Annual changes in sediment entrapment efficiency in lakes lateral to a river (Paranapanema River, São Paulo, Brazil)

Variações anuais na eficiência de deposição de sedimento em lagoas laterais a um rio (Rio Paranapanema, São Paulo, Brasil)

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Abstract: Aim: Sediment entrapment efficiency was evaluated in two lateral lakes of the Paranapanema River (São Paulo, Brazil) in its mouth zone into Jurumirim reservoir, one largely associated with the river (Coqueiral Lake), and the other with little connection (Camargo Lake). **Methods:** Sediment traps (cylindrical shape, 3:1 height/diameter ratio, 10 cm diameter) were incubated in each lake at Secchi depth for 24/30 hours monthly and at the bottom of the water column. After incubation, water samples were filtered and the suspended sediment was measured by gravimetry in an oven at 60 °C for 24 hours. Sediment content was estimated for the whole trap volume, and the sedimentation rate was expressed in $g.m^{-2}.day^{-1}$. The daily river sediment load ($t.day^{-1}$) was obtained by multiplying the suspended matter concentration ($g.m^{-3}$) by the water discharge ($m^3.s^{-1}$). Sediment deposition in the two lakes was estimated by multiplying the sedimentation rates by the surface area of each lake (corrected for temporal variations of water level and hydrologic connectivity with the river). Sediment entrapment efficiency is the ratio (%) of the monthly sediment load deposited in the lake to the respective sediment load in the Paranapanema River. Annual river sediment loads deposited in the lakes were computed from daily values and time variations (days between monthly determinations). **Results:** A high annual variation (CV = 162%, $\bar{x}$ = 474.32 ± 765.42 $t.day^{-1}$ SD) was recorded for sediment loads transported by the Paranapanema River. Annual deposited sediment means in Camargo and Coqueiral Lakes were 3.12 ± 3.34 $t.day^{-1}$ SD (CV = 107%) and 20.90 ± 28.38 $t.day^{-1}$ SD (CV = 135%), respectively. The sediment entrapment efficiency of Camargo Lake was 1.69 ± 1.01% SD (CV = 114%), and of Coqueiral Lake was 10.95 ± 16.93% SD (CV = 155%). The annual load of sediments deposited in the Camargo and Coqueiral Lakes were 1,134.04 and 7,428.33 t, respectively, and deposition efficiencies were 1% and 5%, respectively. **Conclusions:** The low entrapment efficiencies of the two lakes were attributed to the weakening of lateral hydrologic pulses in the river-reservoir transition zone. The fact that the river banks are covered by grass (*Echinochloa polystachya* (H.B.K.) Hitchcock) also contributed to reduce the lateral sediment influx to the lakes during the high water period. Thus, most sediment introduced by the Paranapanema River was transported to the reservoir riverine zone and affected euphotic zone depths.

Keywords: sediment deposition, suspended matter, river, marginal lakes.

Resumo: Objetivo: A eficiência de deposição de sedimentos foi avaliada em duas lagoas laterais ao Rio Paranapanema (São Paulo, Brasil) na zona de sua desembocadura na Represa de Jurumirim, uma com elevada associação com o rio (Lagoa do Coqueiral) e outra com baixa conexão (Lagoa do Camargo). **Metódos:** Câmaras de sedimentação (formato cilíndrico, razão altura/diâmetro de 3:1, 10 cm de diâmetro) foram incubadas mensalmente, em cada lagoa na profundidade do disco de Secchi e no fundo da coluna de água por cerca de 24/30 horas. Após a incubação, amostras de água foram filtradas e o sedimento suspenso foi quantificado por gravimetria (em estufa a 60 °C por 24 horas). O conteúdo em sedimentos foi estimado para todo o volume da câmara, e a taxa de sedimentação foi expressa em $g.m^{-2}.dia^{-1}$. A carga diária de sedimento ($t.dia^{-1}$) transportada pelo rio foi obtida multiplicando-se a concentração de material em suspensão ($g.m^{-3}$) pela vazão de água ($m^{-3}.s^{-1}$). A deposição de sedimentos nas duas lagoas foi estimada através do produto das taxas de sedimentação pela área de superfície de cada lagoa (corrigida em função das variações temporais do nível de água e conectividade hidrológica com o rio). A eficiência de deposição de sedimentos é a razão (%) entre a carga de sedimentos depositada mensalmente na lagoa e a carga respectiva de sedimentos transportada pelo Rio Paranapanema. As cargas anuais de sedimento do rio depositadas nas lagoas foram calculadas a partir de valores diários e variações temporais (intervalo em dias entre determinações mensais). **Resultados:** Elevada variação anual (CV = 162%, $\bar{x}$ = 474.32 ± 765.42 $t.dia^{-1}$ DP) foi registrada para as cargas de sedimento transportadas pelo Rio Paranapanema. As médias anuais de sedimento depositado nas Lagoas do Camargo e do Coqueiral foram de 3.12 ± 3.34 $t.dia^{-1}$ DP (CV = 107%) e de 20.90 ± 28.38 $t.dia^{-1}$ DP (CV = 135%, respectivamente. A eficiência de deposição de sedimento da Lagoa do Camargo foi de 1.69 ± 1.01% DP (CV = 114%), e na Lagoa do Coqueiral foi de 10.95 ± 16.93% DP (CV = 155%). A carga anual de sedimentos depositados nas Lagoas do Camargo e do Coqueiral foram de 1.134 e 7.428 t, respectivamente, e as eficiências de deposição foram 1% e 5%, respectivamente. **Conclusões:** As baixas eficiências de deposição dos dois lagos foram atribuídas ao amortecimento dos pulsos hidrológicos na zona de transição rio-represa. O fato de que as margens do rio apresentam-se cobertas por uma gramínea (*Echinochloa polystachya* (H.B.K.) Hitchcock) também contribuíram para reduzir o influxo lateral de sedimento para as lagoas no período de águas altas. Portanto, a maior parte do sedimento introduzido pelo Rio Paranapanema foi transportado para a zona fluvial do reservatório e afetou as profundidades da zona eufótica.

Palavras-chave: deposição de sedimento, material em suspensão, rio, lagoas marginais.

