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Distribution and sediment yield in the upper basin of the Paraguay River and in the Pantanal Matogrossense, Brazil

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Abstract The upper basin of the Paraguay River begins on a plateau, then undergoes an abrupt fall to a plain named Pantanal in Brazil, and Chaco in Bolivia and Paraguay. This study details the sediment budget for the Brazilian Pantanal (362 376 km^2) based on data collected from the main rivers of the basin between 1977 and 2002. This period coincides with a marked increase in agricultural exploitation in the region; this has triggered increased erosion on the plateau, and increased deposition on the plains. Some 58% of the sediment derived from the plateau was deposited on/in the Pantanal. This can be represented as the deposition of a uniform layer of between 0.062 and 0.33 mm $year^{-1}$. It may have reached a maximum rate of 8.26 mm $year^{-1}$ in some places. Although some of the increases in erosion may be the result of climate change, it is more likely the result of anthropogenic activities associated with land-use changes.

Key words Brazil; degradation; deposition; sediment discharge; sediment transport

INTRODUCTION

The upper basin of the Paraguay River (600 000 km^2), limited by the Apa River to the south, is located in Brazil, Bolivia and Paraguay. It begins on a plateau, then undergoes an abrupt fall of between 30 and 50 m to a plain named Pantanal in Brazil (147 564 km^2) and Chaco in the other countries. The Brazilian stretch covers around 362 376 km^2 and is divided into two areas (plateau and plain) of approximately equal size. The plateau surrounds the Pantanal (ANA/GEF/PNUMA/OEA, 2004).

Settlement of the Upper Paraguay River Basin (UPRB) was based on agriculture and livestock, with the latter almost exclusively limited to the Panatanal. In the 1970s there was a "boom" in soy agriculture that was limited to the plateau. Further, during the same period, mining activities (gold and diamonds) increased. These land-use changes had a significant sedimentological impact on the entire UPRB, and the Pantanal Matogrossense in particular. Erosion and subsequent fluvial sediment discharges increased, as did sediment storage in the riverbeds and on the flood plains.

Some rivers, such as the Taquari River, the largest catchment in the UPRB, underwent substantial morphological changes as a result. Sedimentation increased in the Pantanal to such an extent, that severe flooding could result.

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OBJECTIVES OF THE SEDIMENTOLOGICAL STUDY

The monitoring programme in the Upper Paraguay basin was designed to address a number of sediment and sediment-related issues in a consistent fashion (DNOS, 1990; ANA/ANEEL/DNAEE, 2002). A primary goal was to determine the sediment fluxes at 13 sites in the basin. Additional data were collected on grain-size distributions as well as a variety of other parameters such as water quality sampling and analyses, but these data are not included in this paper. The study also was designed to evaluate whether or not precipitation and river discharge was increasing in the basin, and whether or not this was the result of climate change.

SAMPLING PROGRAMME, SEDIMENT DISCHARGE RESULTS AND ANALYSIS

Suspended and bed sediment samples were collected using the EWI (equal width increment) methodology developed by the US Geological Survey (Guy & Norman, 1970). A variety of US sampling equipment, including the USD 49, the bag sampler, and the BM-54, were used for this purpose. Suspended sediment samples were processed using the bottom withdrawal tube method which provides data on both concentration and granulometry (Guy & Norman, 1970). The same data were generated for bed load samples; however sieves were used to determine granulometry.

Total sediment discharges were computed using the modified Einstein procedure which estimates fluxes based on the grain-size distributions of both the suspended and bed sediments (Stevens, 1985; Braga, 2001). In addition, suspended sediment fluxes were also calculated using concentration and discharge data. The latter approach is likely to produce more reliable flux estimates, and was used for spatial and temporal comparisons in this programme. Average values generated from these computations are provided in Table 1. Sediment yields for the upper and middle reaches of the UPRB were also calculated. Both sediment fluxes and yields appear to be relatively “low” (Fig. 1), compared to other regions, such as the USA (e.g. the Khosla Study cited in PNUD/OMM *et al.*, 1977). However, some rivers (e.g. São Lourenço, Cuiabá, Alto Paraguay, Miranda, Taquari and Coxim) already have substantial sediment loads, and if the current trend continues, will begin to reach elevated levels.

Table 1 Suspended sediment discharge at river stations (DNOS, 1977–1982 and ANA, 1999–2002).

