Geomorphology 113 (2009) 239–252

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

The geomorphologic response of a large pristine alluvial river to tremendous deforestation in the South American tropics: The case of the Araguaia River

E.M. Latrubesse [a,b,*], M.L. Amsler [a], R.P. de Morais [a], S. Aquino [a]

[a] University of Texas at Austin, Department of Geography and the Environment, GRG 334, A3100, Austin TX, 78712, USA
[b] Centro de Investigaciones Geológicas-CIG-LATYR-CONICET, Universidad Nacional de La Plata-FCNyM, Calle 1 N 644 (1900), La Plata, Argentina

ARTICLE INFO

Article history:
Accepted 11 December 2008
Available online 27 March 2009

Keywords:
Araguaia River
Deforestation
Tropical
South America
Large rivers
Geomorphologic response

ABSTRACT

The geomorphic response of the Araguaia River to catastrophic deforestation of the Cerrado since 1970s is discussed. With a mean annual discharge of 6500 m^3/s and a drainage area of ~380,000 km^2, the Araguaia River is the main system draining the savannas of Central Brazil. Here, we demonstrate that the river is undergoing a substantive increase in bed load transport and changes in its geomorphology. A multi-approach methodology was used and involved detailed geomorphologic mapping for three decades (60, 70, and 90), a budget of erosional and deposition areas using GIS, volumetric calculations, and estimations of bed load transport. Our results show that the alluvial plain is undergoing active sedimentation and 233 Mt of sediments were stored by channel activity in a reach 570 km long of the middle Araguaia. The bed load transport has increased 31% from 6.6 Mt in the sixties to 8.8 Mt in the 1990s and the channel pattern has been metamorphosed to some extent. This is an outstanding current example of short term geomorphic response to deforestation in a large pristine tropical fluvial system without direct human interventions in the channel.

1. Introduction

The degradation of the tropical biomes and water resources by deforestation, land use changes, mining, dams and others activities, have driven the focus of the environmentalists and the press during recent decades. Impacts on the Brazilian savannas or Cerrado have been significantly larger than those on the tropical rainforest, although international attention has been much smaller. From the original 2,000,000 km^2 of Cerrado, more than 60% have been converted and fragmented by deforestation and expansion of the agriculture frontier. No other biome in the world has been destroyed so quickly and thoroughly in human history. Within this scenario of dramatic changes and uncertainties, the Araguaia River, the main fluvial artery draining the Cerrado, maintains the most important wetlands of Central Brazil and acts like a sort of last environmental frontier. In spite of the importance of large tropical fluvial systems, like the Araguaia River, studies of geomorphic response and sediment budgets in response to land use change have been concentrated in small basins (Reid and Dunne, 1996). Suggestions of increases in water discharges as response to deforestation in the Amazon (Gentry and Lopez-Parodi, 1980), for example, were erroneous (Nordin and Meade, 1982). So far, evidence of changes in the hydrological regime, sediment load and geomorphologic response of large pristine tropical rivers to deforestation has not been provided. Here we show evidence of the geomorphologic and sedimentary response of the Araguaia River to the accelerated deforestation and land use change of its basin which was appraised by a multi-approach analysis based on three main methodological approaches a) qualitative to semi-quantitative morphometric and morphological description, b) a simplified budget between erosional and depositional processes by area and volume, c) estimations of bed load transport. Details of applied methodologies are described in each section below. Field work was conducted by boat along the entire 570 km length of the studied area from 1999 to 2008.

2. Study area

With 2110 km in length, a drainage area of 375,000 km^2, and a mean annual discharge of 6500 $m^3 s^{-1}$, the Araguaia is the largest river of the wet–dry tropics of Brazil (Fig. 1). The dominant climate is tropical wet–dry and rainfall increases roughly from south to north from 1500 to 2200 mm/y. The river has three major reaches: upper, middle, and lower. The 450 km long upper Araguaia drains Paleozoic and Mesozoic sedimentary rocks as well as hilly landscapes of Precambrian rocks of the Brazilian shield. The middle reach run along 1100 km over a flat area formed by Pleistocene sediments (the Bananal plain) and is characterized by a well developed Holocene alluvial plain 3–6 km width. The lower course flows on bedrock again along 500 km down to the confluence with the Tocantins River (Latrubesse and Stevaux, 2002).

* Corresponding author. Laboratory of Geology and Physical Geography, Federal University of Goias-IESA/CIAMB, Campus II, 74001-970, Goiânia, GO, Brazil.
E-mail address: latrubesse@austin.utexas.edu (E.M. Latrubesse).

0169-555X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2009.03.014

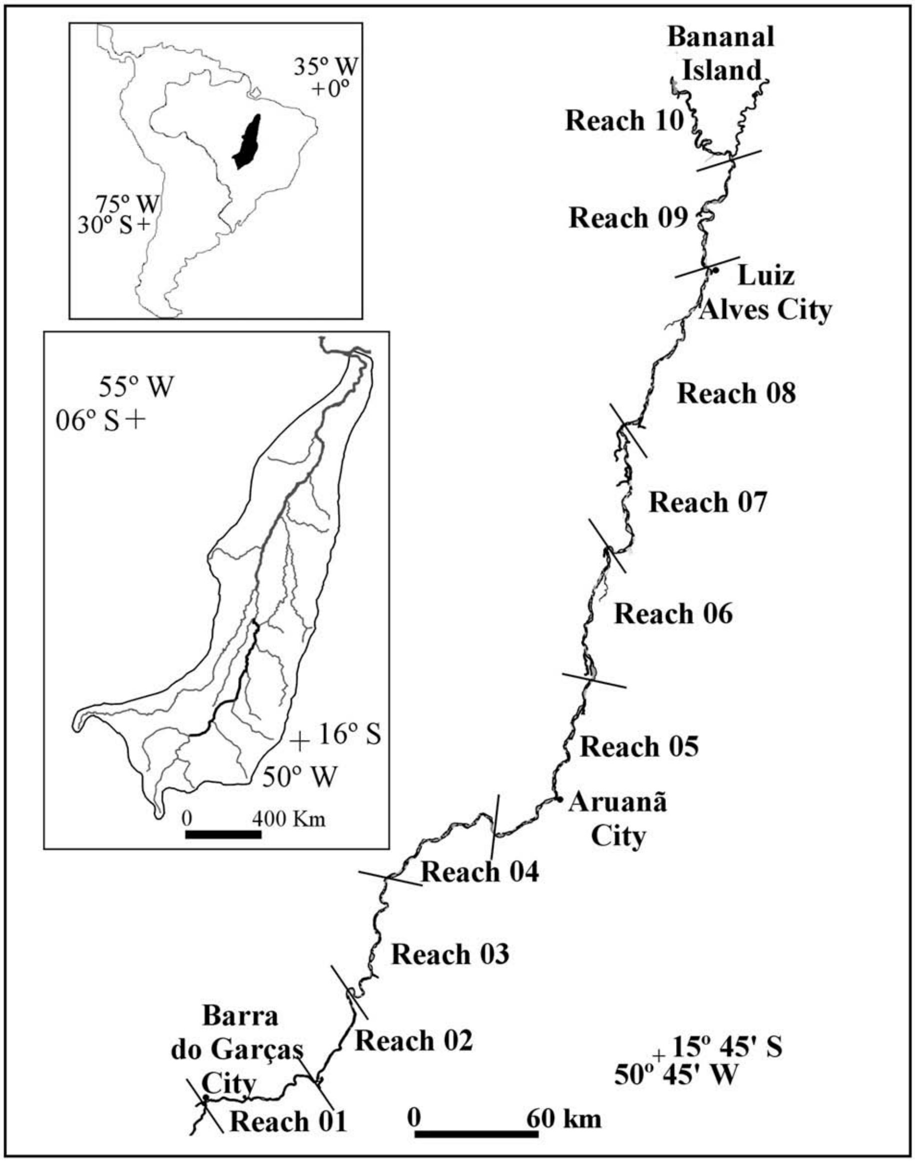

Fig. 1. Location of the Araguaia River and details of the ten studied reaches along the middle course (570 km length).

The middle Araguaia is a low sinuosity anabranching river with a tendency to braid (Latrubesse, 2008) and transports abundant sandy load (up to ~70% of the total sediment load). In this reach the geomorphologic signals dramatically indicate alterations in the sediment budget and in river response. As the agricultural frontier advanced along the upper and middle basin, detailed geomorphologic data are presented for the first 570 km of the alluvial plain, from Barra do Garças city to the confluence of the Araguaia with its tributary, the Cristalino River. The floodplain was divided into ten fluvial geomorphologic reaches (Fig. 1). The drainage area in the studied reach increases from 22,000 km^2 to 118,000 km^2. In this sector, with exception of the Cristalino River, all the tributaries arise in Goias State on the east side, draining mainly Precambrian metamorphic and igneous rocks.

3. Multi-approach analysis

Methodological aspects regarding the multi-approach analysis applied in this study, together with the corresponding results, are given next.

