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Changes in Nutrient Loads (N, P and Si) in the São Francisco Estuary after the Construction of Dams

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ABSTRACT

The aim of this study was to investigate the post-dam conditions of the loads and yields of dissolved inorganic nitrogen (DIN), orthophosphate (DIP, silicate (DSi) and total phosphorous (TP) in the Lower São Francisco river-estuary (NE-Brazil) after the river was regulated to a constant flow by the dams. Loads and yields of monthly measurements performed from November 2000 to March 2002 at a gauging station downstream of the dams (80 km from the coast) showed 4.1 x 10^3 t/yr and 0.006 t/km^2/yr of DIN, 0.2 x 10^3 t/yr and 0.002 t/km^2/yr of DIP, and 448 x 10^3 t/yr and 0.71 t/km^2/yr of DSi, respectively. Over the last 15 years, DIN loads reduced by 94 % and DSi by 31%. The river turned into an oligotrophic system with primary production limited by nitrogen and nutrient yields being among the lowest of Brazilian coastal rivers.

Key words: nutrients, fluvial loads, dam impacts, estuary, São Francisco River (NE-Brazil)

INTRODUCTION

Rivers represent one of the main links of the global hydrological and biogeochemical cycle, acting as transporters of water, and of dissolved and particulate matter from the continents to the oceans. In addition to suspended sediments, rivers carry the biogenic elements such as nitrogen, phosphorus and silica, which are essential nutrients for the maintenance of the biological productivity of aquatic environments (Hay, 1998; Crossland et al., 2005). The origin, composition and transfer of nutrients in the drainage basin are controlled by a number of factors, including the climate, physiography, geological matrix and vegetation cover. During transport, physical and biogeochemical processes transform, recycle and retain materials in lacustrine, estuarine and marine environments (Billen et al., 1991; Bianchi, 2007).

With the increase in world population growth, with 45% of the total population inhabiting coastal regions, there has been increased demand for water, electric power and territorial space, resulting in multiple environmental impacts and altering the natural flows of water and matterials (Milliman and Meade, 1983; Meybeck, 1993; Crossland et al., 2005). Some of these impacts are often coupled to the construction of dams, which

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retain suspended sediments and transform the composition of nutrients in their reservoirs, changing their flows to the coastal region (Halim, 1991; Billen et al., 1999; Vörösmarty et al., 2003; Beusen et al., 2005; Syvitski et al., 2005). Knowledge on the composition and temporal variation of a river's nutrient load allows for inferences to be made about the nature of the human impact on the drainage basin and its effects on the coastal region, and also serves to underpin the implementation of management actions to mitigate the impacts (Crossland et al., 2005). The task becomes more feasible when the human impact is dominated by a single major perturbation, such as the construction of dams. Although hydrological records of Brazil's rivers are well documented and available in national databases (www.ana.gov.br), there is still a lack of information about the contribution of nutrients and the fertilization potential of large number of small and medium-sized basins in the coastal zone (Milliman, 1975; Souza and Knoppers, 2003; Souza et al., 2003).

The São Francisco River, one of the world's medium-sized rivers (Milliman and Meade, 1983; Hay, 1998; Knoppers et al., 1999), represents the largest drainage basin within Brazil territory and has historically been of great socio-economic importance. Despite the existence of information on the flow along its course since 1936 (www.ana.gov.br) and some of the alterations resulting from its dams (Knoppers et al., 2005; Medeiros et al.; 2007), the flow of nutrients from the São Francisco River to the coastal zone was only recorded once at quarterly sampling intervals over the hydrological year of 1984-1985 by Santos (1993), whilst some of the dams were still being implemented.

The aim of this study was to quantify the monthly variability of the flow of nitrogenous nutrients (ammonium, nitrite and nitrate), phosphorus and dissolved silica in the estuary of the São Francisco River after the completion of the dams in 1995.

METHODS

Study area

The headwaters of the São Francisco River (SFR) are situated in the State of Minas Gerais and the river flows into the SW Atlantic Ocean at the border between the States of Sergipe and Alagoas, NE Brazil (Fig. 1). The river is 2,863 km long, and its hydrographic basin covers 639,219 km^2 and corresponds to the most extensive basin within the Brazilian territory. Due to its length, the basin traverses several climatic regimes and comprises several physiographic compartments. It is traditionally divided into the Upper, Middle, Sub-Middle and Lower SFR sector (Fig. 1, www.ana.gov.br).