River and station	*CA* (km^2)	*Q* ($m^3 s^{-1}$)	D_{ss} (t $year^{-1}$)	P_{ss} (t.km^{-2}.$year^{-1}$)
Paraguay River at Cáceres*	33 860	537.3	1487203	43.9
Manso River at Porto de Cima	8 940	169.0	635144	71.0
Cuiabá River at Cuiabá*	21 730	356.5	2345052	107.9
Jorigue River at Pedra Preta	2 400	29.69	802785	334.5
São Lourenço River at Córrego Grande*	21 800	331.0	4205271	192.9
Itiquira River upstream Estrada BR-163	5 100	72.94	347801	68.2
Piquiri River at Estrada BR-163	3 240	33.11	250992	77.5
Cuiabá River at Porto Alegre	–	(702.1)	(3068694)	–
Taquari River at Coxim	27 040	328.6	4119813	152.4
Miranda River at Estrada MT-738 (ant.)	11 820	106.2	1758935	148.8
Aquidauana River at Ponte do Grego	–	(82.77)	(613477)	–
Aquidauana River at Aquidauana*	15 200	125.8	1411400	92.9
Paraguay River at Porto Esperança	363 500	2150	7325634	20.2
Summary				
Upper and medium basins (total referring to stations with data and P_{ss} computations)	151 130	2090.1	17364396	114.9
Porto Esperança (considered as lower reach of the basin)	363 500	2150	7325634	20.2

CA: catchment area; *Q*: discharge; D_{ss}: annual suspended sediment discharge;
P_{ss}: annual suspended sediment yield.
* DNOS and ANA stations with data from 1977 to 2002 (without data between 1983 and 1998).

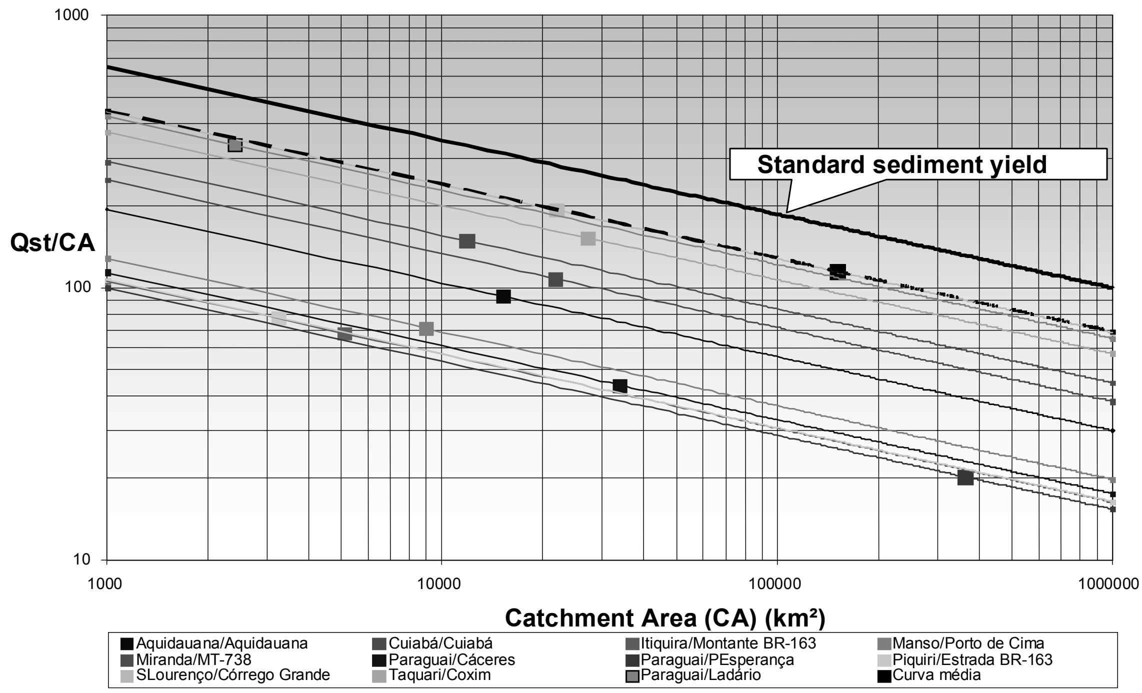

Fig. 1 Suspended sediment yield along the upper Paraguay River *vs* catchment area in comparison with the normal figures for sediment yield in the USA, according to Khosla (lines below standard – São Lourenço, Jorigue, Taquari, Miranda, Cuiabá, Aquidauana, Manso, Paraguai/Cáceres, Piquiri, Itiquira, Paraguai/Porto Esperança).

