precipitation on the water shed of lake i. Both terms $Q_{p_i}^{t+1}$ and $Q_{BV_i}^{t+1}$ are deduced from daily raingauge data located in Curuaí after subtraction of evaporation. The latter is estimated according to (Riou, 1975) as: $ETP = 0.3T_m - 5.9$, where ETP is the potential evapotranspiration (mm day^{-1}), T_m is the monthly averaged maximum temperature (°C). At this stage, due to a lack of data, the model does not take into account any exchanges with the water table. Additional field investigations will be undertaken in order to investigate these exchanges.

Adjustment of the water level of lake i is then deduced by a simple mass conservation equation :

$$Z_i^{t+1} = Z_i^t + \frac{B_i^{t+1} * \Delta t}{S_i^{t+1}} \tag{3}$$

where S_i^{t+1} is the lake area varying with water level according to a third-order polynomial function deduced from altimetry data (JERS) (Martinez *et al.*, 2003).

Once convergence of the hydrologic model is achieved, the model also allows computation of non-reactive tracer fluxes, assuming a convective transport.

At each time-step $t + 1$, the fluxes balance in each lake i $B\Phi_{ij}^{t+1}$ (g m^{-3} s^{-1}) is computed according to (4):

$$B\Phi_i^{t+1} = \left(\sum_{ij} \Phi_{ij}^{t+1} \right) + \Phi_{p_i}^{t+1} + \Phi_{BV_i}^{t+1} \tag{4}$$

where $\Phi_{p_i}^{t+1} = Q_{p_i}^{t+1} C_p$ is the flux linked to the rainfall, C_p is the tracer concentration in rain (g m^{-3}). Similarly, $\Phi_{BV_i}^{t+1}$ is the flux associated with the watershed runoff. $\sum_{ij} \Phi_{ij}^{t+1}$ is the algebraic sum of the input and output fluxes computed according to an upstream scheme.

RESULTS AND DISCUSSION

The model has been applied for a three-year period from January 2001 to December 2003. At this stage, eight interconnected lakes are taken into account as shown in Fig. 1. This topographic description allowed advantage to be taken of the *in situ* collected data

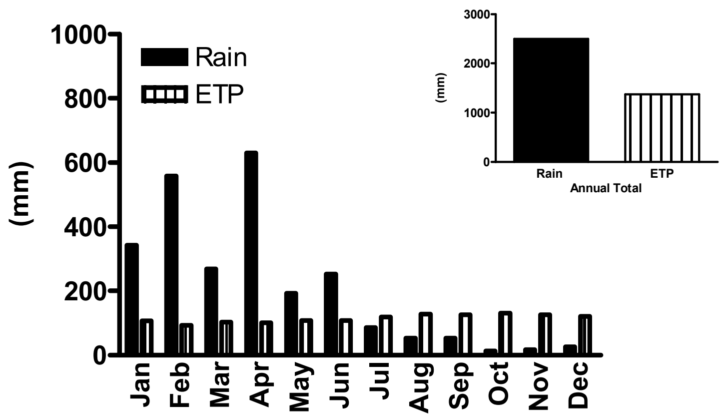

Fig. 2 Measured precipitation and estimated evapotranspiration in Curuai during 2001.

that show that the flood plain is not a homogeneous system, and was necessary in order to give an estimation of the water renewal time in the different lakes of the várzea.

Data required for simulation are evaporation and precipitation. As shown in Fig. 2, during year 2001, evaporation accounts for roughly 55% of the rainfall. Highest precipitation occurs from January to April, while evapotranspiration is nearly constant throughout the year. Besides daily precipitation and evapotranspiration, data requirements for the simulation include water level measured in the Amazon River at the mouths of different connecting channels. This data is provided by the national water agency (ANA, Brazil) at three locations, Parintins (40 km upstream from the várzea), Óbidos and Santarem (40 km downstream from the várzea). Linear interpolation is used to determine the water level at the relevant locations. In addition, an initial water elevation is required for all the lakes.