1. Introduction

One remarkable characteristic of rivers is their interaction with lateral plains. Except in canyon stretches, where the surrounding terrestrial ecosystems slope is extremely steep, particulate material deposition on lateral plains is evident, especially in intermediate and high order stretches in rivers at water overflows. The particulate material sedimentation is responsible for the construction and remodeling of plains lateral to watercourses. Several sediment accretion processes may contribute to the formation of floodplains, depending upon the features of the nearby rivers (Stevaux and Souza, 2004). An important process is the vertical accretion of sediment in levees, crevasses, and back swamps by a single river channel with a low slope gradient (Stevaux and Souza, 2004). Overbank sediment deposition is the main component of floodplain evolution (Walling and He, 1997). Lateral variation of particulate matter storage depends on the distance from the river channel, the sediment nature, and inundation frequency and duration (Walling and He, 1998; Kronvang et al., 2007). Floodplain morphology determines the dispersion patterns of overbank sediment fluxes (Foster and Thoms, 2001). Lateral deposition results in build-up of adsorbed nutrients and contaminants to sediments, their subsequent accumulation on the floodplain, and the reduction of nutrient/contaminant flux downstream the watershed (Walling and Owens, 2003; Kronvang et al., 2007).

In a lake complex interconnected with the Amazon River, Moreira-Turcq et al. (2004) found highly spatially variable sedimentation fluxes of particulate matter; however, the highest values of organic carbon vertical fluxes occurred during the water level falling period when suspended particulate matter concentrations were also very high. The authors attributed these findings to the re-suspension of bottom material that occurred during the falling period. They concluded that the heterogeneous spatial sedimentation was probably a function of the distance from the river main channel, increasing with closer proximity to the Amazon River. Bourgoin et al. (2007) estimated that 19% of conveyed sediment loads, as measured along a stretch of the Amazon River, were deposited in the same lake complex. According to that study, the annual retention varied between 41 and 53% of the annual sediment flux into the floodplain through the main channels. In the semi-arid wetland Las Tablas de Daimiel (Spain), Sanchez-Carillo et al. (2001) found the highest wetland input sedimentation rates and decreased with the increase in the inflow distance. They did not record any temporal relationship between sedimentation fluxes and water level, but they observed a seasonal variability coincident with the growth period of submerged aquatic vegetation.

Human activities can alter the lateral connectivity between rivers and floodplains. According to Thoms (2003), constructing dikes and other water retention structures within a river channel or modifying natural hydrological patterns of water pulses can alter casual associations between rivers and their lateral environments. The disruption of lateral connectivity downstream from dams in rivers disturbs populations, communities, and ecosystems (Sparks et al., 1990; Ward and Stanford, 1995). In floodplains submitted to water lateral pulses at low gradient stretches of a river, the intense matter, nutrient and biota exchange affects biodiversity and ecological processes such as production, respiration, and nutrient consumption in lotic and adjacent lentic areas (Junk et al., 1989). The storage of water by dams also affects the zones upstream of reservoirs, because it modifies the natural pattern of hydrologic pulses from their tributaries. Retained waters in dams act as a true plug system, weakening the inflow pulses and significantly affecting the lateral connectivity (Henry, 2005). The alteration of natural patterns on water level variations and inflow to lateral plains change gradually from typical lotic stretches of tributaries up to mouth zones into reservoirs. Multiple hydrologic pulses were detected in the Paranapanema River over a year at a site located 60 km upstream from the river-Jurumirim Reservoir transition zone (Henry et al., 1999), as compared to a single annual change in water level at the river mouth zone into the reservoir (Henry et al., 2005).

The aim of this work was to show the seasonal variation pattern of suspended particulate matter loads conveyed by the Paranapanema River at the mouth zone into the Jurumirim Reservoir and sediment deposition in two lateral lakes. Since sediment retention is very high in the Jurumirim Reservoir (Henry et al., 1999), and since sedimentation dynamics differ between upstream and downstream zones in large reservoirs (Phillips, 2001), lentic environments connected to rivers are probably sites of significant sediment deposition.

2. Material and Methods

2.1. The study area

The study site was the Paranapanema River mouth into the Jurumirim Reservoir (São Paulo, Brazil) (Figure 1). The river-reservoir transition zone is a true wetland, constituted by many marginal lakes that have distinct hydrologic associations with the river. The lakes selected for the study (Coqueiral and Camargo Lakes) are connected with the Paranapanema River for most of the year and are submitted to annual water level variation around from 2.7 to 3.0 m (Figure 2). During a prolonged drought period from October/99 to December/00, both lakes remained isolated from the river (Henry et al., 2006; De Nadai and Henry, in press). At the upstream study site, the Paranapanema River drains a watershed (5,779 km^2 area) predominantly covered by forests (24%), reforestation areas (20%), and pastures (33%). The export coefficient of suspended solids sums to 13.7-15.5 $t.km^{-2}.year^{-1}$ (Henry and Gouveia, 1993). The annual sediment load introduced into the reservoir by the watercourse in 1993 and 1992 was estimated at 82,049 and 92,740 t, respectively, which corresponds to 240 $t.day^{-1}$ (Henry et al., 1999). At the mouth zone, the Paranapanema River has a reduced current velocity (Henry et al., 2005), and consequently high sediment deposition rates when compared with the sediment deposition rates in the dam zone of the Jurumirim Reservoir (Henry and Maricatto, 1996). Coqueiral and Camargo Lakes have distinct areas (641,263 and 224,465 m^2, respectively), volumes (1,012,957 and 719,867 m^3), maximum (3.5 and 3.9 m) and mean depths (3.2 and 1.6 m), and connections with the Paranapanema River (Henry, 2005).