INCREASE IN THE SEDIMENT DISCHARGE AS TIME PASSES

The impacts of climate change are insidious. Increases in global temperatures trigger increases in evaporation, rainfall and river discharge. In turn, these increases lead to greater erosion and higher sediment yields. An analysis of the data generated from this study indicates that river flow and sediment fluxes in the UPRB are increasing over time (Figs 2 and 3).

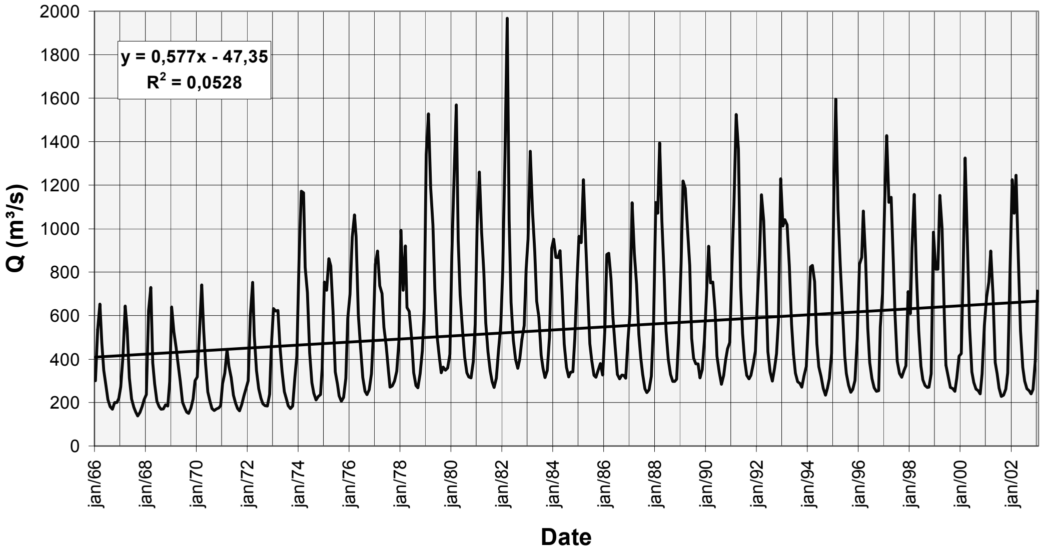

Fig. 2 Paraguay River at Cáceres: river flow *vs* time showing an increase during the period 1966–2002.

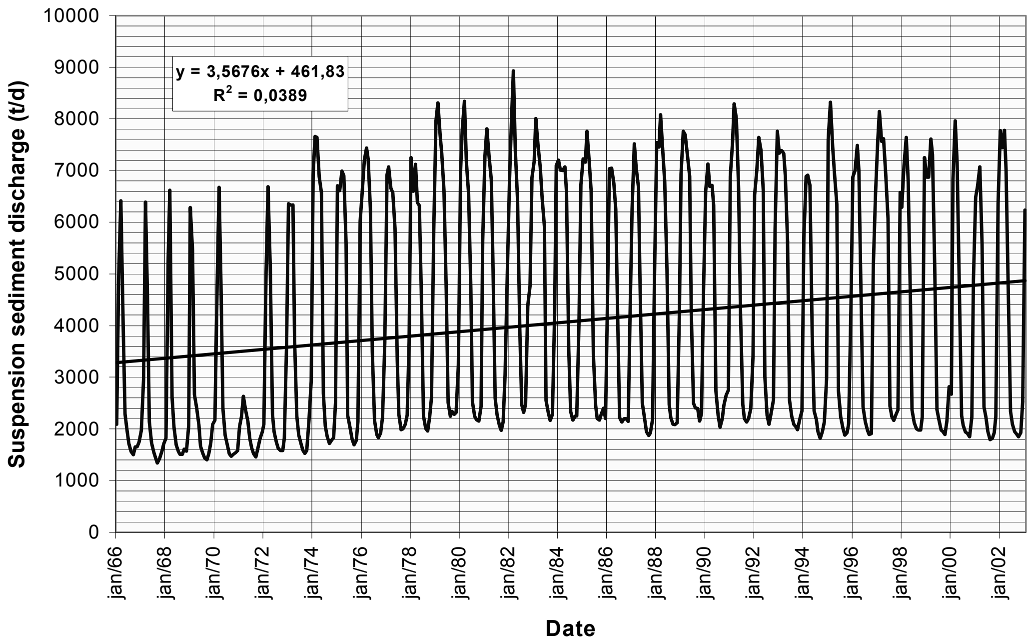

Fig. 3 Paraguay River at Cáceres, suspended sediment discharge *vs* time showing an increase during the period 1966–2002.