3.1. Qualitative to semi-quantitative morphometric and morphological description

A comparison of the geomorphologic fluvial records of 1965, 1975 and 1998 was obtained during the low river stage season (July). Landsat 1 MSS, 5 TM images for several years, SLAR mosaics from 1976, topographic charts, aerial photographs 1:60,000 from 1965, and field work surveys, were used. All these datasets were compiled and processed using a Geographic Information System. Morphometric parameters and geomorphologic elements, such as variability in the number of islands, type of bars (lateral, central, accreted to islands), sinuosity, mean channel width, maximum width, minimum width, number of secondary channels, number of secondary channels suffering net aggradation, islands that increased in area and islands that decreased in area were compared (Table 1). The mean river stage for the period 1970–1998 during July was 1.64 m in Araguaia station (StD = 0.38). River average stages were 1.45 m in July, 1975 and 1.52 m in 1998, respectively.

No important changes were recorded when comparing the 1965 and 1975 data, indicating that the river was not undergoing conspicuous transformations in that period (Fig. 2). The islands remained relatively

Table 1
Changes in channel landforms and morphological elements.

Channel landforms and morphological elements	Reach 1		Reach 2		Reach 3		Reach 4		Reach 5		Reach 6		Reach 7		Reach 8		Reach 9		Reach 10	
	1965	1998	.1965	1998	.1965	1998	.1965	1998	1965	1998	1965	1998	1965	1998	1965	1998	1965	1998	1965	1998
Number of islands	2	1	00	00	16	7	32	15	33	24	21	19	30	23	21	23	27	20	20	16
Number of new islands	–	00	–	00	–	2	–	8	–	17	–	10	–	17	–	17	–	12	–	08
Number of remnants islands	–	1	–	00	–	5	–	7	–	7	–	9	–	6	–	6	–	8	–	8
Variability in the occurrence of islands (1965-1998)	1		0		9		17		9		2		7		+2		7		4	
Number of missing islands	1		0		11		25		26		12		22		15		19		12	
Number of sand bars	0	4	4	5	31	26	39	35	64	74	32	43	25	39	37	45	31	23	27	15
Number of silted/fill up channels	–	0	–	0	–	1	–	6	–	11	–	5	–	8	–	10	–	7	–	3
Number of channels affected by siltation	–	1	–	0	–	1	–	5	–	4	–	4	–	6	–	5	–	8	–	3
Minimum width	64.1	72.4	220	198	286	144,	237	233	299	222	199	208	262	166	255	233	209	191	106	127
Maximum width	646	535	536	491	1440	1421	1204	1340	1257	1357	1811	2088	2028	2223	1253	1424	2338	1985	2338	1954
Mean width	227	218	375	336	515	489	649	535	654	624	665	599	723	654	620	613	661	567	505	454

stable with negligible changes and the channels were characterized by the presence of large lateral bars. Between the 1960s and the 1990s, however, the changes were remarkable (Table 1). They are described next.

3.1.1. Islands

The number of islands decreased substantially because of processes such as: accretion of islands to the floodplain by infilling of second-order and relatively sinuous and narrow branches; destruction of small islands along the main channel; and accretion of large lateral bars to the floodplain embracing small lateral islands. The quantitative budget of islands was obtained as

$$I_{1965} = (Ie+Iap+Iai+Ir) \quad (1)$$

$$I_{1998} = (In+Ir) \quad (2)$$

Where: $I_{1965(1998)}$ = number of islands in 1965 or 1998; Ie = eroded islands; Iap = islands attached laterally to the floodplain; Iai = islands accreted to other island; Ir = relict islands; In = new islands.

Between 1960s and the end of the 1990s, the number of islands changed from 202 to135 (Fig. 3). Taking account the total of islands existing in 1965, 27% of them become attached laterally to the floodplain by 1998 while 31% were eroded, 30% remained (classified as relict islands) and 12% were attached to pre-existing islands coalescing by bar accretion. From the 135 islands existing in 1998, 64 were new islands generated by channel sedimentation during the last 33 years. It is important to discriminate the size of the islands in these numbers. We identified four categories: very small islands (Ivs) from 0.005 to 0.01 km^2, small islands (Is) between 0.011 and 0.10 km^2, middle size islands (Im) between 0.11 and 1 km^2 and large islands (Il) from 1.1 and 5 km^2 (Fig. 4).

The number of very small and small islands reduced drastically from19 to 9 and from 102 to 64, respectively. Interestingly, from the original 102 small islands, 45 were eroded, 34 accreted by lateral sedimentation to the floodplain (as shown in Figs. 5–7) were amalgamated to other islands or between them by channel deposition generating larger islands. Channel processes were able to generate 48 new small islands. Large islands can be considered relatively stable forms in a decadal scale. From the ten original large islands mapped in 1965, 9 remained in the channel, and the other was attached laterally to the floodplain. One of the nine residual large islands was transformed into two large islands and, a new one, formed by the accretion of two medium size islands. Medium size islands had a different response because the number reduced was from 71 to 53, i.e. ~25%. With respect to the small islands, however, some kind of equilibrium existed between erosion and generation of new islands (7 and 8, respectively). On the other hand, the reduction in the number of medium size islands happened because lateral accretion to the floodplain of 18 of them and the attaching of 9 to other islands (Fig. 4).

The number of silted channels can also be correlated with the quantity of islands which became part of the floodplain. Second or third order channels, with a width ~1/3 to 1/5 that of the main channel, were silting and suffering atrophy mainly by sedimentation, accreting islands to the floodplain (Fig. 5 and Table 1). Reaches 4 to 9 showed the largest quantity of obliterated channels. Fig. 5– a show some examples of channel silting and atrophy with sandy sediments and the subsequent attachment of islands to the floodplain.

3.1.2. Bars

Large sand bars are characteristic in the Araguaia River. Lateral bars, middle channel bars and bars accreted to islands are typical. Lateral bars usually generate in more straight reaches. Point bars are present in a few curves, and are considered here as a kind of lateral bars.

Large lateral bars are relatively flat and low, with high length/width relationships. They are formed by downstream migrating dunes and by lateral accretion when the opposite bank recedes by erosion (Fig. 7b). These bed forms can be several kilometers long and occupy relatively stables areas.

Middle Channel bars are also typical features. In general middle channels bars have steeper lateral or upstream slopes than lateral bars. They are usually formed by sets of planar cross-stratification up to 1 meter thick topped by beds of trough cross-stratification, planar beds and ripples some decimeters thick (Fig. 7c).

Bars accreted to islands are formed because of bar interference in the channel that triggers the generation of a bar that, generally, accretes laterally to the island. The bar eventually becomes part of the island by lateral development and vertical sedimentation which favors the tropical vegetation fixation. The islands generation model and the role of accreted bars follow the general model described by Latrubesse and Franzinelli (2002) in the Amazon River.

Variations in the number of channel bars are significant. We considered, for balance, only two categories: middle channel and lateral bars discarding other types. The number of lateral bars increased slightly between the 1960s and 1990s but the quantity of middle channel bars increased significantly (Figs. 3 and 8).

3.2. Simplified budget between erosion and depositional processes by area and volume

3.2.1. Area approach

A simplified budget by area between 1965 and 1998 was applied using Eq. (3) to estimate the area balance:

$$Cy = Cx - Als + Ae - (Aiy - Aix) - (Aby - Abx) \quad (3)$$

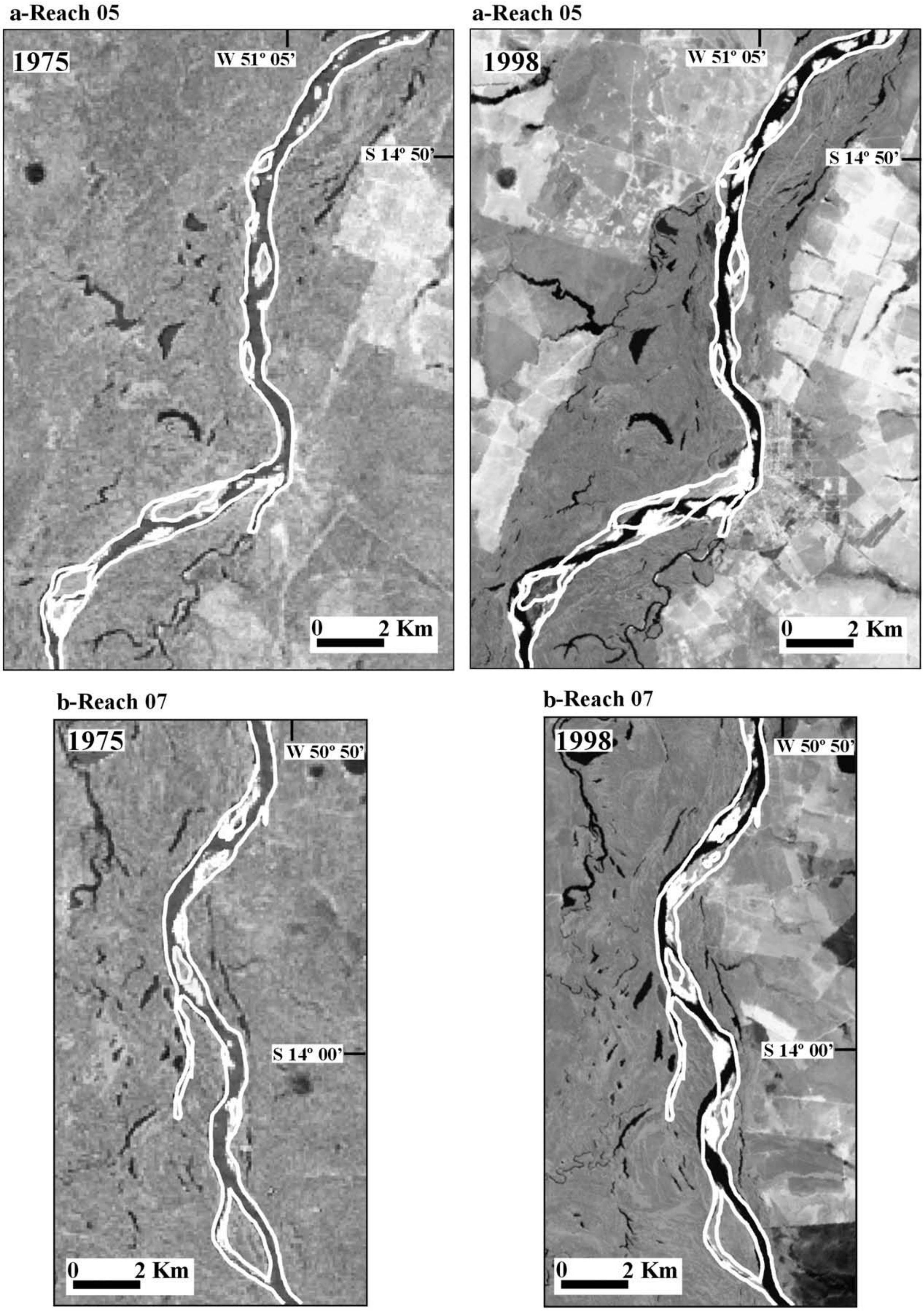

Fig. 2. Comparison of channel changes between 1965 (white line) with satellite images of 1975 (left), and 1998 (right). a) detail of reach 5 and b) detail of reach 7.

Where x = beginning period; y = end period; Cy = water area for channel in time y; Cx = water area for channel in time x; Als = area of lateral sedimentation; Ae = eroded area; Aiy = island area in time y; Aix = island area in time x; Aby = area occupied by bars in time y; Abx = area occupied by bars in time x.

The 1960s information was preferentially used in the analysis because of its higher quality (aerial photographs and georeferenced charts) compared to the 1970s. Sand bars were not included in the sedimentary balance of net sedimentation/erosional processes in the floodplain but were included in the channel processes.

To characterize properly the erosion and sedimentation processes involved in the budget of Eq. (3), the next categories were identified and mapped (Figs. 9 and 10): I; Channel erosion processes, such as lateral erosion, erosion in residual islands, totally eroded islands, and erosion in laterally accreted islands. II; Sedimentary processes in the channel such as lateral sedimentation, sedimentation in cores of residual islands, islands accreted to the floodplain, residual islands accreted to erosion areas, cores of residual islands, new island in an eroded area, new islands, and lateral sedimentation in a floodplain eroded sector. Detailed maps showing each of these processes along the whole 570 km reach were made (Fig. 10). Two radiocarbon dates from wood and leaves in river banks were used to corroborate the age of modern areas of sedimentation as identified by remote sensing. The ^{14}C activity in both samples indicated that the trees died some time after 1950 (Waikato 9692 and 9693, samples 1 and 2, respectively of Fig. 11).

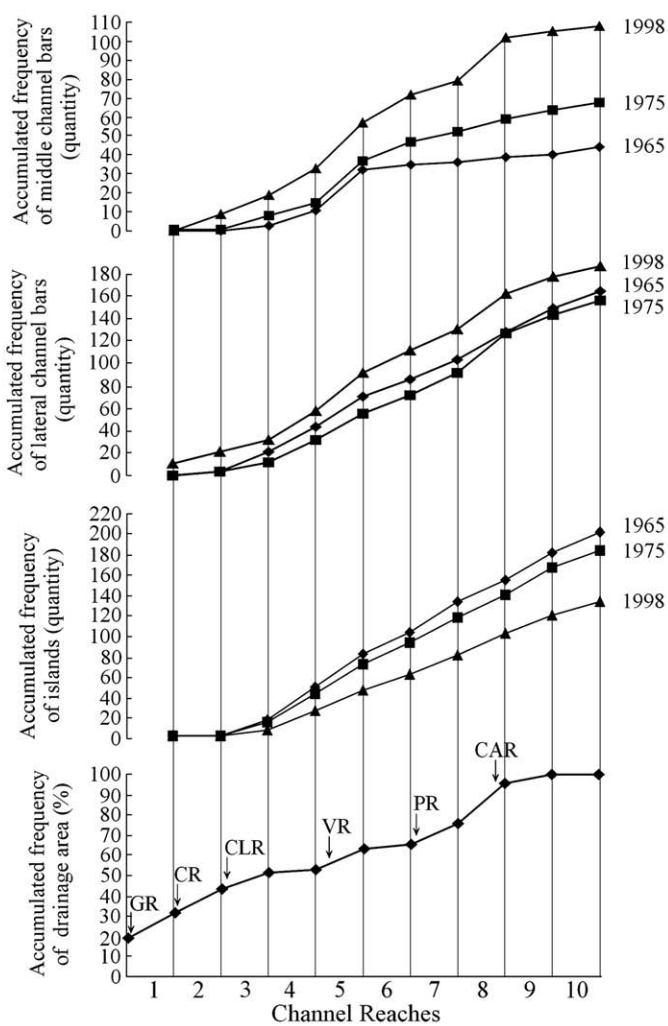

Fig. 3. Cumulative frequency of drainage area, number of islands, number of side-channel bars and mid-channel bars in the ten studied reaches. Arrows and letters indicate the confluence of main tributaries with the Araguaia River: GR = Garças River, CR = Caiapó River, CLR = Claro River, VR = Vermelho river; PR = Peixes River and CAR = Crixás Açú River.

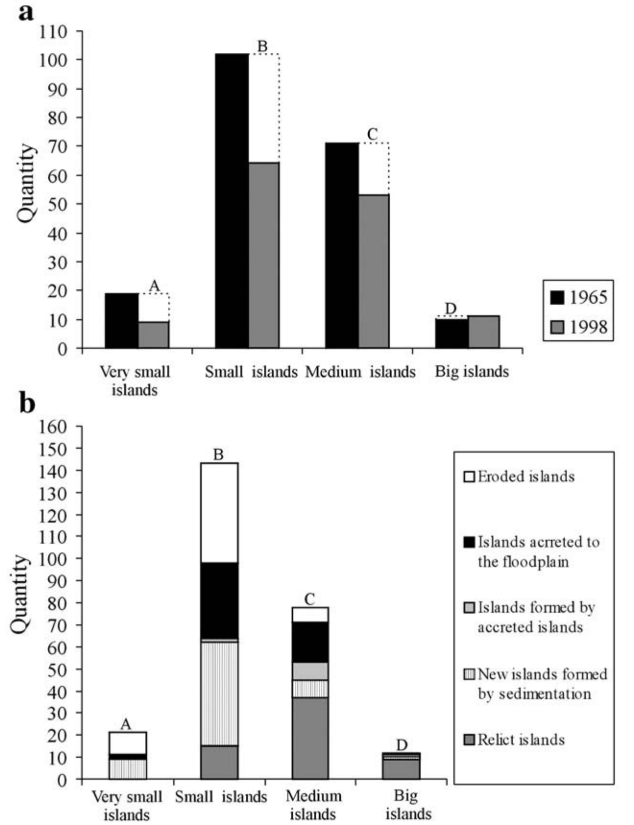

Fig. 4. a) Distribution of islands by size categories: very small (0.002 (o 0.005?)–0.01 km^2); small (0.011–0.1 km^2); medium (0.11–1 km^2); large (1.1–5 km^2) in 1965 and 1998. b) Distribution by processes leading to islands "missed" between 1965 and 1998. Negative feedback in island number means erosion, lateral accretion to the floodplain and accretion to other islands while positive means generation of new islands which did not compensate the island reduction except the big ones whose number remained almost stable).

Table 2 shows the deposited or eroded area in the 10 reaches. Reaches 4 to 7 and 9 stored the largest volumes of sediment (Fig. 12 and Table 2). Reaches 1 to 3 stored a relatively low quantity of sediments because the low development of the floodplain in these reaches. Along reaches 4 to 7, ~62% of the total sediment was stored while the drainage area increased nearly 24% (from 51 to 75%), because the tributaries coming from the Brazilian shield on the East side. Reach 9 also stored a significant quantity of sediments that can be the consequence of the Crixas Açú River input which joins the Araguaia at the end of reach 8.