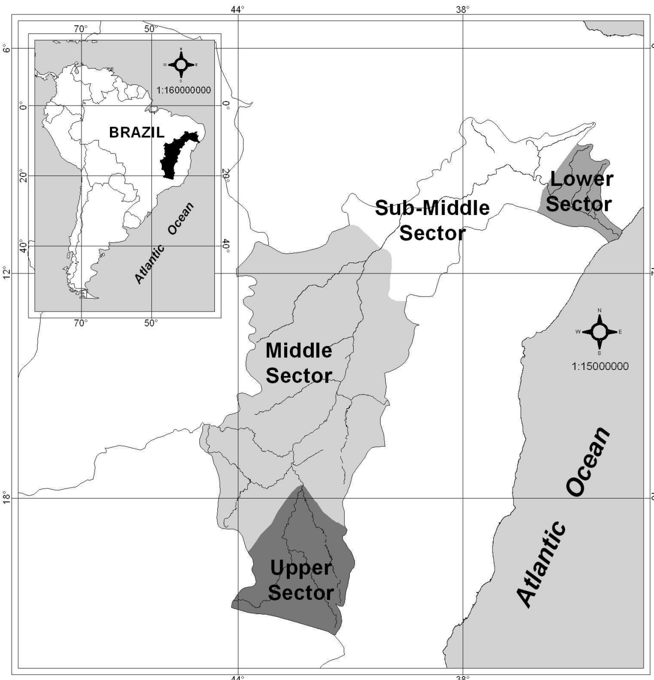

Figure 1 – Subdivisions of the São Francisco River Basin. Source (modify) www.ana.gov.br.

The climate along the basin varies from tropical humid (i.e. Upper SFR and Lower SFR) to semi-arid (i.e. Sub-Middle SFR). Precipitation in the Upper SFR and Lower SFR basin sectors is in the order of 1,500 mm/year and only about 350 mm/year in the semi-arid Sub-Middle SFR, (Bernardes, 1951; www.ana.gov.br). The hydrographic basin from the Upper to the Lower compartments is composed of Cretacean (mountain ranges), Tertiary (Formação Barreiras) and Quarternary deltaic formations. The "Tertiary Barreiras Formation" (Formação Barreiras), which consists of tablelands, covers most of the Sub-Middle and Lower SFR. The fluvial-marine deltaic plains of the Lower SFR include Pleistocene marine terraces and are surrounded by the base of the Tertiary tablelands (Dominguez, 1996). The predominant vegetation is *caatinga* (scrubland). The total area of dense, open and degraded caatinga lands corresponds to 24.6 % of the total basin area and remnants of the Atlantic Forest (www.ana.gov.br) also occur in the Lower SFR compartments.

The need for hydroelectric power generation created a cascade of seven dams and reservoirs along the Sub-Middle SFR, which have caused major changes in the river's natural river flow and diminished the total discharge to the coast by 35%. Fig. 2 shows the natural river flow conditions from the 1930's, its perturbations during the construction of the dam cascade between the 1970s and 1990s, as well as the constant flow after final regulation by the dams from 1995 onwards, after completion of the late Xingó dam (180 km from the coast). In 2001, the flow was reduced drastically due to an extreme drought event. Further information on the hydrological-sedimentological alterations have been described by Medeiros (2003), Knoppers et al., (2005) and Medeiros et al., (2007).

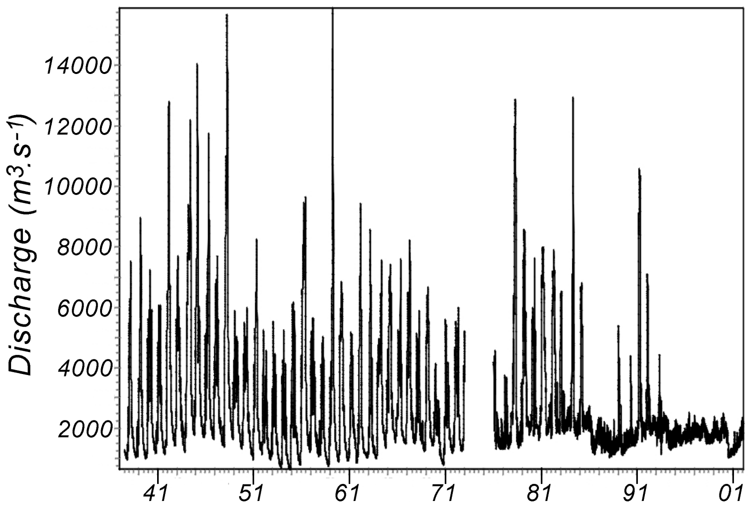

Figure 2 - Long term hydrograph (1938-2002) of river discharge at the Traipú gauging station located 120 km from the coast. Source: www.ana.gov.br.