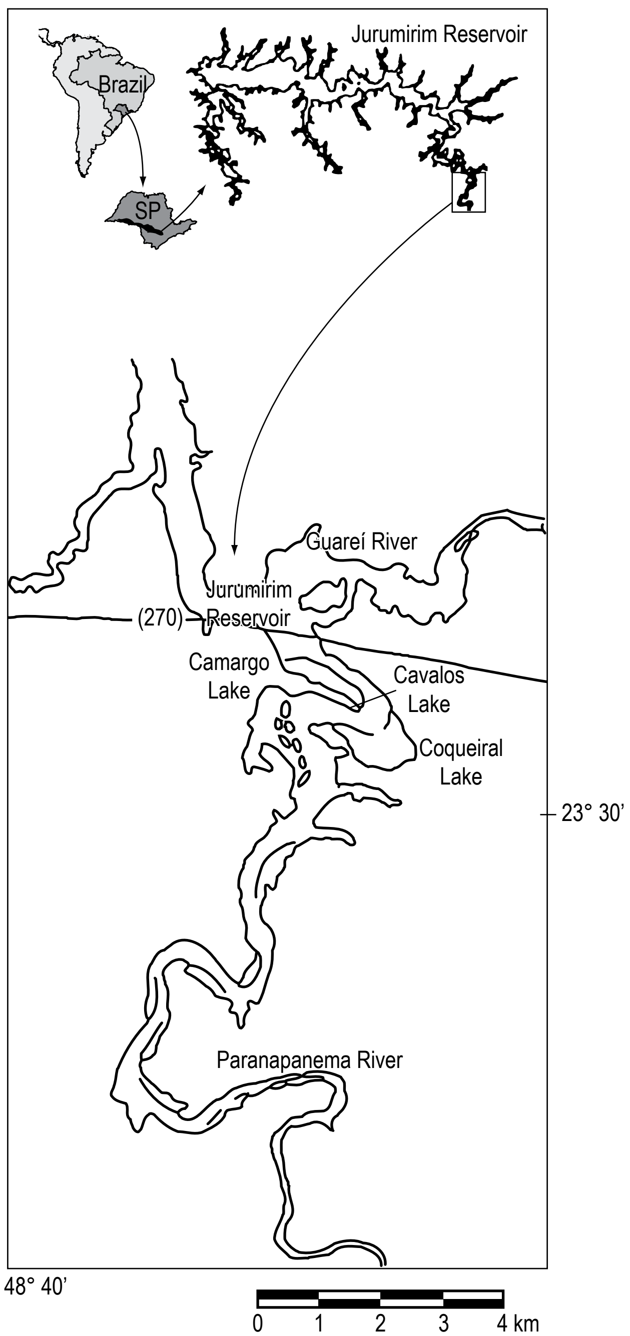


Figure 1. Study area: The Paranapanema River mouth zone at the Jurumirim Reservoir (São Paulo, Brazil).

2.2. Settling measurements and data analysis

Several methods can be used to evaluate overbank sediment deposition on floodplains, including estimations using $^{137-}$Cs fallout in sediment cores (Walling and Owens, 1998) or $^{210-}$Pb radioisotope dating (Moreira-Turcq et al., 2004), and experiments measuring particulate matter accumulation on either mats or sediment traps (Walling and He, 1998).

To evaluate the total settling particulate matter (SPM) deposition rates in Camargo and Coqueiral Lakes, cylindrical sediment traps made of PVC tubes (3:1 height:diameter) were incubated for 24-30 hours at a site near the connection of the lakes with the Paranapanema River (Figure 1). At each site, two four-trap sets were placed at two water column levels, at the depth of visual disappearance of a Secchi disk (Z_{DS}) and another at the lake bottom (Z_{MAX} – 0.5 m). After incubation, water sub-samples from each trap were filtered through AP 40 Millipore filters. The SPM concentrations were determined by gravimetry in an oven at 60 °C, for 24 hours and the settling particulate inorganic matter (SPIM) was calculated by combustion losses (in a muffle at 550 °C for 1 hour). The total amount of SPM was estimated for the total trap volume, and the sedimentation rates were expressed in $g.m^{-2}.day^{-1}$.

The SPM and SPIM concentrations at two sites on the Paranapanema River (near the connection with the lakes, Figure 1) and at three depths (water column surface, middle, and bottom) of the two lacustrine systems were measured by gravimetry and combustion losses, respectively. Water transparency was also determined at each site by the Secchi disk method.

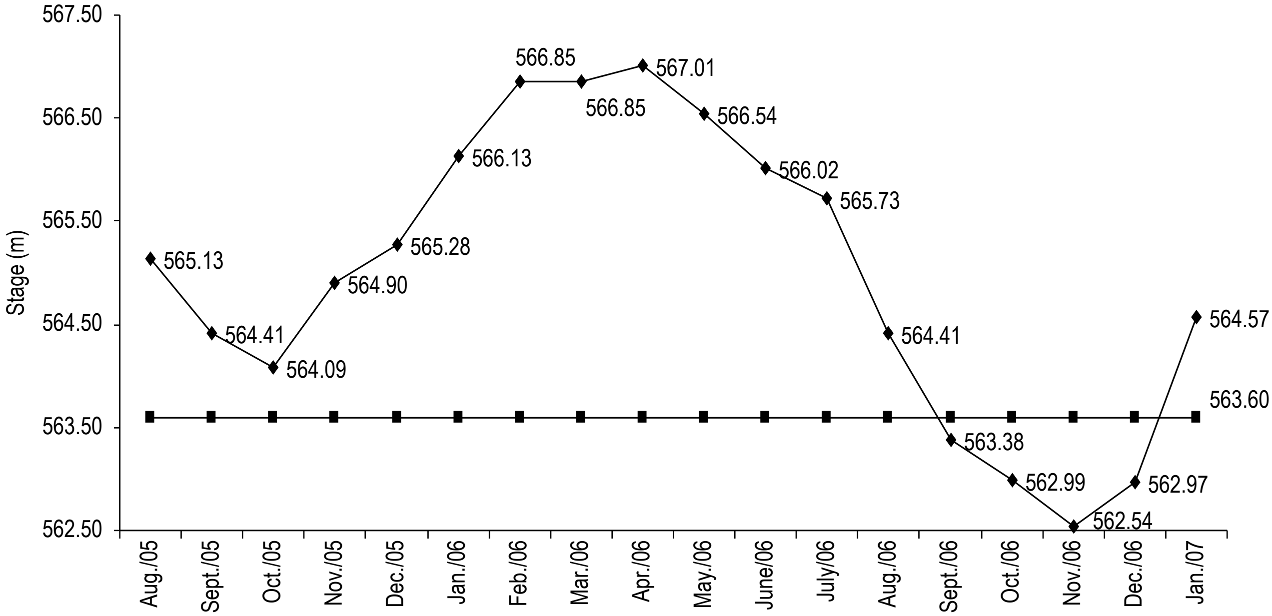


Figure 2. Annual variability in stages (m) of the Paranapanema River from August/05 to January/07.

The daily SPM load ($t.day^{-1}$) conveyed by the Paranapanema River was estimated through the product of SPM concentration ($g.m^{-3}$) and water discharge ($m^3.s^{-1}$, mean of the two sites near the connection with the lakes). Water discharge in river is the product of transversal section area (m^2) and mean current velocity ($m.s^{-1}$). Transversal section area was estimated after acquisition of bottom profile of each of the sites in July 24, 2001, using an Ocean Echosounder (Mod. Bathy - 500). Considering the significant variation in river water levels during the year (Figure 2), the values were corrected based on estimated area (336.6 m^2) for each month of the study. For water current velocity, monthly data were used from a previous study (Henry et al., 2005).