The conservative categories, such as islands or part of islands accreted to the floodplain, and relict island cores, were, of course, not included in the mass budget (Table 2). The mass balance included the new areas of sedimentation, such as lateral sedimentation, that accounted for 77.9% of the total area, 14.8% of new sedimentation accreted laterally to remnants islands and new islands formed in the relict part of original channel (6.5) % (Table 2).

Lateral erosion was the main mechanism of erosion in the channel and explained 80% of the total eroded area while erosion of relic islands, islands accreted to the floodplain and fully eroded islands, represented 11.4%, 4.7% and 3.8%, respectively. Reaches 3 to 9 were the most active exchanging sediment, averaging 10.35 km^2 for sedimentation and 7.26 km^2 for erosion. In reach 5 the largest sedimentation and erosion areas were measured: 12.6 km^2 and 8.8 km^2, respectively.

As explained above, sand bars were not included in the area balance but were analyzed. The number of middle channel bars increased but the mean area of individual bars decreased (Fig. 8). The total area and number of middle channel bars increased from 4.21 km^2 to 9.81 km^2 and from 44 to 124, respectively, explaining the 17% decrement in individual size, from 0.095 to 0.079 km^2. The number of lateral bars also increased but the total area decreased slightly. As a consequence, it resulted in nearly a 30% decrease of individual bar size. Because of the generally smooth surface slopes of bars, small differences of river stage can introduce substantial changes in the exposed areas. Despite the uncertainties implicit in the area estimation of bars and because of the dependence on river stage, our estimations can be considered reasonable because of the control of river stage in this analysis. The Landsat images of 02/071998 captured a river stage of 1.65 m at the Aruanã gauge station while the average stage during July 1975 was 1.45 m.

3.3. Volumetric and mass calculations

The volumetric calculations were based on the area values presented above. The mean thickness of the sedimentary deposits was related to the mean lower water stage and calibrated using the

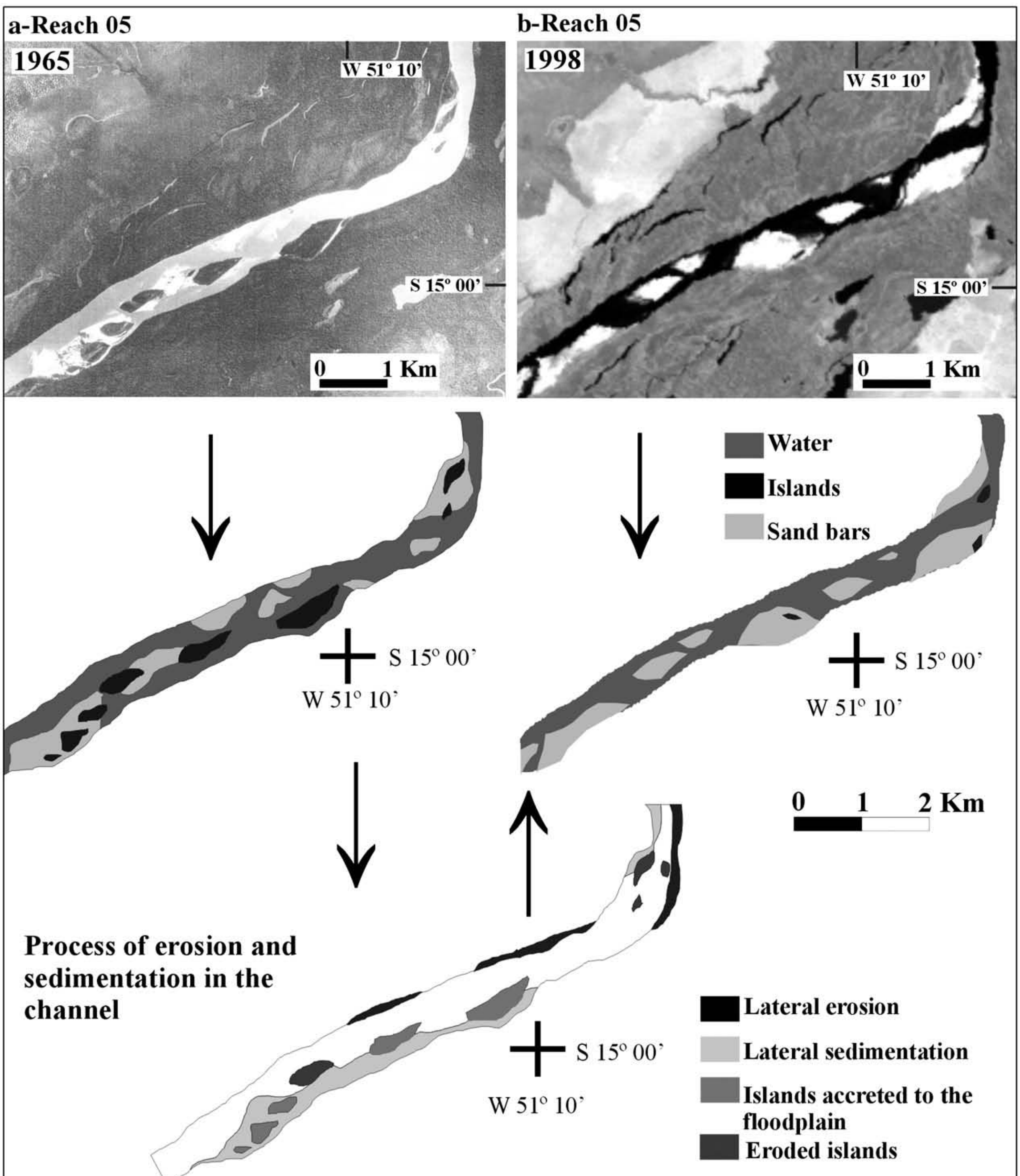

Fig. 5. Changes in the Araguaia River between 1965 and 1998 along a sector of reach 5.

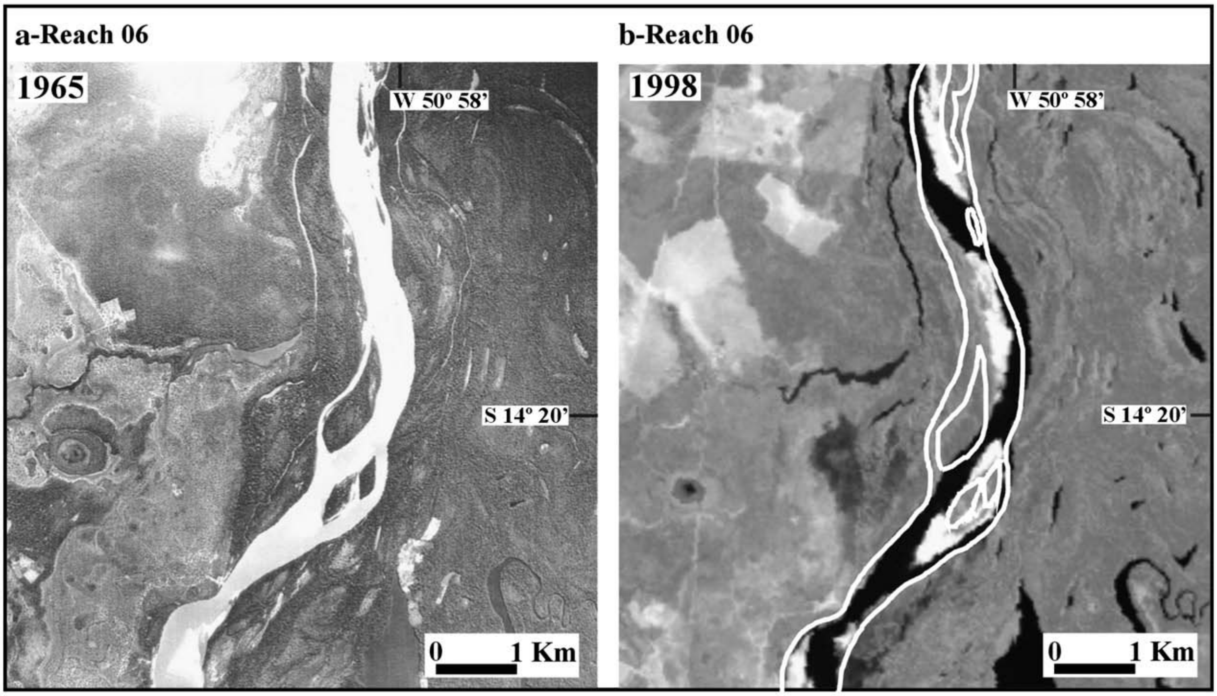

Fig. 6. Silting/infill of a second-order channel which accreted a medium size island to the floodplain in reach 6. White lines indicate the channel configuration in 1965.

available gauge stations along the river, hydraulic geometry equations, bankfull and barfull stages, a survey of more than two hundred bank profiles and a few vibro-core drillings. A mean thickness of 6.7 m was computed from these sources. The sandy deposits averaged 4.7 m and 2 m were estimated for the fine uppermost deposits (Fig. 7d). A bulk density of 1490 kg/m^3 was used for sandy deposits and of 1328 kg/m^3 for floodplain deposits (20% sand + 50%silt + 30% clay). The net sedimentation presented in Fig. 12 was calculated as the volumetric difference between erosion and depositional processes at each reach and expressed in mass units.