The model was calibrated against water level measured in Curuaí and discharges measured at the different várzea–Amazon River connecting channel mouths. The parameters that require calibration are related to channel geometry (width, depth, length) and the roughness coefficient, *Ks*. Among all these parameters, the latter is the least sensitive; it has been fixed to 40 for all channels. Channel length was deduced from satellite imagery and field data, whereas channel depth and width were mostly deduced from current profiles acquired during the field campaigns.

The simulated water level shows a very good agreement with measured water level (Fig. 3), the mean absolute difference does not exceed 7 cm and is similar for each simulated year of the study (calibration period (2002) and the validation period (2001 and 2003)). Moreover, for most of the várzea–Amazon River channels, the computed flow rate is in good agreement with the data acquired during the field campaigns (Fig. 4). However, additional discharge measurements would be necessary to establish realistic rating curves of the different connecting channels in order to get more confidence in the model validation. As seen from Fig. 4, upstream channels AI 10 to AI 30 only operate as a source of water for the várzea, whereas the downstream channel AI80 mainly behaves as a sink.

During an annual hydrological cycle, the várzea behaves as a source of water for the Amazon River, but exported fluxes only account for roughly 0.45% of the annual average water flux of the Amazon River estimated at Óbidos (the mean average flow

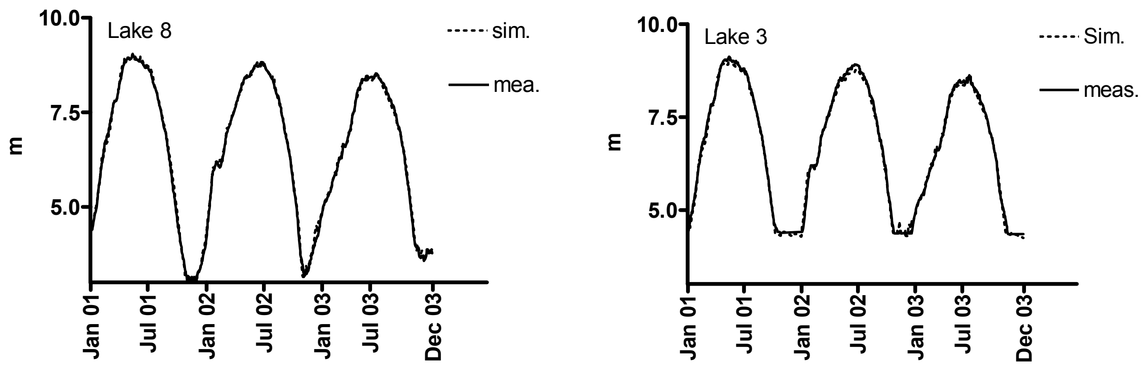

Fig. 3 Comparison of the measured and simulated water levels in the eastern part of the várzea (Lake 8) and the western part (Lake 3) of the várzea.