Sampling and assays

The study was carried out in the Lower São Francisco river compartment at the Propriá (SE)/ Porto Real (AL) gauging station of the National Water Agency (www.ana.gov.br) set 80 km upriver of the estuary (Fig.3). Monthly *in situ* measurements of the physico-chemical parameters were performed and water samples for nutrient analysis were collected along four pre-calibrated transverse sectors of the river during the period of November 2000 to March 2002. The sampling and calculation of the nutrient flows, including the usage of water flow records provided by the São Francisco Hydroelectric Company (CHESF) were followed as described by Medeiros et al. (2007). In general, the flux estimates were performed by the formula:

$$F_m = Q\sum_{i=\mathrm{I}}^{\mathrm{IV}} a_i C_i$$

Fm = momentary nutrient flow i

Q = outflow (m^3/s)

ai = flow coefficient in sectors i from 1 to N

$C\ I$ = nutrient concentration

The *in situ* determinations of the physico-chemical parameters tºC, pH, and Electrical Conductivity were performed with a YSI multiparameter water quality probe (Yellow Springs Instruments, Model 6600D). The samples were collected from the subsurface (at a depth of 0.5 m), using a Van Dorn-type bottle. The dissolved inorganic nutrients (nitrate, nitrite, ammonium, phosphate and silica) and total phosphorus were determined as described by Carmouze (1994) and chlorophyll α according to Strickland and Parsons (1972).

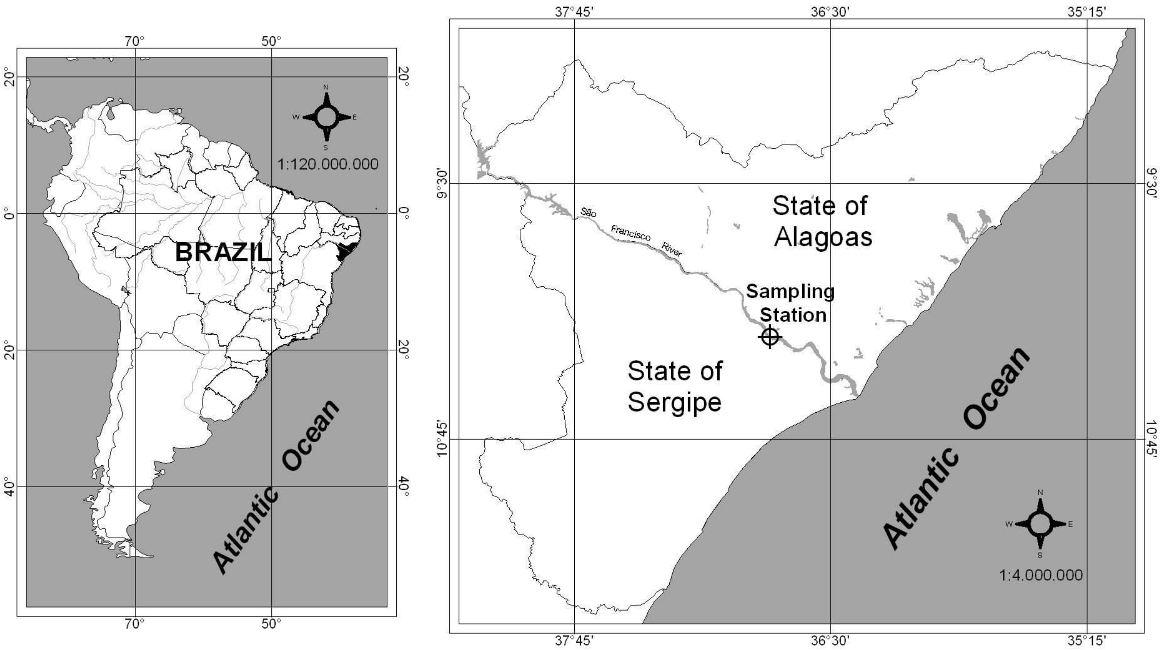

Figure 3 - Location of the sampling station approximately 100 km downstream from the Xingó Dam and 80 km upstream from the SFR mouth.

RESULTS AND DISCUSSION

Hydrological variability during the period

The impact caused by dams is a subject of international (Vorosmarty et al., 1997; Hay, 1998; Syvitski et al., 2005) and national concern (Tundisi et al., 1998; Knoppers et al., 2005). One of the most notable modifications in the construction of river dams is the change in the natural flow pattern, which affects several biogeochemical processes.