Data on Fig. 12 show that good correlations exist between the area and volumetric data because of the low height variability of the floodplain banks and islands and the use of "bar-full" and "bank full" parameters to calculate the thickness of sandy and fine flood deposits respectively. These parameters were determined during the field surveys. The pre-existing areas of accumulation that were accreted to the floodplain, such as some islands and the unstable/active landforms such as some sandy bars, were not included in the volumetric calculations. Moreover, the fine sediments deposited on laterally accreted areas and islands during the last decades were considered, i.e. the transference of fine deposits into the distal floodplain was excluded. That means that our calculation of fine sediment silting in relation to the floodplain is underestimated and only represents the deposition associated with the channel and marginally accreted deposits.

Within these constraints, the data show that a trend to aggradation exists, which is in agreement with the area calculations discussed above. We estimated that at least a net amount of ~232 million tons of sediments were stored in the alluvial plain related to channel activity from 1965 to 1998 (Fig. 12).

3.4. Transport of bed material

The quantification of the changes in the Araguaia channel presented above was also corroborated through estimations of the total bed material load transported near Aruana city. The Araguaia drainage area at this point is 77,700 km^2 with a mean annual discharge of 1180 m^3/s. This station was chosen because of the availability of historical streamflow measurements since 1970 and its proximity to the beginning of the alluvial plain. Therefore, the calculations of the bed sediment transport here can be used as representative values of the sedimentary load arriving to the middle Araguaia from the upper basin and from one of the main tributaries, the Vermelho River.

Sediment transport data do not exist for the Araguaia River at this reach to check the computations, therefore the following strategy was designed to get the total bed material load information with certain accuracy.

a) Bed load transport (G_{sf}), was measured for a given river stage ($Q = 700$–800 m^3/s) at a fairly regular channel reach (~2,000 m long) located a few kilometers downstream Aruana city. The values for bed load were obtained by means of the well known "dunes displacement method" applied at four longitudinal profiles. The longitudinal profiles were defined by using floats displacement downstream along the reach. Each profile was recorded using an echosounder coupled to a DGPS system and surveyed two times with a time difference of seven days between surveys. The dunes recorded at one of the measured profiles are shown in Fig. 13. Bed material samples were also collected with a modified Petersen sampler and a drag conical sampler. Surface current velocities, obtained with the floats, were converted to mean vertical velocities with appropriate coefficients. The bathymetric data were processed in the software Fugawi and Surfer and drafted and adjusted in Autocad. Characteristic recorded dunes formed in medium to coarse sand were 0.8 to 1.3 m height with mean displacement velocities between ~7 and 10 m/day.

b) Using the hydraulic and sedimentologic data measured at each longitudinal profile, several renowned criteria were applied to compute the bed load in alluvial sand bed rivers, and the results compared with the values measured with the dunes displacement method. The criteria of Einstein–Brown (Brown, 1950), Einstein (1950), Laursen (1958), Engelund-Hansen (1967), Ackers-White (1973), Rijn (1984, 1993) and Molinas-Wu (2001) were tested (the reader interested in the details of these formulas is referred to any of the textbooks related with the topic of the mechanics of sediment

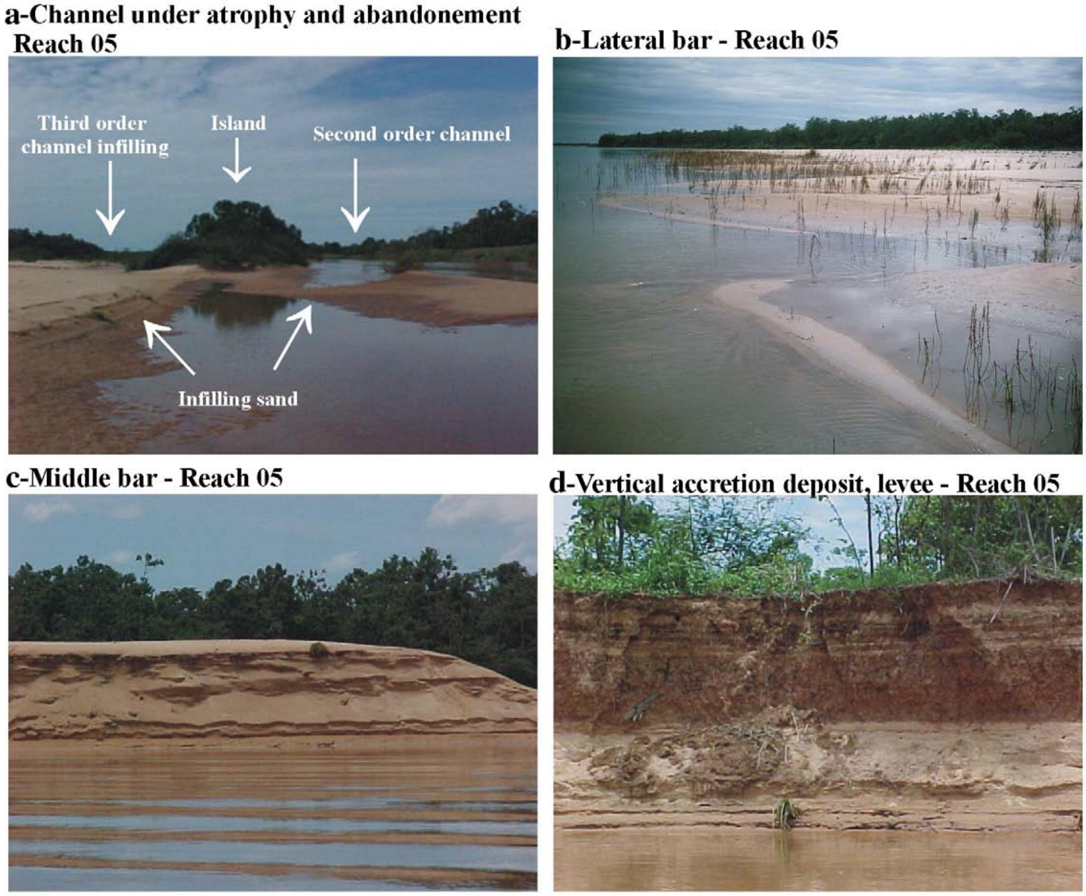

Fig. 7. Examples of silting/infill environments in reach 5. a) Second order channel obliterated, atrophied and in definitive abandonment. Note the relic island between the sand dunes is blocking the mouth and infilling the channel. This case represents the silted/infilled area in Fig. 5a. b) Typical lateral bar. c) Typical middle channel bar upstream Aruanã. d) Example of vertical accretion deposit in a levee.

transport in alluvial streams). The Rijn's equation yielded the best fit with the measured values of bed loads at each longitudinal profile. The results of the comparison with this criterion can be seen next:

Longitudinal profile	Bedload (kg/s/m)	
	Dunes displacement method	Van Rijn equation
1(1)	0.029	0.033
2(2)	0.050	0.048
3(2)	0.030	0.035
4(3)	0.093	0.087

(1)Mean value of a computation with 8 dunes and local hydraulic parameters.
(2)Mean value of a computation with 24 and 34 dunes, respectively, with local hydraulic parameters.
(3)Mean values of a computation with 10 dunes and local hydraulic parameters.

c) Based on the previous results and considering that the bedload and the suspended bed material load (G_{ss}), can be both formulated with the same hydraulic and sedimentologic parameters, the Van Rijn's criteria to estimate G_{ss}, was also adopted. Adding this one to G_{sf} the total bed material transport (G_s) was obtained. The computation was made by means of the streamflow data measured at Aruana station since 1970. A series of 16 streamflow charts, covering a wide range of discharges between 296 m^3/s and 4130 m^3/s, were selected and the Van Rijn criteria for G_{sf} and G_{ss} were applied with the hydraulic data measured at each vertical for a given discharge. The appropriate spanwise summation of the total bed material transport gave the G_s at the section for the given discharge.

d) The result of the procedure explained in *c* was a total of sixteen G_s values that were plotted against the corresponding discharges to obtain the bed sediment transport rating curve in Aruana station (Fig. 14). The scatter for the smallest discharges is rather large, but a few computations of annual transports made with curves adjusted discarding the lowest G_s data points, yielded negligible differences with the curve of Fig. 14. It could be explained considering the small

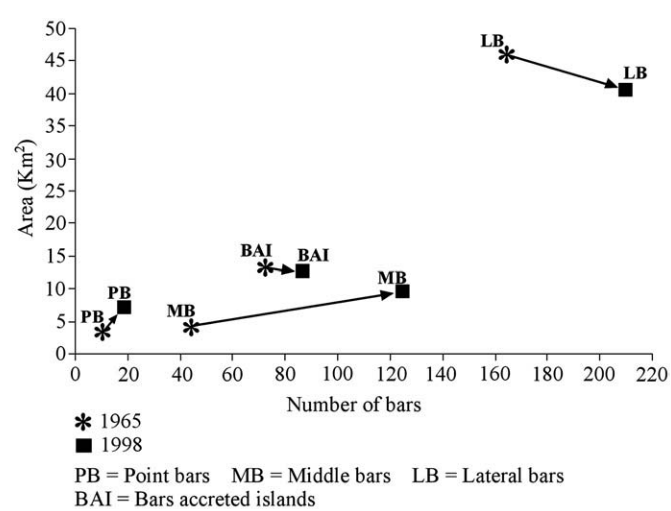

Fig. 8. Changes in the number and area occupied by lateral bars (LB), bars accreted to islands (BAI), point bars (PB) located mainly in a few sinuous low lateral migration meanders and middle channel bars (MB). Arrows indicate the direction of changes.