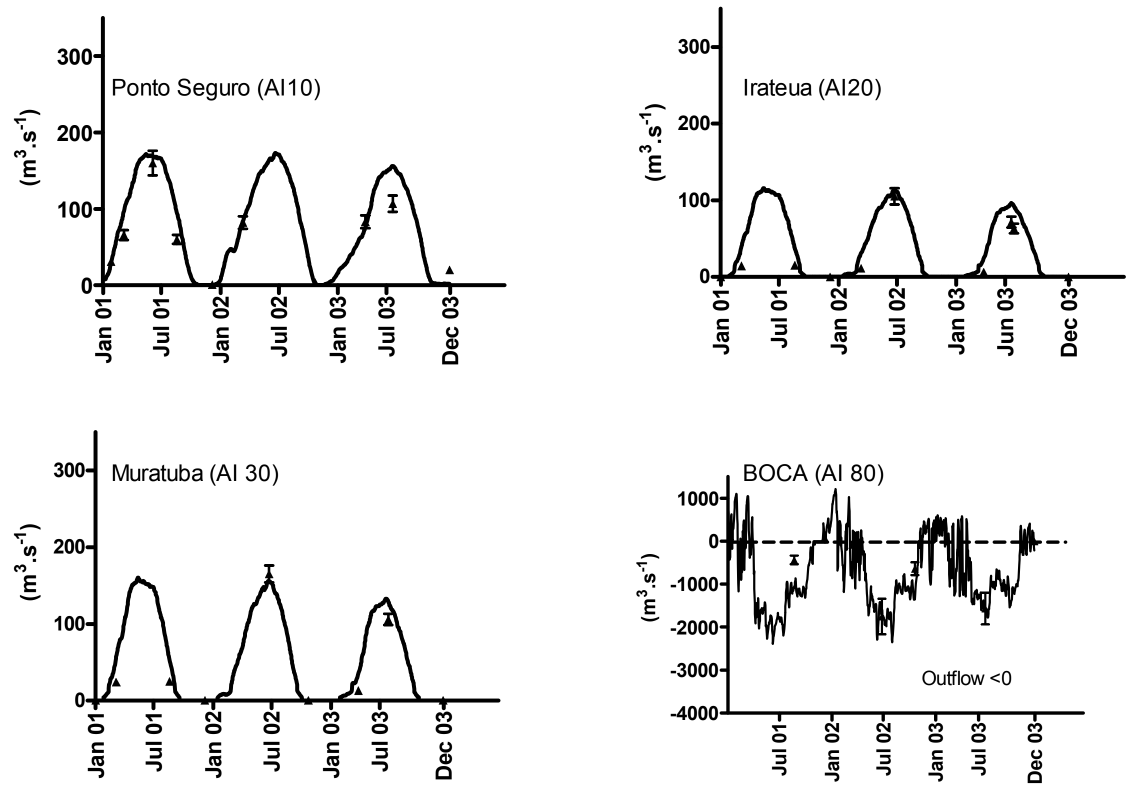

Fig. 4 Comparison between measured (triangle) and simulated (solid line) discharges in different connecting channels.

being 169 000 $m^3 s^{-1}$). However, assuming a similar behaviour for all the flood plains in the Basin (300 000 km^2), we find that about 35% of the Amazon River and major tributaries is routed through these systems. This value is very close to that found by Richey *et al.* (1989) as mentioned in the introduction.

Once the exchanges with the Amazon River were calibrated, the model was applied to describe the transport of nonreactive tracers. This step was necessary to calibrate the exchanges between the different parts of the várzea, in order to give insights on the renewal time in the different lakes constituting the study area. The results of chlorine simulation for the two main lakes of the várzea are shown in Fig. 5.