The particulate matter deposition over the total area in the two lakes was estimated by multiplying the sedimentation rate (monthly mean value of the four traps incubated at Z_{DS} depth, in $g.m^{-2}.day^{-1}$) by the lake area (value corrected as a function of water level variation and hydrologic connectivity with river). Sediment entrapment efficiency (%) is the ratio of total load of deposited particulate matter in lake ($t.day^{-1}$) to the respective particulate matter load conveyed by a river ($t.day^{-1}$). Annual sediment loads conveyed by the Paranapanema River and deposited in the two lakes were computed by planimetry from values ($t.day^{-1}$) and time (days) between sampling periods. The area summations over the year correspond to the annual load.

Factorial variance analysis (ANOVA) was carried out in order to assess variations in SPM and SPIM concentrations using the following variation factors: sampling periods (11 monthly collections) and the environments (three, Paranapanema River and Camargo and Coqueiral Lakes). The behavior of the SPM and SPIM sedimentation rates was analyzed by factorial ANOVA using the variation factors: sampling months (11), lakes (2), and trap incubation depths (2). The SAS system was used for ANOVA. A Tukey test was used to distinguish significant ($P < 0.05$) differences within each factor (periods, lakes, and incubation depths).

The amounts of re-suspended bottom sediment were estimated according to the Weyhenmeyer (1997) method based on regression between SPIM and SPM in the deposition. In cases with no SPIM deposited in the traps, all the SPM would be organic matter produced by plankton. Thus, the intercept between the SPIM/SPM regressions is the quantity of organic matter produced by plankton, which can be differentiated from re-suspended SPIM. For the application of the Weyhenmeyer (1997) method, sedimented organic matter must be produced in the lake, and the casual contribution of allochthonous matter to the lentic system must be insignificant. For the computation of re-suspended bottom matter, the Horppila and Nurminen (2005) method was applied. SPM and SPIM values ($g.m^{-2}.day^{-1}$) of each incubation period for each bottom trap were calculated separately in the regression analysis. When the correlation coefficient between SPM and SPIM was significant ($P < 0.05$), we concluded that sediment re-suspension had occurred during the measurement period. The re-suspended particulate matter amount (R) is the difference between SPM values and their respective intercept.

3. Results

During most of the study, the two lakes maintained hydrologic connectivity with the Paranapanema River. The water hydrometric levels were above 563.60 m, which is the connection threshold for the two lacustrine ecosystems and the lotic environment (Figure 2). During the rising water period, which lasted from October 2005 to February 2006, the water level increased by 2.76 m. Hydrologic stability occurred from February to April 2006. In the last month, a low water period began; it finished at the end of August with the disconnection (level < 563.60 m) of the Coqueiral and Camargo Lakes from the Paranapanema River. Drought period extended from October to December 2006 (Figure 2).

Great variability (measured by the coefficient of variation, CV, CV = 144%) in SPM concentrations were recorded in the Paranapanema River and the annual mean was 39.5 ± 56.9 $mg.L^{-1}$ (Figure 3). However, the annual mean in watercourse was around half the value of Coqueiral Lake and around threefold the mean of Camargo Lake (Figure 3). No significant difference was found between the SPM monthly values (F = 2.12, P = 0.08) or between sites (F = 1.25, P = 0.30) due to the great variability of Coqueiral Lake data. The lowest annual mean concentration of SPIM was recorded in Camargo Lake followed by the Paranapanema River and Coqueiral Lake values (Figure 3). Significant differences in inorganic matter concentrations were found between months (F = 2.59, P = 0.04), with the highest values being recorded in December, February, October, and July in decreasing order. However, no significant difference was found between the three environments (F = 1.25, P = 0.31).

An evident annual variation in water transparency, as measured with Secchi disk, was observed in the three environments (Figure 4). In general, the lowest values were recorded during the water level rising period (from October/05 to February/06). An increasing transparency trend was observed from March to June/06 (except in April). From June to August, the Secchi disk readings decreased. The annual mean transparency value of Coqueiral Lake (0.80 ± 0.44m, CV = 55%) was higher than that of Camargo Lake (0.58 ± 0.28m, CV = 48%).

Higher deposition rate annual variations of SPM (CV = 107%, mean: 13.9 ± 14.9 $g.m^{-2}.day^{-1}$) and SPIM (CV = 102%, mean: 5.6 ± 5.7 $g.m^{-2}.day^{-1}$) were found for traps incubated at the ZDS depth of Camargo Lake (Figure 5). However, the sedimentation rate annual means of both SPM (16.5 ± 9.3 $g.m^{-2}.day^{-1}$, CV = 56%) and SPIM (6.1 ± 4.8 $g.m^{-2}.day^{-1}$, CV = 78%) were higher for the bottom traps.

Sedimentation rates were higher in Coqueiral Lake than in Camargo Lake (Figure 5); its surface annual mean reached 32.6 ± 44.2 $g.m^{-2}.day^{-1}$ (CV = 135%) for SPM and 19.1 ± 35.6 $g.m^{-2}.day^{-1}$ (CV = 186%) for SPIM. The annual means of the bottom traps were around threefold higher for SPM (91.9 ± 140.8 $g.m^{-2}.day^{-1}$ SD, CV = 153%) than for SPIM (50.2 ± 129.0 $g.m^{-2}.day^{-1}$ SD, CV = 257%) (Figure 5). ANOVA revealed significant differences in SPM sedimentation rates between months (F = 341.33, P < 0.001), lakes (F = 960.72, P < 0.001), and trap incubation depths (F = 434.00, P < 0.001). A Tukey test showed higher values for Coqueiral Lake bottom traps and months. The highest values were recorded in a decreasing order in December, August, April and October, January, February, March, July, November and May, and June. With regard to SPIM, significant differences were found between sampling months (F = 538.00,

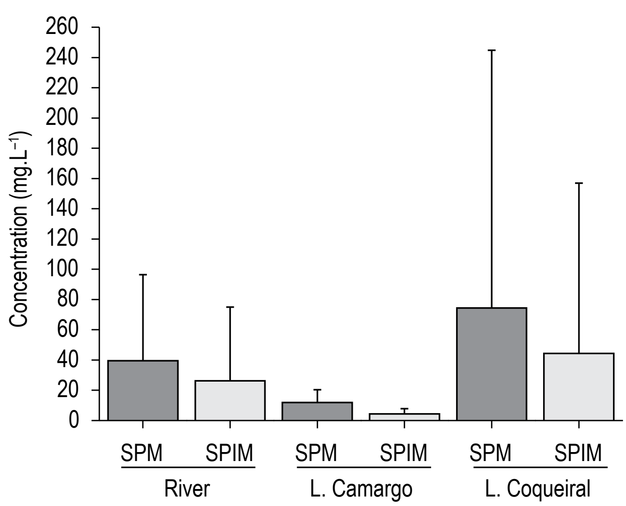


Figure 3. Suspended particulate and inorganic matter contents ($mg.L^{-1}$) in the Paranapanema River (means of the two sampling site values) and in the Camargo and Coqueiral Lakes (means of the three water column depth values) from October/05 to August/06 (annual means ± standard-deviations).