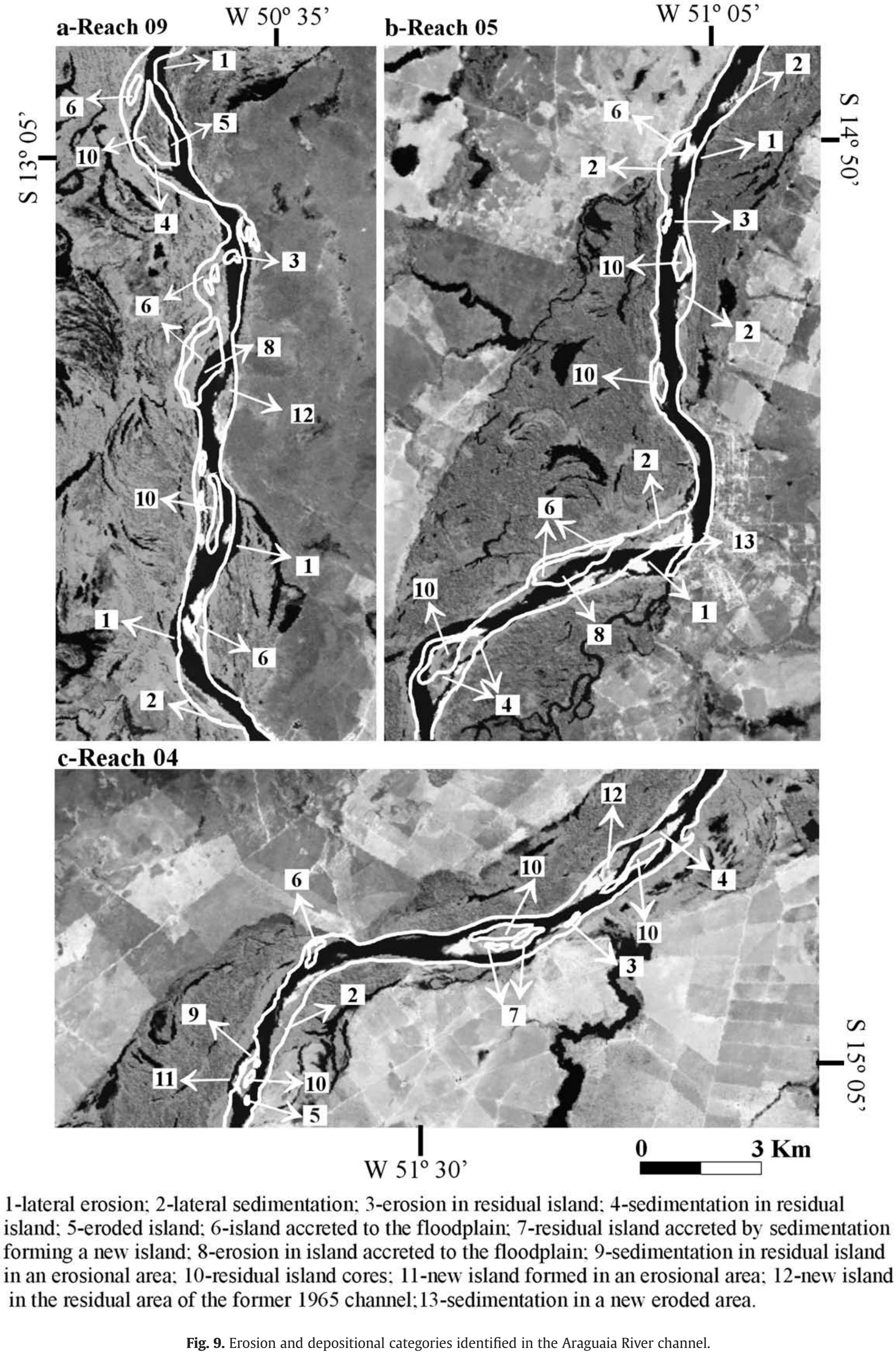

Fig. 9. Erosion and depositional categories identified in the Araguaia River channel.

amounts of bed sediment transported during the very low river stages in an annual cycle.

e) Finally with the results of the steps *c* and *d* and the daily discharges in Aruana gauge station, the values of annual bed material transported (G_{sf}, G_{ss} and G_s) were computed between 1971 and 1998 (Table 3). The averages for each decade, included in the table, reveal an increase of 31% in the total sand transported by the Araguaia River since the 1970s. Suspended sand, very important

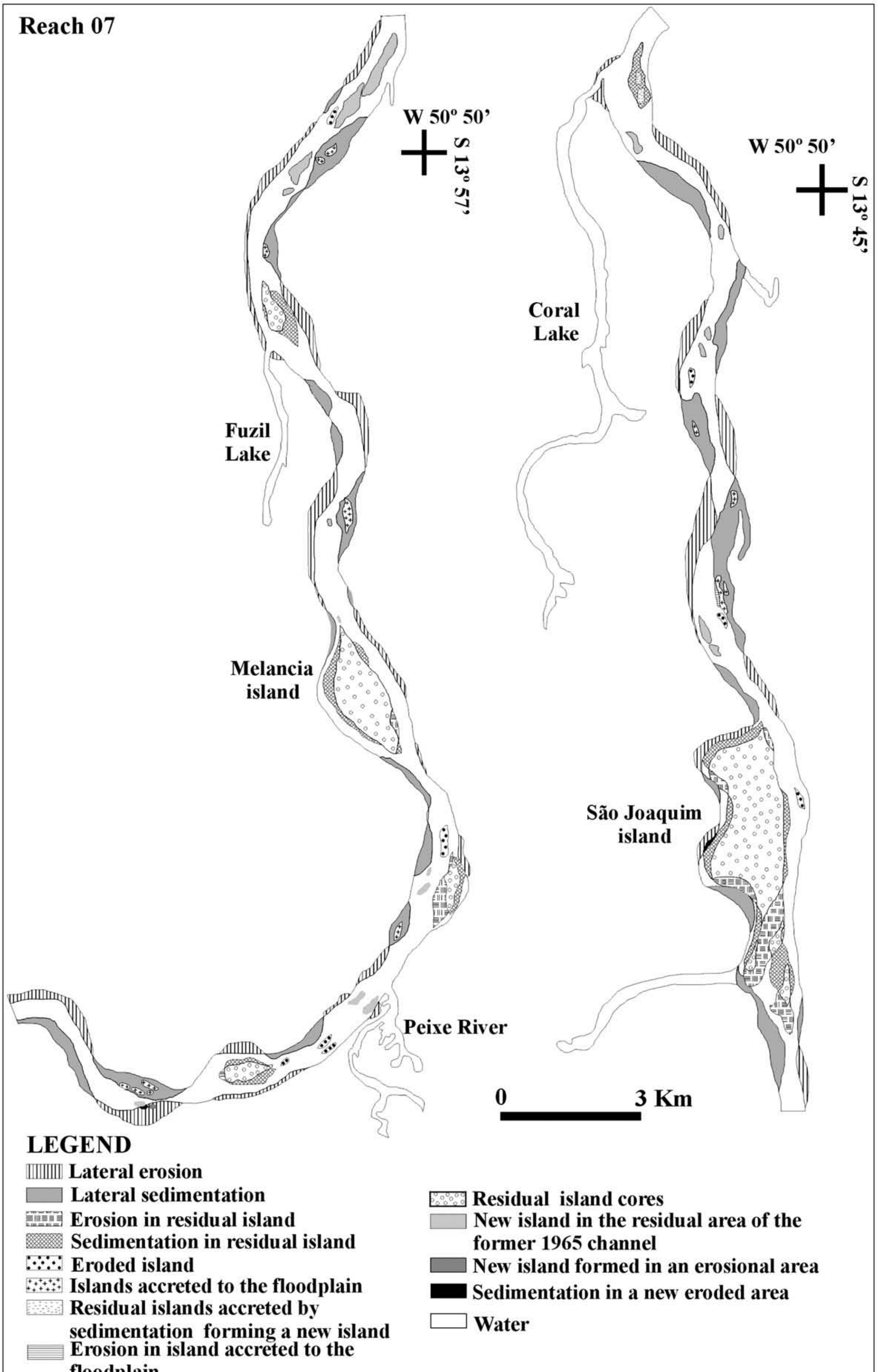

Fig. 10. Maps of erosion and depositional categories identified in this study as described in Figs. 7 and 8. Maps represent the whole study area of 570 km.