The cascade of dams altered the magnitude and natural pulsation of water reaching the Lower SFR and its coastal zone (Knoppers et al., 2005; Medeiros et al., 2007). After 1995, the flux was finally regulated to an official operational threshold of about 2060 $m^{3/}s$, eliminating the natural seasonal variability. During the pre-dam period (1938-1973), the average annual water flow was 94.9 km^3/year ± 26.9 km^3/year (average annual flow of 3010 m^3/s ± 850 m^3/s). During the post-dam period (1995-2001), the average annual flow declined to 55.5 km^3/year ± 7.4 km^3/year (average annual flow of 1760 m^3/s ± 235 m^3/s), which corresponded to a reduction of 44 %. Part of the loss was the result of water evaporation from the reservoirs and water diversion for irrigation, estimated at approximately 300 m^3/s (www.ana.gov.br).

To a certain extent, the hydrological period under the study represented an anomaly when compared with the regulated pattern of the post-dam period. The annual fluvial flux during the period of November 2000 to March 2001 was 50.3 km^3/year (average flow of 1595 m^3/s), which was 10% lower than the annual average in the post-dam period (Medeiros et al., 2007).

Various climatic phenomena, including El Niño and La Niña, interact on several spatial scales on the drainage basin (Ropelewski and Halpert, 1987). The period of this study was affected by a climatic anomaly of low precipitation along the entire drainage basin, causing a drastic change in the regulated flux regime of the Sub-Middle SFR, which resulted in a lower average annual flow of 1756 m^3/s than the normal regulated flow and also included an intermediate maximum decline down to 1100 m^3/s in July 2001. The decline in the precipitation in the basin and the consequent reduction of the flux led to an electric power crisis, which intensified in the second half of 2001. The volumes in the reservoirs declined drastically during the critical period of the crisis. The volume of the Sobradinho reservoir (BA/PE), for instance, whose maximum storage capacity was about 34 km^3, dropped to 17 km^3 in January 2001 and to 7 km^3 in November 2001.

Composition of nutrients

Natural factors such as geology, climate and vegetation cover are usually the primary features controlling the quantity and composition of materials transported by rivers (Meybeck, 1993). The average concentrations and standard deviations of dissolved inorganic nutrients, with the exception of silicate (Table 1), indicated a substantial degree of impoverishment of these elements in the Lower SFR. The concentration of nitrogenous nutrients in the SFR showed lower concentrations than the contents in the rivers of the East Coast of Brazil (Souza et al., 2003; Knoppers et al., 2005). The Vaza Barris, Real and Contas Rivers of the northern sector of the East Coast, with semi-arid conditions in the sectors upstream of the basin, contain dissolved inorganic nitrogen contents (DIN = ammonium + nitrite + nitrate) in the range of 150 to 300 µgN/L, while those of the SFR remained in the order of 100 µgN/L. Phosphate generally presented similar or lower contents by a factor of 2 than the rivers of the East Coast, while silicate exhibited contents in the same order of magnitude or even higher (Souza et al., 2003). The low concentrations of total phosphorus compared to phosphate indicated conditions of impoverishment of both the dissolved and particulate organic forms of this element.

Table 1 – Averages and standard deviation of nutrient concentrations by weight of the biogenic element analyzed in the Lower SFR from 1984-1985 (Bessa andParedes, 1990; Santos, 1993) and Nov 2000 to Mar 2002 (this study). Nutrient concentrations in µg/L

Parameter	Average	Standard Deviation	Average	Standard Deviation
	1984-1985		2000-2002	
Conductivity(µScm)	-	-	73	8
pH	-	-	8.0	0.1
N -Ammonium	56.0	89.0	27.02	16.52
N-Nitrite	23.0	55.0	2.24	3.36
N-Nitrate	750.0	1074.0	59.08	57.12
DIN	829.0	-	88,34	2850,87
P-Phosphate	-	-	16.74	29.14
Total phosphorus	-	-	66.96	106.64
Si-Silicate	6700.0	1200.0	9732.8	3424.4

Comparisons with the studies of Bessa and Paredes (1990) and Santos (1993), (see Table 1) revealed a reduction in DIN contents of one order of magnitude, while silicate remained at the same order of magnitude. The decrease of DIN, principally of nitrate, led to a sharp increase in the ratio of dissolved silicate to nitrogen (DSi:DIN) from 8:1 in 1984-1985 (Bessa andParedes, 1990; Santos, 1993) to 110:1 in the period of 2000-2002. When compared to the low ratio of DIN:DIP (5:1), nitrogen evolved into the main limiting element of the primary productivity of the waters (Knoppers et al., 2005).