The next step in the study was to develop mass curves for the various catchments in the UPRB. These curves provide a means of comparing the cumulative amount of sediment fluxes with the cumulative amount of river discharge. Evaluating the differences between adjacent lines of the mass curves permits an evaluation of the differences in sediment flux for selected time intervals. Thus, the rate of change can be computed from the slopes of each line using equations (1) and (2).

$$E_c = \frac{r_2 - r_1}{r_1} \tag{1}$$

$$(1+R)^n = 1 + E_c \tag{2}$$

with r_1 and r_2 being the slopes of the first and second straight lines, respectively; E_c the total variation within the period; and R the annual rate.

Figure 4 displays data from the Paraguay River at Cáceres. Note that the sediment load at each station increased contemporaneously with the agricultural "boom" that began in the 1970s. Since 2001, these elevated rates have remained fairly constant. Similar results were obtained for all the sites sampled during this study.

The annual increases in fluvial sediment fluxes during the "boom" period were quite high. For example, 66.8% in the São Lourenço River, 50.8% in the Cuiabá River, 48.3% in Taquari River, and 41.3% in the Miranda River. Currently, the annual rate of increase appears to have stabilized at between 1 and 2% per year. The increased level of erosion and sediment yield attributable to changing agricultural practices during the "boom" may have been enhanced by the contemporaneous increase in deforestation, intended to increase the amount of arable land.

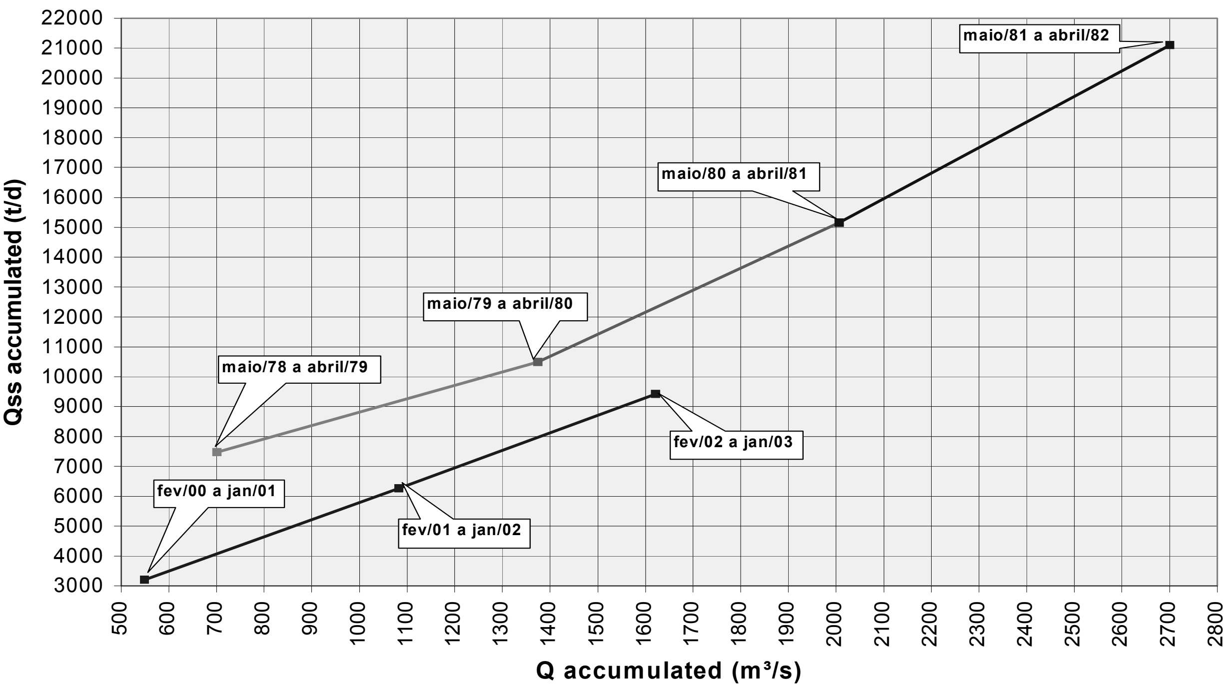

Fig. 4 Paraguay River at Cáceres, mass curve produced by plotting the accumulated river flows *vs* the accumulated suspended sediment fluxes.