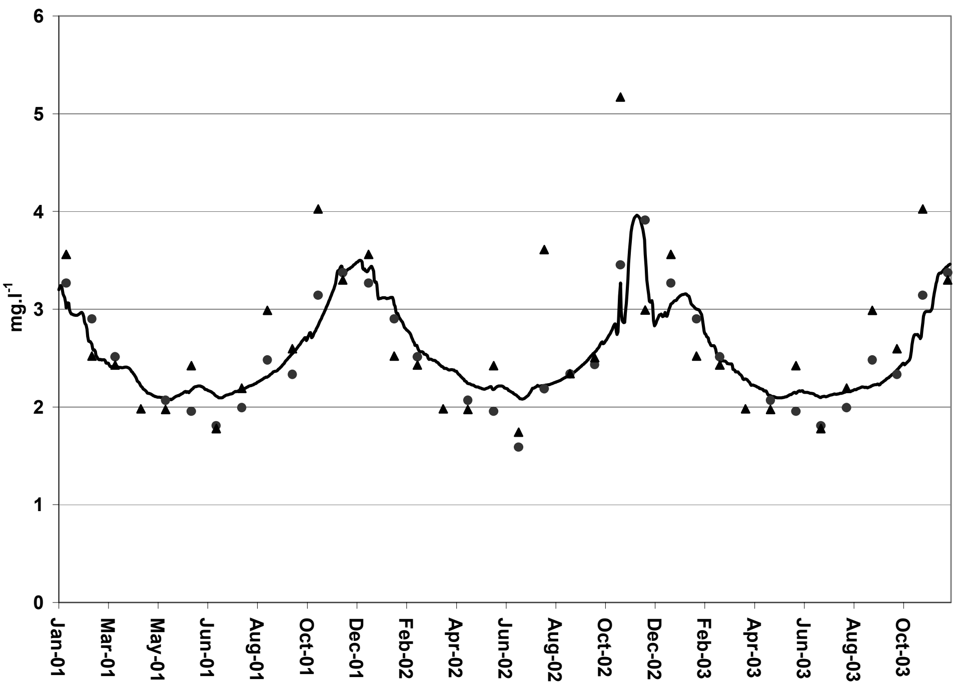

Fig. 5 Comparison of the measured (circle) and simulated (solid line) chlorine concentration in the eastern part of the várzea. Chlorine concentration in the Amazon River is also reported (triangle).

A good agreement between the simulation and the data is obtained for lake 8, which corresponds to Lago Grange of Curuaí in the eastern part of the várzea. This lake is very well connected with the Amazon River as shown in Fig. 1. Temporal variation of its chlorine concentration is mainly driven by that of the Amazon River, with a small dilution by rain. Once more, some additional calibration work is required in order to simulate the temporal variations in the other parts of the várzea properly. Moreover, the model shows large heterogeneities in the water residence time from lake to lake, with a minimum of less than 1 month and a maximum of more than 6 months. The mean water renewal time is about 3.5 months which is in good agreement with value proposed by Kosuth (2002).

As mentioned by Seyler & Boaventura (2003), redox conditions prevailing in the várzea may induce dissolution or desorption of some trace elements. In particular, it is expected that the várzea behaves as a net source of elements such as arsenic (As), iron or manganese. In order to verify this assumption, we used the model to compute exchanged fluxes of As, using the measured concentration in the eastern part of the várzea. Results of the model confirm that the várzea behaves as a source of As (Fig. 6). Export occurs mainly during the decreasing water level stage (May–October) and is maximal during the low water level period. The exported flux from the várzea to the Amazon River accounts for only about 0.3% of the annual average As flux at Óbidos. Using a similar approach as used for water fluxes (see above) to extrapolate to all the flood plains, we find that these systems could account for 24% of the As flux at Óbidos. These results are in good agreement with Seyler & Boaventura (2003). The highest export of As, especially during low water periods, can be explained by the increase of the water residence time and by reductive conditions at the sediment–water interface.