Nitrate corresponded to the main nitrogenous nutrient, also presenting lower concentrations than those of the other rivers of the East Coast (Souza et al., 2003). This suggested that nitrification in the reservoirs must be moderate in comparison to the other rivers, possibly as a function of the limitation of organic substrate. The low total phosphorus and chlorophyll *a* contents (1.6 ± 1.1 µgChl./L) were evidence of oligotrophic conditions in the Lower SFR and were similar to those found by Tundisi et al. (1998) in the Xingó dam reservoir.

The high concentrations of dissolved silicate, both in this study and of Santos (1993), indicated that silicate bypassed the reservoirs without undergoing major internal transformations. It has been suggested that the incorporation of dissolved silicate by phytoplankton (i.e. diatoms or silicoflagellates), which use silicate for the construction of their amorphous frustules, was not a significant mechanism controlling silicate concentrations in the oligotrophic Xingó dam reservoir, located 100 km upstream of the Propriá gauging station. Thus, the mechanism of retention, which usually occurs in eutrophic reservoirs through the sedimentation of frustules during the senescence of organisms (Humborg et al., 1997; Jennerjahn et al., 2006) must have been negligible for the control of silicate fluxes downstream to the estuary.

The presence of weathering/leaching processes, which were more intense in the Upper and Middle SRF and contribute with siliclastic minerals (Jennerjahn et al., 2006), were likely responsible for the high silicate concentrations encountered. High values of pH (around 8.1), similar to those of the rivers with semi-arid climate in the north sector of the East Coast (states of Sergipe and partially Bahia), revealed a greater contribution of bicarbonate originating from weathering of carbonaceous rocks, which formed a buffer system at high pH (Berner and Berner, 1987; Souza et al., 2003). This confirmed that the composition of the water of the Lower SFR was affected by the weathering/leaching of diverse siliclastic and carbonaceous matrices, as was also the case of some of the larger rivers of the East Coast (Souza et al., 2003).

Nutrient fluxes

The concentration of dissolved and particulate material transported by rivers normally shows a relationship with the magnitude of pulsation of river flow (Restrepo and Kjerfve, 2001). In this study, the relationship between the flow and concentrations of the dissolved materials was practically inexistent, as also indicated by Spearman's non-parametric correlation analyses (Table 2). The coefficients of determination (r^2) were extremely low, varying from 0.01 to 0.18. The regulation and management of the flow and the high degree of material retention in the reservoirs must have been the factors responsible for the conditions encountered.

Table 2 – Coefficients of determination (r^2), level of significance (p), and number of observations (n) between the flow and the analyzed parameters. Spearman's nonparametric correlation.

Parameter	r^2	p	n
Nitrate	0.08	0.24	17
Ammonium	0.03	0.49	17
Phosphate	0.07	0.29	17
Total phosphorus	0.01	0.64	17
Silicate	0.18	0.08	17

The results in Table 1, with their high standard deviations, demonstrated that several mechanisms acted concomitantly on the dynamics of the nutrient contents and flow, such as the atypical climate-related variations in the flows, the decrease in volume and increase in dwell time of the waters in the reservoirs, and intense management of the flux for hydroelectric power generation.

Nitrogen

The monthly fluxes of ammonium, nitrite, nitrate and dissolved inorganic nitrogen (DIN) (Fig. 4 a, b, c and d) showed different patterns. The ammonium loads oscillated between 12 and 240 tons/month. These loads increased during two distinct periods, one being during the decrease of water flow (February to May 2001) and the other with the recovery of the flow (October 2001 to March 2002). This behavior suggested that changes in the dwell time of the waters in the reservoirs could induce alterations in the process of degradation of the organic matter in bottom sediments and likely release ammonium. On the other hand, the fluvial load of nitrate showed a significant unimodal pattern before and during the decrease in flow between January and August 2001, varying from about 50 to 740 tons/month, which was indicative of the presence of nitrification (Seitzinger, 1988).

The inversion of the monthly fluxes of ammonium and nitrate that occurred from October to December 2001 might also have been induced by an increment of organic matter from the aquaculture enterprises in the Xingó reservoir and/or the discharge of some domestic sewage into the river downstream from Xingó. The impacts of possible local eutrophication by these sources still have to be envisaged.