COMPARISON OF STUDIES

The majority of the long-term monitoring sites included in this study tend to display annual increases in river flow during the period-of-record (Table 2). These discharge increases may have been triggered by several factors, such as increasing annual rainfall since 1966 and/or a local long-term climate change. These increases in discharge are matched with concomitant annual increases in sediment fluxes (based on the sediment discharge curves). An analysis of the mass curves also indicates increasing annual rates of erosion and sediment yield, at almost all the long-term sites. The exceptions are on the Cuiabá River at Porto Alegre, in the Pantanal, where the geomorphology favours sediment deposition. Despite this generally increasing trend, the Aquidauana and Miranda rivers displayed slight decreases. These exceptions may be due to declining land-use and/or local reductions in precipitation. Trends at short-term monitoring sites (e.g. the Jorigue River at Pedra Preta and the Aquidauana River at Ponte do Grego) were not detectable.

Table 2 Summary of the river flow, sediment discharge and mass curve graphical analyses.

River/station	Flow ($m^3 s^{-1}$)	Sed. discharge ($t\ year^{-1}$)	Period	Increase sed. discharge Ten-dency	Rate (%)	Period	Remark
Paraguay River at Cáceres	↑	↑	1966–02	↑	1.09*	1978–03	Intensive erosion from 1977 to 1981
Manso River at Porto de Cima	↑	↑	1931–95	↑	1.09	1978–82	Intensive erosion from 1980 to 1982
Cuiabá River at Cuiabá	↑	↑	1962–02	↑	0.86*	1978–02	Intensive erosion from 1999 to 2002
Jorigue River at Pedra Preta	↓	↓	1979–01	↓	–38.2	1979–82	Short-term observation period
São Lourenço River upstream Córrego Grande	↑	↑	1969–01	↑	9.05*	1978–02	Intensive erosion from 1999 to 2002
Itiquira River upstream Estrada BR-163	↑	↑	1931–97	↑	35.8	1979–82	Intensive erosion from 1979 to 1982
Piquiri River at Estrada BR-163	↑	↑	1969–88	↑	20.7	1978–82	Intensive erosion from 1977 to 1981
Cuiabá River at Porto Alegre	↑	↓	1968–95	↓	–11.6	1978–81	Bed deposits upstream
Taquari River at Coxim	↑	↑	1966–95	↑	30.3	1978–82	Intensive erosion from 1980 to 1982
Miranda River at Estrada MT-738 (old)	↑	↓	1978–95	↑	41.3	1978–82	Intensive erosion from 1977 to 1981
Aquidauana River at Ponte do Grego	↓	↓	1982–95	–	–	–	Short-term observation period
Aquidauana River at Aquidauana	↓	↓	1976–02	↑	1.03*	1978–02	Intensive erosion from 1980 to 1982
Paraguay River at Porto Esperança	↑	↑	1964–95	↑	5.33	1978–81	Should be smaller. Influenced by Taquari.

* Recent rate, which has already reached higher figures in the past.

ASSESSMENT OF MORE RECENT SEDIMENT DEPOSITS IN THE PANTANAL

The most downstream sampling site in the UPRB, where sediment data have been collected, is Porto Esperança, which can be viewed as the outlet for the basin (Table 3). Much of the sediment load for this site, covering the 26-year period between 1977 and 2002 appears to have been deposited along the upper river reaches in the Pantanal where some 58% of the sediment discharge was trapped. On the other hand, some 42% was released downstream. The suspended sediment load of 17.4×10^6 t year^{-1} resulted from an area of 151 130 km^2. This annual flux represents an 80% contribution from suspended sediment and a 20% contribution from bed load. The flux is equivalent to 13.9×10^6 m^3 year^{-1}, assuming a bulk density of 1.5 t m^{-3}. This sediment volume represents a soil loss of 0.092 mm year^{-1}, bearing in mind that within 10 years, this figure would reach 0.92 mm, and 2.3 mm in 25 years (from 1978 to 2002).