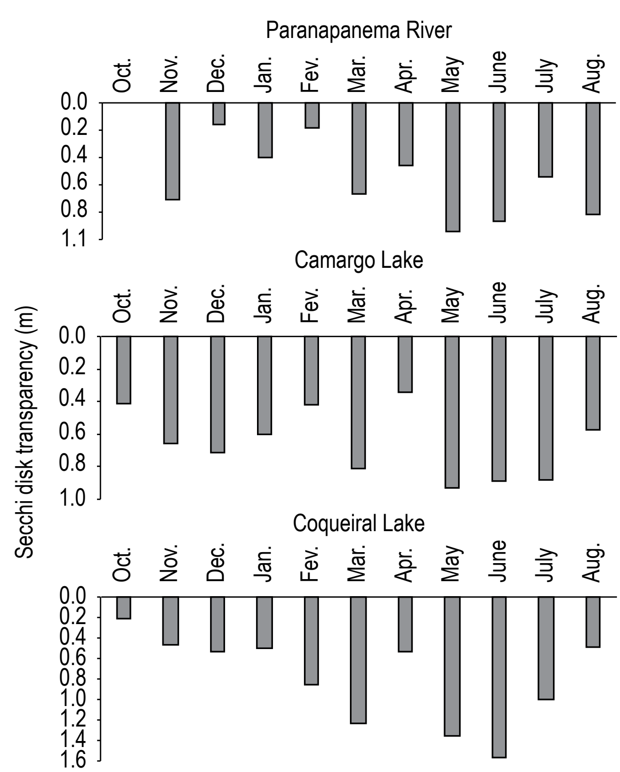
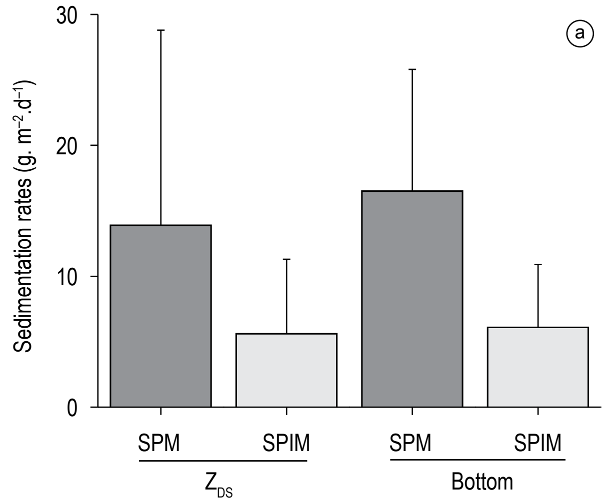


Figure 4. Secchi disk reading monthly variations in the Paranapanema River and Camargo and Coqueiral Lakes from October/05 to August/06.



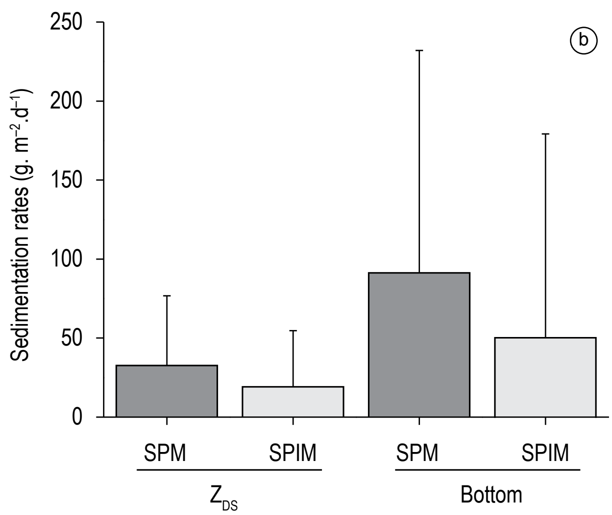


Figure 5. Annual means ± standard-deviations of suspended particulate matter and inorganic matter sedimentation (g.m^{-2}.day^{-1}) in a) Camargo and b) Coqueiral Lakes measured at the ZDS and the bottom of the water column.

$P < 0.001$), lakes ($F = 769.44$, $P < 0.001$), and incubation depths ($F = 2,559.68$, $P < 0.001$). A Tukey test gave results similar to those for SPM, except the decreasing temporal sequence, which was December, October, February, November, August, April, January, March, July and May, June.

Large annual variability (CV = 162%, mean = 474.31 ± 767.42 t.day^{-1}) was observed for SPM loads (monthly measurements) conveyed by the Paranapanema River (Table 1). Annual variation ranged from around 26 (June 2006) to 2,712 t.day^{-1} (December/05). The Camargo Lake annual mean of deposited sediments was 3.12 ± 3.34 t.day^{-1} (CV = 107%), ranging from 0.61 (January/06) to 11.95 t.day^{-1} (April/06) (Table 1). Thus, the sediment deposition efficiency of Camargo Lake was calculated to be 1.69 ± 1.91% (CV = 114%) of the load conveyed by the Paranapanema River (Table 1). The annual mean deposited sediment (20.90 ± 28.38 t.day^{-1}, CV = 135%) was around tree- to six-fold higher in Coqueiral Lake than in Camargo Lake (Table 1). The amplitude of variation increased from 1.67 (June/06) to 87.92 t.day^{-1} (December/06). Annual mean sediment deposition efficiency in Coqueiral Lake relative to the load conveyed by the watercourse was 10.95 ± 16.93% (CV = 155%) (Table 1). No significant differences were found between the two lakes for either the amounts of deposited sediment ($F = 3.78$, $P = 0.08$) or deposition efficiencies ($F = 2.89$, $P = 0.12$). The annual load was estimated at 149,164 t from daily SPM load values (monthly measurements) conveyed by the Paranapanema River, corresponding to approximately 409 t.day^{-1}. Annual deposited sediment loads of Camargo and Coqueiral Lakes reached 1,133.04 and 7,428.33 t, respectively. These values correspond to a deposition efficiency of 1 and 5% for the Camargo and Coqueiral Lakes, respectively relative to the annual load conveyed by the Paranapanema River.

Since the deposited sediment loads in the Camargo and Coqueiral Lakes correspond to 1 and 5% of total an-

Table 1. Daily loads (t.d^{-1}) of sediments transported by Paranapanema River and deposited in Camargo and Coqueiral Lakes and, entrapment efficiency (%) from October/05-August/06.