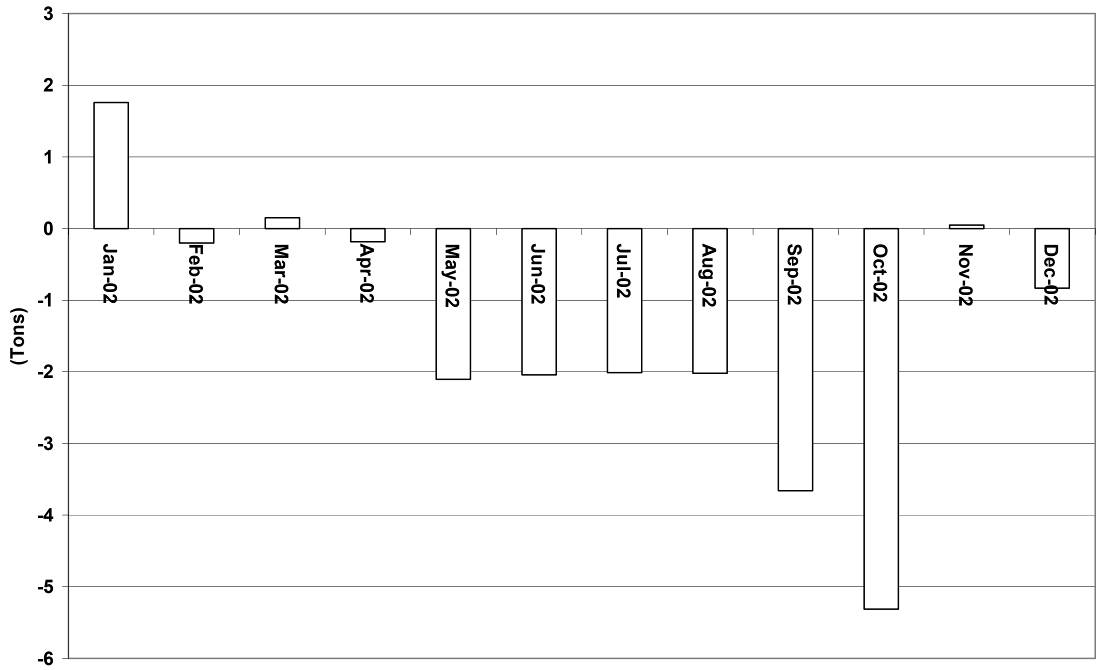

Fig. 6 Exchanged arsenic mass between the várzea and the Amazon River. Negative values indicate exportation from the várzea.

CONCLUSIONS

In this study, we propose a model to quantify exchanged fluxes between the Amazon River and one of its flood plain lakes systems. Despite a relatively low level of complexity, the model showed a good agreement with the *in situ* data. The várzea behaves as a source of water for the Amazon River. Extrapolating to similar hydrosystems, we found that the whole flood plain in the Amazonian Basin may account for 35% of the mean annual flux at Óbidos. Using the model to quantify the exchanged flux of arsenic, a redox sensitive element, we showed that the várzea behaves as a source of such types of element. Extrapolation to the whole Amazon River flood plain indicates that such systems could account for 24% of the mean annual As flux at Óbidos. The computed residence time for the whole várzea is about 3.5 months but large heterogeneities are expected from lake to lake, from less than 1 month to more than 6 months. However, the latter result needs to be confirmed by additional calibration work.

REFERENCES

Dunne, T., Mertes, L. A. K., Meade, R. H., Richey, J. E. & Forsberg, B. R. (1998) Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. *Geol. Soc. Am. Bull.* **110**, 450–467

Junk, W. J. (1985) The Amazon floodplain: a sink or source for organic carbon? In: *Transport of Carbon and Minerals in Major World Rivers*, 267–283 Pt3. SCOPE/UNEP.

Junk, W. J. (1997) *The Central Amazon Flood Plain: Ecology of a Pulsing System*. Ecological Studies 126. Springer-Verlag, Berlin, Germany.

Junk, W. J., Bayley, P. B. & Sparks, R. E. (1989) The flood pulse concept in river-floodplain systems. (In: Proc. Int. Large River symp.) *Can. Special Publ. Fish Aquat. Sci.* **106**, 110–127

Kosuth, P. (2002) Water and sediment dynamics in the Várzea of Lago Grande de Curuaí. In: *Second International LBA Scientific Conference*) Manaus, 7–10 July 2002.

Martinez, J. M., Kosuth, P., Cochonneau, G., Guyot, J.-L., Seyler, F., Bourrel, L. & Maurice-Bourgoin, L. (2003) Application of remote sensing data for the quantification of an Amazon floodplain extension, dynamic and river water storage. In: *Proc. Joint Conference of European Geophysical Union and American Geophysical Union* (Nice, France, Avril 2003).

Quay, P. D., Wilbur, D. O., Richey, J. E., Hedges, J. I., Devol, A. H. & Victoria, R. (1992) Carbon cycling in the Amazon River: implication from the ^{13}C compositions of particles and solutes. *Limnol. Ocean*. **37**(4), 857–871.

Richey, J. E., Mertes, L. A. K., Dunne, T., Victoria, R. L., Forsberg, B. L., Tancredi, A. C. N. S. & Oliveira, E. (1989) Sources and routing of the Amazon River flood wave. *Global Biogeochem. Cycles* **3**, 191–204.

Riou, C. (1975) La détermination pratique de l'Evaporation. Application à l'Afrique centrale. Thèse. Mémoires Orstom no. 80. Orstom, Paris, France.

Seyler, P. & Boaventura, G. R. (2001) Trace elements in the mainstream Amazon River. In: *The Biochemistry of the Amazon Basin* (ed. by M. E. McClain, R. L. Victoria & J. E. Richey), Chap. 16. Oxford University Press, Oxford, UK.

Seyler, P. & Boaventura, G. R. (2003) Distribution and partition of trace metals in the Amazon Basin. *Hydrol. Processes*. **17**, 1345–1361.