The suspended sediment discharge and the total sediment discharge averaged 7.3×10^6 t year^{-1} and 8.8×10^6 t year^{-1} respectively; this corresponds to a total downstream load of 5.9×10^6 t year^{-1}. The difference between this quantity and the one related to eroded areas in the plateau is 8.0×10^6 m^3 year^{-1}. The Pantanal area upstream of the Porto Esperança site represents 130 000 km^2; hence, the inferred average thickness of the annual deposition layer is 0.062 mm year^{-1}, 0.62 mm for 10 years, and 1.54 mm year^{-1} for 25 years.

There were substantive changes in the annual sediment fluxes in the upper part of the basin between the 1970s and 2002. However, if the average rate was assumed to be 10%, even though interannual variability could range from 1 to 66%, then the total volume for the 25-year period-of-record would be some 1.4×10^6 m^3. This leads to a total soil loss of about 9.0 mm, or an average of 0.36 mm year^{-1}. On the other hand, the sediment load trapped in the Pantanal, upstream from Porto Esperança, for the 25-year period, was estimated assuming a rate of 5.3% (Table 2). This equates to a depositional volume of 1.1×10^6 m^3. On average, this corresponds to a deposition height of 8.3 mm,

Table 3 Summary of the results concerning soil loss and deposition.

Basin	*CA* (km^2)	Q_{ss} (t year^{-1})	Q_{st} t year^{-1}	V_{st} (m^3 year^{-1})	h_t (mm year^{-1})	$h_{t/10\ years}$ (mm)	$h_{t/25\ years}$ (mm)
Upper basin	151 130	17.4×10^6	20.84×10^6	13.9×10^6	0.092 degradation	0.92 degradation	2.30 degradation
Pantanal, upstream Porto Esperança	130 000	7.3×10^6	8.8×10^6	8.0×10^6 (Vol. in Pantanal)	0.062 deposition	0.62 deposition	1.54 deposition
Upper basin	151 130		$2,049 \times 10^6$ (accumulated figure)	1.4×10^6	0.36 degradation		9.04 degradation
Pantanal, upstream Porto Esperança	130 000		439×10^6 (accumulated figure released)	1.1×10^6 (trapped volume)	0.33 deposition		8.3 deposition

Considering annual sediment yield increasing between 1978 and 2002, corresponding to a total of 10% within. *CA*: catchment area; Q_{ss}: suspended sediment discharge; Q_{st}: total sediment discharge; V_{st}: total sediment volume; h_t: sediment height (1 year, 10 years and 25 years).

or averages to 0.33 mm year^{-1} (Table 3). Based on these various calculations, it appears that 56% of the total sediment load from the upper part of the basin remains in the Pantanal, whereas some 44% moves downstream.

The soil loss estimated for various segments of the UPRB ranges from 0.092 to 0.36 mm year^{-1}. These figures are substantial when compared to other river basins. For example, the estimated value for the Colorado (US) and Mekong Rivers (Thailand) is 0.12 mm year^{-1}, whereas that for the Yangtze (China) is 0.15 mm year^{-1} (computing from Lou *et al.*, 1982 (citing Holeman, 1968)). Deposition heights in the Pantanal also appear substantial, ranging from 0.062 to 0.33 mm.year^{-1} (Table 3).

CONCLUSIONS AND RECOMMENDATIONS

The results from this study indicate significant increases in both fluvial and sediment discharges in the UPRB for the 25-year period from 1978 to 2002. The greatest increases occurred during the 1970s and 1980s, apparently as a result of agricultural land-use changes. Some of the discharge increases also might be due to climate change, although this is less certain than that attributable to land-use. Further, the local petrology (predominantly sedimentary rocks) in the UPRB also favours erosion. Some forethought relative to the growth in agriculture in the region might have limited the increases in erosion through the contemporaneous introduction of soil conservation measures. As a general "rule-of-thumb", the production of 1 kg of grain triggers the erosion of 10 kg of soil, and requires 1000 l water. Current estimates for 2004, in Brazil, predict production levels in excess of 120×10^6 t of grain, some of this within the study area. It is more than time to think about introducing soil conservation measures in the basin in order to avoid additional fertility losses, and to reduce the amount of sediment and water discharges in the rivers.

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