Date	Daily load (t.d^{-1}) of sediments in Paranapanema River	Camargo lake		Coqueiral lake	
		Sediment settling (t.d^{-1})	Entrapment efficiency (%)	Sediment settling (t.d^{-1})	Entrapment efficiency (%)
October, 10	220.32	6.35	2.88	56.28	25.54
November, 16	44.06	2.30	5.22	5.70	12.94
December, 20	2,712.10	2.31	0.01	87.92	3.24
January, 12	274.75	0.61	0.22	4.04	1.47
February, 16	601.34	3.64	0.61	7.33	1.22
March, 15	236.87	1.08	0.46	3.02	1.27
April, 18	450.14	11.95	2.65	35.28	7.83
May, 16	114.46	1.87	1.63	3.66	3.20
June, 20	25.92	1.23	4.74	1.67	6.44
July, 12	496.80	0.76	0.15	1.92	0.39
August, 15	40.61	2.26	0.06	23.10	56.88

nual load conveyed by the Paranapanema River, it can be assumed that the allochthonous influence of SPM is negligible. Thus, the SPIM in the lakes probably originates from re-suspension of bottom material. In the 11 measurements made over the annual cycle, it was observed five episodes of bottom inorganic matter re-suspension in Camargo Lake, while six out of nine measurements in Coqueiral Lake (it was impossible to measure sedimentation rates in the two first months) exhibited re-suspension of bottom material (Table 2). The particulate matter in the Camargo Lake traps appeared to have come from the lake bottom in all months, except November/05. In Coqueiral Lake, only in December/05 and June/06 did the R values (re-suspended SPIM) not correspond to sedimented SPM.

4. Discussion

Sediment overbank deposition can vary: a) laterally, as a function of the distance from the main river channel; b) longitudinally, as a consequence of cumulative concentration effect of particulate matter conveyed by the river, and c) temporally, determined by the frequency and duration of floodplain hydrological pulses.

Walling and He (1997) found no evident longitudinal trend in particulate matter deposition in the Culm River, Devon (United Kingdom) floodplain. They attributed this evidence to the gradual reduction of suspended sediment loads in the studied stretch of river, due both to losses via lateral deposition and increased plain width. Conversely, a longitudinal decrease in particulate matter sedimentation was found by Sanchez-Carillo et al. (2001) in the semi-arid wetland of Las Tablas de Daimiel (Spain) due to the presence of emergent and submerged aquatic macrophytes, which significantly reduced water current velocity. This factor increases suspended matter deposition in reservoirs, with a reduction from one (Jurumirim Reservoir, according to Henry and Maricatto, 1996) to two orders of magnitude (Itaipu Reservoir, after Pagioro and Thomaz, 2002) when compared to measurements on the main tributary mouth and dam zones.

Lateral variation on sediment overbank deposition is a common observation in floodplains. Higher sedimentation rates near the river channel, as well as a decrease (negative exponential) in the rates with increasing distance from the river, were evident in many floodplains (Walling and He, 1997; 1998; Kronvang et al., 2002; Moreira-Turcq et al., 2004). However, in some transects in central Atchafalaya (LA, USA) Basin, Hupp et al. (2008) found two other spatial patterns of lateral deposition: a) uniform or no lateral trend with increasing distance from the channel river; b) positive exponential, that is, an increase of sediment deposition rates with the increase of distance from the river bed channel. Lateral pattern in particulate matter sedimentation depends on the nature (coarse or fine) of the conveyed sediment, plain topography, and inundation frequency and duration.

Damming river segments causes the disappearance of floodplains at sites where the lateral topography is not very pronounced, such as occurred in the location currently known as Porto Primavera Reservoir, Paraná River (Sendacz and Monteiro Jr., 2003). The pluri-modal hydrological pulses recorded on rivers like the Mogi-Guaçu (Krusche and Mozeto, 1999) and the Paranapanema Rivers, São Paulo (Henry et al., 1999) may change to a uni-modal hydrologic pulse, as happened in the Jurumirim Reservoir transition zone. In our study site, hydrometric level variations in three distinct periods were identified during the year: a water level rising phase (from October to February), a short-term high water phase (from February to April), and a water level falling phase (from April to the beginning of September) (Figure 2). No significant relationship was detected between water levels and SPM (r = –0.20) or SPIM concentrations (r = ⁻0.23) in the Paranapanema River. Hydrological level

Table 2. Re-suspended inorganic particulated matter (R), Pearson correlation (r) and intercepts of relationships between suspended total and inorganic matter of sedimentation rates in two lakes from October/05 to August/06.

Date	Camargo lake			Coqueiral lake		
	r	Intercept	R ($g.m^{-2}.day^{-1}$)	r	Intercept	R ($g.m^{-2}.day^{-1}$)
October, 10	0.99*	–0.15	7.7	-	-	-
November, 16	0.95*	1.42	11.5	-	-	-
December, 20	0.92*	–1.16	15.0	0.99*	15.5	431.3
January, 12	0.86*	–12.08	8.0	0.65	-	-
February, 16	–0.15	-	-	0.98*	–36.0	17.8
March, 15	–0.61	-	-	0.99*	–4.4	39.9
April, 18	0.12	-	-	0.99*	–0.1	53.8
May, 16	–0.58	-	-	0.49	-	-
June, 20	0.93*	–2.89	5.1	0.49	-	5.7
July, 12	0.69	-	-	0.82*	–0.4	10.2
August, 15	0.64	-	-	0.98*	1.6	126.7

* P<0.05

increases could be affecting the SPM content by re-suspending the surface material on the edges of the river channel. However, the SPIM amounts showed significant increases during the water rising phase. Thus, water overflow from the river channel resulted in fast inorganic matter dissolution immediately after the inundation of the river-land border. However, the annual changes in suspended matter content may be related to rainfall episodes during the year, particularly from October to February, modifying water discharges and introducing watershed sediment loads into the Paranapanema River.