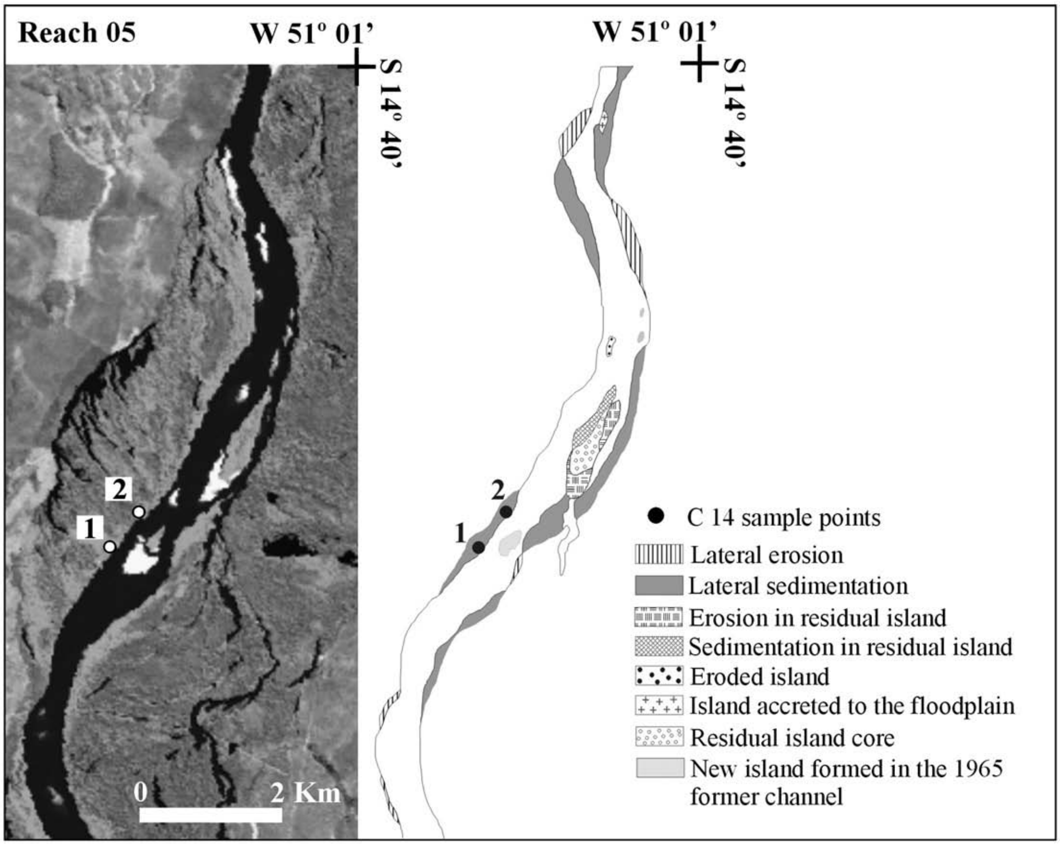

Fig. 11. Area of recent sedimentation identified by mapping and verified in field by radiocarbon date of logs. The C_{14} activity indicated that the trees died sometime after 1950.

component, represents up to 93% of the total sand transported by the river.

4. Deforestation and river response

As mentioned above, the Cerrado Biome is suffering huge rates of deforestation and changes of land use. The expansion of the agricultural frontier and its associated environmental impact were exponential with time in the Araguaia basin. Nearly 75% of the study area is affected by deforestation and land use changes at present (Franco, 2003).

The increasing live stock settlements followed by soybean farms have been the engine of the regional economic development but with a high environmental cost. Nowadays, the Cerrado is one of the twenty five Hot Spots for conservation priorities on the planet (Myers et al., 2000) because of its deep biodiversity and environmental instability. Within this context, the Araguaia floodplain represents the last nearly untouched natural frontier from two point of view 1) the largest remnants of Cerrado wetlands are located in the Araguaia basin and 2) it is the only large fluvial system of Central and South Brazil that has not been dammed or affected by other direct human interventions in the channel itself.

Table 2
Budget between erosion and depositional processes by area.

		Reaches and areas per processes (km^2)										
Processes		01	02	03	04	05	06	07	08	09	10	Total
Sedimentation	Lateral sedimentation	2.94	3.27	7.22	9.01	10.01	7.63	7.39	6.89	6.99	5.56	66.91
	Sedimentation on remnants islands in eroded sectors	0.00	0.00	0.00	0.04	0.12	0.05	0.09	0.03	0.00	0.04	0.37
	New island in eroded sector	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.10	1.16	0.04	1.46
	New island	0.00	0.00	0.06	0.77	0.23	0.54	1.03	1.24	1.40	0.28	5.55
	Lateral sedimentation on eroded sector	0.00	0.00	0.00	0.00	0.07	0.03	0.02	0.00	0.00	0.00	0.12
	Sedimentation in remnants islands	0.00	0.00	1.09	1.22	2.17	2.28	1.68	0.85	2.21	1.26	12.76
Erosion	Lateral erosion	2.33	1.41	6.81	3.52	6.19	6.10	5.90	6.77	4.35	5.11	48.49
	Erosion in remnants islands	0.00	0.00	0.52	0.31	1.15	1.44	1.39	0.51	0.91	0.65	6.88
	Totally Eroded islands	0.11	0.00	0.18	0.41	0.33	0.20	0.31	0.48	0.26	0.05	2.32
	Partial Erosion of islands that were accreted to the floodplain	0.00	0.00	0.00	0.21	1.13	0.13	0.00	0.61	0.76	0.00	2.84
Net budget		0,5	1,86	0,86	6,61	3,8	2,68	2,61	0,74	4,32	1,37	25,35
Other processes and remnants landforms (not included in the budget)	Island or part of islands accreted to the floodplain	0.0	0.0	0,05	1.30	0.92	0.86	0.45	1.90	1.32	0.29	7.09
	Remnants islands accreted between them generating a new island	0.0	0.0	0.02	0.18	0.25	0.00	0.06	0.06	0.00	0.01	0.60
	Core of remnants islands	0.20	0.00	2.01	1.04	2.28	3.91	6.36	0.96	3.98	4.19	24.93

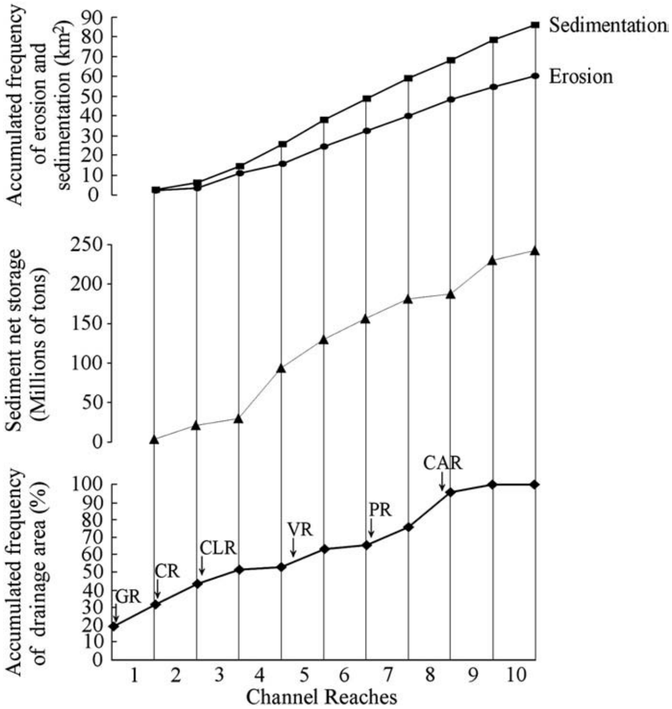

Fig. 12. Cumulative frequency of drainage area, mass of net sediment storage (in millions of tons) and area of sediment net storage. A total amount of 232 Mt of sediment was stored in the 570 km length reach (see Fig. 3 for the tributaries nomenclature).

Deforestation triggered erosion all over the basin. The most spectacular features of linear erosion were recorded in the upper basin where Mesozoic sedimentary rocks outcrop. Big gullies, hundred meters length and near 20 m depth, developed in that area since the 1970s favored by thick soils and deep saprolite in the sedimentary rocks (Castro et al., 1999, Marinho et al., 2006). In the uppermost Araguaia basin 91 large gullies were identified recently in an area of 2747 km^2 (Marinho et al., 2006).