The annual output of dissolved inorganic nitrogen reported by Santos (1993) for the hydrological year 1984-1985, with a fluvial water discharge of 100 km^3, was about 69.6 x 10^3 t/year. In this study, only 4.1 x 10^3 t/year were asserted with a water output of 52 km^3. This corresponded to an approximately 17-fold reduction of the DIN load in a period of 15 years. Even when compared to the load of 5.1 x 10^3 t/year estimated for the entire period of the study (i.e.17 months), Santos's estimate (*Op. cit.*) was 14-fold higher. This drastic decrease of the DIN load by 94 % occurred due to both the reduction of the water flux and the decrease in DIN concentrations themselves.

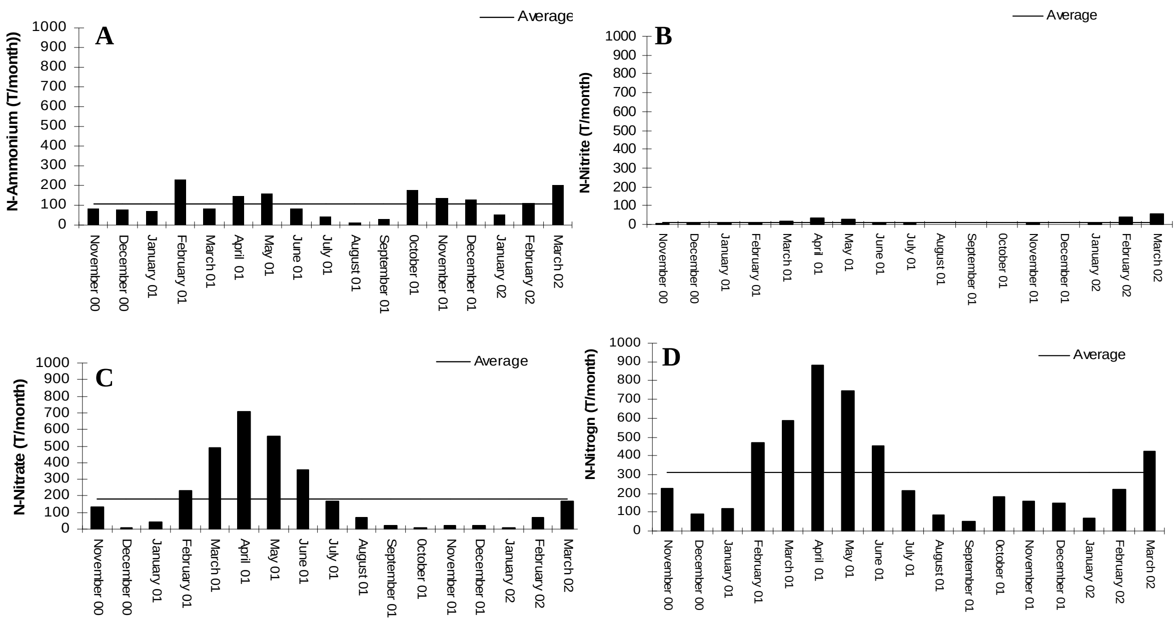

Figure 4 – Monthly and average fluvial loads of ammonium (A), nitrite (B), and nitrate (C) and (D) total inorganic dissolved nitrogen, in tons per month of the element nitrogen.

Phosphorous

The dissolved inorganic phosphate (DIP) and total phosphorus fluxes (Figs. 5 a and b) displayed a smaller variation throughout the study, except for the recovery period of water flow from October 2001 to March 2002. The lowest monthly load of DIP occurred in September 2001, reaching about 6 t/month. Henceforth, the fluxes increased from November 2001 onwards due to both the increment of water discharge and also the phosphate concentrations themselves. Total phosphorus loads also displayed a similar trend as for DIP in late 2001 and early 2002. The load of DIP from November 2000 to October 2001 was estimated at 0.2 x 10^3 t/year and that of total phosphorus at 1.16 x 10^3 t/year.