Significant temporal differences in vertical sedimentation fluxes were observed in the Camargo and Coqueiral Lakes, with the highest rates recorded in water level rising months (e.g. December, November, October, and February) for SPIM and (e.g. December and October) for SPM, and the lowest being found during the water level falling phase. The Curuaí floodplain (Amazonas, Brazil), like our study site, is submitted to a uni-modal hydrologic pulse from the river. Moreira-Turcq et al. (2004) attributed the highest particulate matter vertical sedimentation fluxes found during the falling period to re-suspension of bottom material, since concentrations in the water column were very high. In an Amazonian "igapó" (Tarumã Mirim River), Walker (1995) recorded large amounts of re-suspended material during the rising and high water periods. Water level values showed no significant relation to SPM deposition rates (measured at Z_{DS}) in the Coqueiral ($r = -0.43$) and Camargo Lakes ($r = -0.51$). Nevertheless, the SPM and SPIM bottom settling rates in both lakes were higher than those of Z_{DS}, which may be attributed to sediment re-suspension. In the semi-arid wetland of Las Tablas de Daimiel (Spain), Sanchez-Carillo et al. (2001) also found no significant relationship between SPM sedimentation rates and water levels. However, discrepancies between lakes were noted when SPM and SPIM deposition rates were correlated with their respective concentrations in the Paranapanema River. No significant relations were noted between SPM ($r = 0.02$) and SPIM ($r = 0.28$) concentrations in the river and sedimentation rates in Camargo Lake. Significant positive correlations were detected between SPM ($r = 0.82$, $P < 0.05$) and SPIM ($r = 0.88$, $P < 0.05$) concentrations in the river and the deposition rates in Coqueiral Lake. This last lacustrine system presents an association with the Paranapanema River that is wider than that of the Camargo Lake, making the lateral inflow of suspended particulate matter from the watercourse easier. In the case of Camargo Lake, the connection with the Paranapanema River is narrow. Only in a high water period could a significant overbank amount of SPM be introduced in the lake by such a marginal border. However, broad *Echinochloa polystachya* covering, 17% of the aquatic area of the Paranapanema River – Jurumirim Reservoir transition zone, together with *Polygonum spectabile* Mart., another dominant plant according to Pompeo et al. (1999), occurs on the borders of the Paranapanema River and the Coqueiral and Camargo Lakes. This grass is rooted on the two borders of the watercourse and projects its stems to the middle of the river. It plays an important role in the retention of particulate matter when the water level rises. Pompeo et al. (1997) found significant differences in *E. polystachya* stand suspended particulate matter values along the year between of the Paranapanema River littoral zone and the Camargo Lake pelagic zone. Similar values were recorded in the river and macrophyte stands and lower values in Camargo Lake. According to Olde Venterink et al. (2006), the type of plant community (grasslands, woodlands, and reedbeds) affects the sediment and adsorbed nutrient trapping in floodplains during inundations, because it modifies the lateral inflow water velocity. In wetlands, the presence of aquatic macrophytes and their seasonal growth patterns show a direct relationship with particulate matter deposition (Sanchez-Carillo et al., 2001).

The remarkable presence of *E. polystachya* in sand threads between the river and the Coqueiral and Camargo Lakes constitutes a true ecotone, whose primordial function is to shape a particulate matter barrier or filtration structure between the lentic and lotic ecosystems (Kolasa and Zalewski, 1995). Thus, it can explain the relatively low overbank sediment entrapment efficiency in the Paranapanema River lateral lakes when compared to floodplain values in the Swale and Aire Rivers, United Kingdom (Walling and Owens, 2003). Consequently, the conveyance rate reaches from 95 to 99% of the annual suspended sediment load from the upstream watershed relative to the studied river stretch. The annual sediment load estimated in this study was 59% higher than a previous estimation carried out in the 1990's (Henry et al., 1999). This increase may be attributed to a change in vegetation covering in the watershed, which causes a greater surface lixiviation, and also a reduction in marginal forest areas at the entire drainage system. However, the previous work data were collected in a site at Paranapanema River 60 km upstream of the river–Jurumirim Reservoir transition zone, making the comparison difficult.

The SPM and SPIM concentrations showed no significant spatial variations (between the river and lakes and between the lakes). Despite the important role of *E. polystachya* on particulate matter retention in the river, the homogeneity of particulate matter concentrations may be attributed to re-suspension. Episodes of bottom material re-suspension were detected in five (Camargo Lake) and six (Coqueiral Lake) out of the eleven measurements. Both lakes have a low mean depth; Coqueiral Lake shows very little pronounced bottom topography, and fetch in Camargo Lake is parallel to maximum length (Henry, 2005). These morphometric parameters are the causes of frequent re-suspension of bottom material within the water column. Re-suspended matter probably affected some bottom trap sediment settling measurements. Therefore, some entrapment efficiencies may have been overestimated, as for example, in Coqueiral Lake in August 2005, when the stage values were low.

In conclusion, overbank sediment entrapment efficiencies on lakes lateral to the Paranapanema River were relatively low due to the retention of SPM lateral inflow by *E. polystachya* aquatic grass from the river. Thus, the major portion of sediments conveyed by the Paranapanema River is introduced in the zone upstream of the Jurumirim Reservoir, affecting the euphotic zone depths.

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References

BOURGOIN, LM., BONNET, MP., MARTINEZ, JP., KOSUTH, P., COCHONNEAU, G., MOREIRA-TURCQ, P., GUYOT, JL., VAUCHET, P., FILIZOLA, N. and SEYLER, P. Temporal dynamics of water and sediment exchanges between the Curuaí floodplain and the Amazonas River, Brazil. *J. Hydrol.* 2007, vol. 335, no. 1-2, p. 140-156.

De NADAI, R. and HENRY, R. Temporary fragmentation of a marginal lake and its effects on zooplankton community structure and organization. *Braz. J. Biol.,* In press.

FOSTER, JM. and THOMS, MC. The influence of large-scale geomorphology on floodplain sedimentation processes. *Verh. Internat. Verein. Limnol.* 2002, vol. 28, no. 3, p. 1185-1190.

HENRY, R. The connectivity of the Paranapanema River with two lateral lakes in its mouth zone into the Jurumirim Reservoir. *Acta Limnol. Brasil.* 2005, vol. 17, no. 1, p. 57-69.

HENRY, R. and GOUVEIA, L. Os fluxos de nutrientes e seston em cursos de água do Alto Paranapanema (São Paulo) – sua relação com usos do solo e morfometria das bacias de drenagem. *An. Acad. Bras. Ciênc.* 1993, vol. 65, no. 4, p. 439-451.

HENRY, R. and MARICATO, F. Sedimentation rates of tripton in Jurumirim Reservoir (São Paulo, Brazil). *Limnologica*, 1996, vol. 26, no. 1, p. 15-25.

HENRY, R. The connectivity of Paranapanema River with two lateral lakes in its mouth zone into Jurumirim Reservoir. *Acta Limnol. Bras.* 2005, vol. 17, no. 1, p. 57-69.

HENRY, R., FERREIRA, RMP. and USHINOHAMA, E. Fitoplâncton em três lagoas e no Rio Paranapanema na zona de sua desembocadura na Represa de Jurumirim. *Rev. Brás. Bot.* 2006, vol. 29, no. 3, p. 399-414.