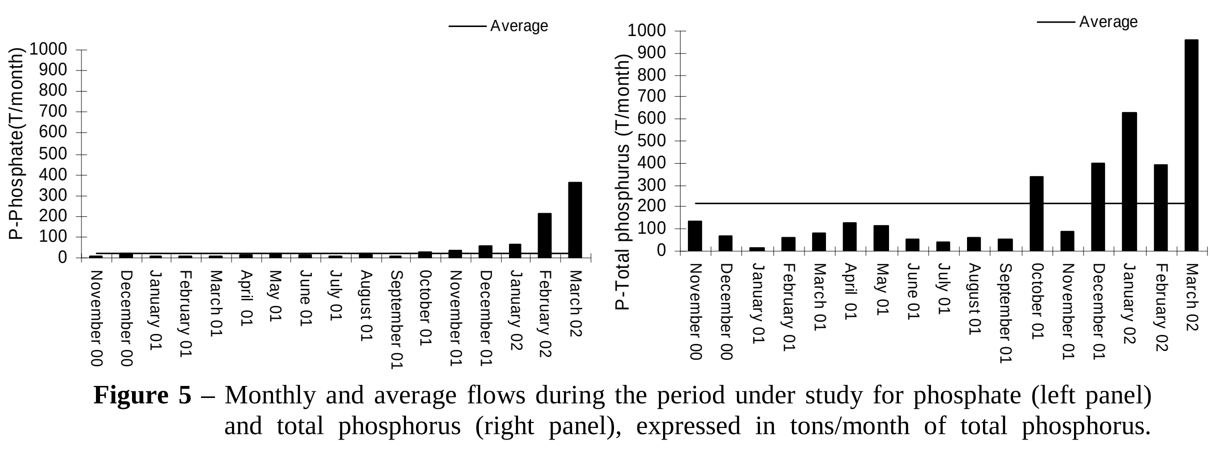

Figure 5 – Monthly and average flows during the period under study for phosphate (left panel) and total phosphorus (right panel), expressed in tons/month of total phosphorus.

Dissolved Silicate

The Si-Silicate fluxes (Fig. 6) showed a behavior similar to that of the suspended particulate matter (i.e. SPM; Medeiros et al., 2007). The fluxes behaved in a bimodal pattern, with the first oscillation occurring from November 2000 to June 2001 and the second from October 2001 to March 2002. Starting in November 2001, the silicate fluxes increased abruptly, reaching their maximum value of about 68,000 t/month in March 2002.

The annual load of silicate during the hydrological year addressed was 448 x 10^3 t/year, while Santos (1993) estimated 650 x 10^3 t/year, i.e., 202 t/year or 31% higher than the current estimated load. Clearly, the silicate fluxes underwent the influence of variations in the level of the reservoirs of the hydroelectric plants, and probably also of the weathering processes in the basin upstream of the cascade of dams, as discussed earlier on. The physical-chemical alterations caused by the variations in the dwell time of water and materials and the exposure of the sediments of the cascade reservoirs prevent a more precise interpretation of the behavior of this nutrient at the scale of this study.

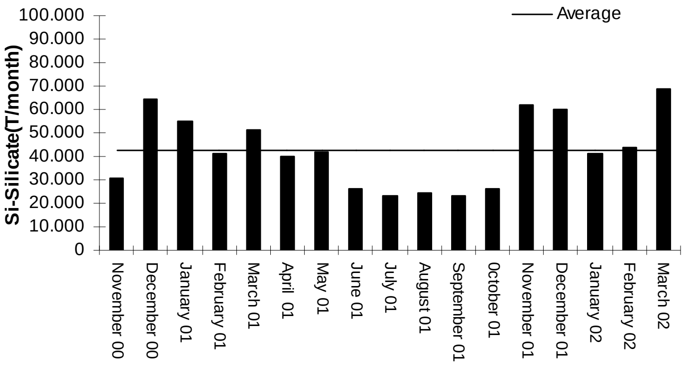

Figure 6 - Monthly and average Silicate fluxes during the period under study.

Specific loads (yields)

The specific load corresponds to the annual load normalized by the area of the drainage basin (t/km^2/year). It reflects the yield over time of the element for each square kilometer of the basin. This is an important rate that allows for comparison with the yields of other drainage basins, since it removes the influence of the weight of the drainage basin area from the load of the element in question (Milliman and Meade,1983).

The yield of dissolved inorganic nitrogen (DIN) of 0.006 tons/km^2/year of the hydrological year of this study should be considered extremely low when compared to the 0.11 tons/km^2/year calculated by Santos (1993) from the 1984-1985 data, and principally that of the other medium and large tropical rivers (Table 3). At the time of Santos's (1993) study, the São Francisco River, albeit already impacted by its dams, still presented specific DIN loads comparable to those of the Orinoco and the Tocantins, and lower by a factor of 2 or 3 than those of the humid tropical rivers Madalena, Purari, Paraíba do Sul and Amazonas, all set in the humid tropical belt. On the other hand, after the conclusion of the cascade of dams and the definitive regulation of river flow after 1995, the specific DIN load declined sharply to levels well below those of the tropical Congo (or Zaire) and Zambezi rivers, which already had lower specific loads. It is important to emphasize that these two rivers in Africa have basins with lower physiographic reliefs and ample plains along their river courses when compared to SFR and, in the case of the Zambezi, it also harbors dams.