HENRY, R., PANARELLI, EA., CASANOVA, SMC., SUIBERTO, MR. and AFONSO, AAO. Interações hidrológicas entre lagoas marginais e o Rio Paranapanema na zona de sua desembocadura na Represa de Jurumirim. In NOGUEIRA, MG., HENRY, R. and JORCIN, A. (Orgs.). *Ecologia de reservatórios*: impactos potenciais, ações de manejo e sistemas em cascatas. São Carlos: Rima Editora, 2005. p. 57-82.

HENRY, R., SANTOS, AAN. and CAMARGO, YR. O transporte de sólidos suspensos e N e P total pelos rios Paranapanema e Taquari e uma avaliação de sua exportação na Represa de Jurumirim (São Paulo, Brasil). In HENRY, R. (Ed.). *Ecologia de Reservatórios*: estrutura, função e aspectos sociais. Botucatu: Fundibio; Fapesp, 1999. p. 687-710.

HORPPILA, J. and NURMINEN, E. Effects of calculation procedure and sampling site on trap method estimates of sediment resuspension in a shallow lake. *Sedimentology,* 2005, vol. 52, no. 4, p. 903-913.

HUPP, CR., DEMAS, CR., KROES, DE., DAY, RH. and DOYLE, TW. Recent sedimentation patterns within the Central Atchafalaya Basin, Louisiana. *Wetlands*, 2008, vol. 28, no. 1, p. 124-140.

KOLASA, I. and ZALEWSKI, M. Notes on ecotone attributes and functions. *Hydrobiologia*, 1995, vol. 303, no. 1-3, p. 1-7.

KRUSCHE, AV. and MOZETO, AA. Seasonal variations in water quality of an oxbow lake in response to multiple short-time pulses of flooding (Jataí Ecological Station – Mogi Guaçu River, Luiz Antonio, SP – Brazil). *An. Acad. Bras. Ciênc.* 1999, vol. 71, no. 4, p. 777-790.

KRONVANG, B., ANDERSEN, IK., HOFFMANN, CC., PEDERSEN, ML., OVESEN, NB. and ANDERSEN, HE. Water exchange and deposition of sediment and phosphorus during inundation of natural and restored lowland floodplains. *Water, Air and Soil Pollut.* 2007, vol. 181, no. 1-4, p. 115-121.

MOREIRA-TURCQ, P., JOUANNEAU, JM., TURCQ, B., SEYLER, P., WEBER, O. and GUYOT, JL. Carbon sedimentation at Lago Grande de Curuí, a floodplain lake in the low Amazon region: insights into sedimentation rates. *Palaeogeogr. Palaeoclim. Palaeoecol,* 2004, vol. 214, no. 1-2, p. 27-40.

OLDE VENTERINK, H., VERMAAT, JE., PRONK, M., WIEGMAN, F., VAN DER LEE, GEM., VAN DEN HOORN, MW., HIGLER, LWG. (B.) and VERHOEVEN, JTA. Importance of sediment deposition and denitrification for nutrient retention in flooplain wetlands. *Appl. Veg. Sci.* 2006, vol. 9, no. 2, p. 163-174.

PAGIORO, TA. and THOMAZ, SM. Longitudinal patterns of sedimentation in a deep, monomictic subtropical reservoir (Itaipu, Brazil-Paraguay). *Arch. Hydrobiol.* 2002, vol. 154, no. 3, p. 515-528.

PHILLIPS, JD. Sedimentation in bottomland hardwoods downstream of an east Texas dam. *Environ. Geol.* 2001, vol. 40, no. 7, p. 860-868.

POMPEO, MLM., HENRY, R., MOSCHINI-CARLOS, V. and PADOVANI, CR. A influência da macrófita aquática *Echinochloa polystachya* (H.B.K.) Hitchcock nas características físicas e químicas da água na zona de desembocadura do Rio Paranapanema na Represa de Jurumirim – SP. *Rev. Brasil. Ecol.* 1997, vol. 1, no. 2, p. 44-53.

POMPEO, MLM., HENRY, R. and MOSCHINI-CARLOS, V. Ecologia de *Echinochloa polystachya* na Represa de Jurumirim (zona de desembocadura do Rio Paranapanema-SP, Brasil). In HENRY, R. (Ed.). *Ecologia de reservatórios*: estrutura, função e aspectos sociais. Botucatu: Ed. Fundibio; Fapesp, 1999. p. 735-768.

SÁNCHEZ-CARRILLO, S., ÁLVAREZ-COBELAS, M. and ANGELER, DG. Sedimentation in the semi-arid freshwater wetland Lãs Tablas de Daimiel (Espanha). *Wetlands*, 2001, vol. 21, no. 1, p. 112-124.

SPARKS, RE., BAYLEY, PB., KOHLER, SB. and OSBORNE, LL. Disturbance and recovery of large floodplain rivers. *Environ. Manag.* 1990, vol. 14, no. 5, p. 699-709.

STEVAUX, JC. and SOUZA, IA. Floodplain construction in an anastomosed river. *Quater. Internat.* 2004, vol. 114, no. 1, p. 55-65.

THOMS, MC. Floodplain-river ecosystems: lateral connections and the implications of human interference. *Geomorphology*, 2003, vol. 56, no. 3-4, p. 335-349.

WALKER, I. Sedimentation in the inundation forest flanking the Central Amazon blackwater stream Rio Tarumã Mirim (Manaus, Amazonas State). *Amazoniana*, 1995, vol. XIII, no. 3-4, p. 237-243.

WALLING, DE. and HE, Q. Investigating spatial patterns of overbank sedimentation on river floodplains. *Water, Air and Soil Pollution*, 1997, vol. 99, no. 1-4, p. 9-20.

WALLING, DE. and HE, Q. The spatial variability of overbank sedimentation on river floodplains. *Geomorphology*, 1998, vol. 24, no. 2-3, p. 209-233.

WALLING, DE. and OWENS, PN. The role of overbank floodplain sedimentation in catchment contaminant budgets. *Hydrobiologia*, 2003, vol. 494, no. 1-3, p. 83-91.

WARD, JV. and STANFORD, JA. Ecological connectivity in alluvial river ecosystem and its disruption by flow regulation. *Regul. Riv.: Res.& Manag.*, 1995, vol. 15, no. 1, p. 105-119.

WEYHENMEYER, GA. Quantification of resuspended particles in sedimentation traps. *Verh. Internat. Verein. Limnol.* 1997, vol. 26, no. 1, p. 271-276.

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