As for the 24 rivers of the East Coast of Brazil studied by Souza et al. (2003), the information is available in the form of daily specific loads. Comparing the daily values of this study, the specific DIN load of the lower SFR was lower than those of the rivers of the East Coast, indicating that both the dams and the low potential of water and material replenishment of the semi-arid Sub-Middle and Lower SFR compartments led to DIN impoverishment of it's estuary.

Table 3 - Comparison of DIN, DIP and DSi yields of medium and large humid tropical rivers. Sources: *Meybeck and Ragu (1995), ** Carneiro (1998), [1]Santos (1993) and [2] this study.

River	Drainage basin	Annual flow	DIN	DIP	DSi	Country
	(10^6 Km²)	(Km³)	t/Km²/year			
Purari (*)	0.03	84	0.220	0.005		Papua
Paraíba do Sul (**)	0.05	28	0.180	0.020		Brazil
Madalena (*)	0.24	237	0.292	0.121	5.942	Colombia
São Francisco(1)	**0.64**	**100**	**0.110**		**1.020**	**Brazil**
São Francisco(2)	**0.64**	**52**	**0.006**	**0.002**	**0.710**	**Brazil**
Tocantins (*)	0.76	372	0.074	0.001	2.666	Brazil
Orinoco (*)	1.1	1135	0.119	0.010	3.040	Venezuela
Zambezi (*)	1.33	106	0.010	0.001	0.626	Mozambique
Zaire (*)	3.7	1200	0.031	0.008	1.426	Zaire
Amazonas (*)	6.11	6590	0.173	0.024	3.479	Brazil

In the post-dam period, the current yield (Table 3) of dissolved inorganic phosphorus (DIP) or orthophosphate of 0.002 tons/km^2/year calculated in this study should also, like DIN, be considered as being low when compared with other medium and large tropical rivers, comparable only with the Zambezi and Tocantins rivers. The other tropical rivers, with both steep and low physiographic gradients, have higher specific DIP loads, including also the other rivers of the East Coast of Brazil (Souza et al., 2003).

The specific load of dissolved silica (DSi or silicate) of 0.71 t/km^2/year estimated in this study was 31% lower than the specific load of 1.02 t/km^2/year calculated from the 1984-1985 data of Santos (1993) (Table 3). The decrease in specific load was caused mainly by the reduction of the flow in the 15 years between the two studies. In comparison with the other humid tropical rivers, the SFR continues to be the one with the lowest specific DSi load, except for the Zambezi River with dams.

The comparison of the specific loads of DIN, DIP and DSi of the RSF against those of other tropical rivers indicated that the differences in gradient, size, vegetation cover and engineering works had a different effects upon the specific loads of nutrients. The study of Souza et al. (2003), which compared 24 rivers on the East Coast, pointed out that daily specific loads of nutrients and suspended material varied by one or two orders of magnitude in response to the climatic regime and the geological matrix, which controlled the weathering/leaching of materials, as well as anthropic impacts such as deforestation, dam construction, and the entrance of domestic effluents.

The main fact that the Lower SFR presented lower specific loads and fluxes of materials than those of other rivers was the location of the cascade of dams in the semi-arid region of the Sub-Middle SFR located relatively close to the coast. The reduction of fluxes and specific loads to the estuary was largely induced by the extreme proximity of the dams to the coast. At present, the percentage of the basin controlled by the dams upwards from the Xingó dam at the lower end of the cascade was 96 %, which was extremely high, practically eliminating the capacity of the basin to replenish the fluxes of both water and materials downstream of the dams to the estuary (Souza et al., 2003; Knoppers et al., 2005)

CONCLUSIONS

This study indicated that between 1985 (Santos, 1993) and 2001, there was a decrease of 94% in the output of DIN and of 31% in DSi from the river to the estuary. Although this study involved a more atypical drought event, the impoverishment of nutrient concentrations, loads and changes in composition was attributed to the construction of the dams, particularly due to the final regulation of the flow after the implementation of the Xingó dam in 1995. The estuary was now oligotrophic and transparent, most of the suspended matter (Medeiros et al., 2007) and nutrients were being retained by the dam reservoirs. The potential of material replenishment downstream of the Xingó dam reservoir to the coast has become insignificant being unable to compensate for the reduction of nutrient fluxes to the estuary. These alterations diminished the potential fertilization of the coastal waters by the São Francisco river and, likely also, the magnitude of primary production.

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