As observed in Fig. 15a, deforestation in the Araguaia basin increased exponentially since the 1970s. The increase in the total load of bed material and, consequently, the tendency of the river to change its form can also be correlated with both the rate of deforestation since the seventies and the gross domestic product (G.D.P.) of the 58 counties of Goias State that cover approximately 79% of the studied area (Fig. 15b). Economic data were obtained from the data base of the Brazilian Institute of Geography and Statistic-IBGE. We plotted the total sand discharge vs. the sum of the fifty eight counties gross product of the Araguaia basin in Goiás State. The counties economy is closely linked to cattle ranches production and the pressure on the Cerrado environment is clearly reflected by the increasing bed material transport of the Araguaia River (Fig. 15b).

5. Conclusions

The multi-approach analysis applied to the Araguaia shows that the river is increasing the transport of bed sediments and also undergoing a geomorphologic metamorphosis as a response to the rapid human-induced changes suffered by the Cerrado biome. All the reaches in the middle course show a tendency to sedimentation and indicate a rapid fluvial response to deforestation to produce disequilibrium and new adjustments.

Because of the tremendous impacts of the accelerated deforestation in the Araguaia basin a critical geomorphic threshold was surpassed and caused the introduction of large sediment loads into the channel. In response, complex geomorphologic changes took place along all the reaches of the Araguaia River. A total of 232 Mt of sediments were stored in the main channel and proximal areas of the alluvial plain. It is necessary yet to estimate the transference of fine sediments to the floodplain because only the area related to channel processes was analyzed herein. The bed load transport increases 31% from 1970s to 2000 from 6.7 Mt of sandy sediments to 8.8 Mt.

The river is storing sediments by infilling of secondary channels, accreting the more stable lateral bars, and eliminating some obstacles

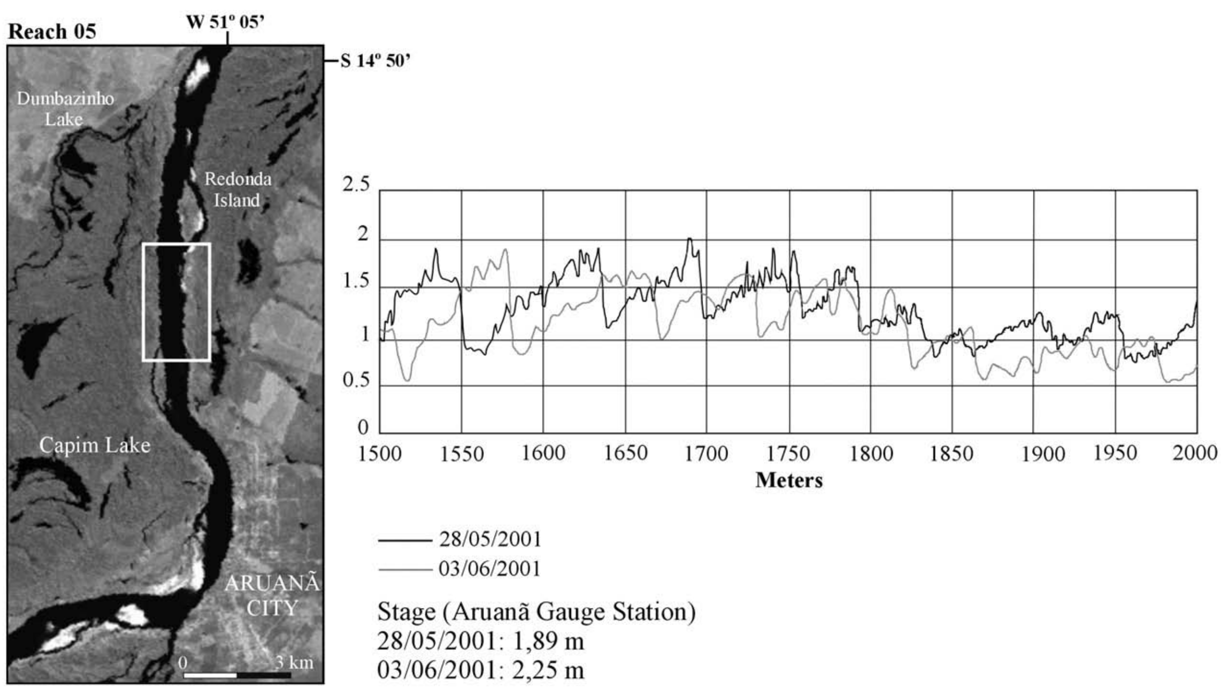

Fig. 13. Example of bathymetric survey identifying the movement of dunes in the Araguaia River. The white lines show the reach location where dunes were recorded.

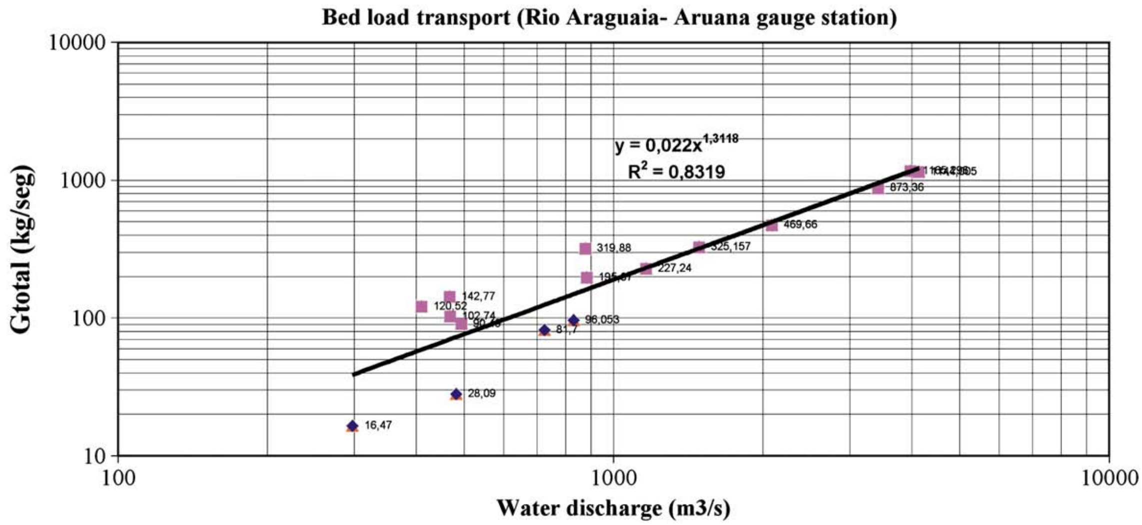

Fig. 14. Bed sediment transport rating curve for the Aruana station.

such as the smallest islands. As result, the channel is partially changing its most typical anabranching pattern while large relict islands act as agglutinants of sand bars. In other words, the river is opening a relatively efficient central corridor to transport the increased bedload supply, through a more braided pattern with a higher amount of small and ephemeral mid-channel bars than in the 1960s.

Our results show that also large systems can react rapidly to widespread human disturbances like deforestation in the basin. The period of the fluvial system reaction after the anthropic perturbation was on the order of a decade, which could be expected to be a characteristic reaction time for small or medium size basins.

Regarding the relations between human impact-fluvial geomorphology, the Araguaia case is the most spectacular example of geomorphologic response of a pristine large alluvial river without interventions in the channel to the highest rates of large scale deforestation suffered by a biome during human history.

Table 3
Total transport of sand load (suspended and bed sand).

Year	Gsf (ton)	Gss (ton)	Gs (ton)	Gsf/Gss	Gss/Gs	Gsf/Gs
1971	314816	2657880	2972696	0.12	0.89	0.11
1972	423011	4825915	5248927	0.09	0.92	0.08
1973	475350	5650303	6125654	0.08	0.92	0.08
1974	541653	7451474	7993127	0.07	0.93	0.07
1975	403323	4226025	4629348	0.10	0.91	0.09
1976	477660	5793087	6270747	0.08	0.92	0.08
1977	522305	6936101	7458406	0.08	0.93	0.07
1978	596387	8569581	9165968	0.07	0.93	0.07
1979	651425	10372710	11024136	0.06	0.94	0.06
Average	489547.8	6275897	6765445	0.08	0.92	0.08
1980	718424	13006924	13725348	0.06	0.95	0.05
1981	531754	7903665	8435419	0.07	0.94	0.06
1982	673106	11716415	12389522	0.06	0.95	0.05
1983	671858	11728732	12400591	0.06	0.95	0.05
1984	473403	5772659	6246063	0.08	0.92	0.08
1985	530257	7999969	8530227	0.07	0.94	0.06
1986	355248	3713141	4068390	0.10	0.91	0.09
1987	398001	4773511	5171513	0.08	0.92	0.08
1988	511261	7836157	8347418	0.07	0.94	0.06
1989	502724	6997014	7499739	0.07	0.93	0.07
Average	536603.6	8144819	8681423	0.07	0.93	0.07
1990	499540	6535181	7034721	0.08	0.93	0.07
1991	594510	8973067	9567578	0.07	0.94	0.06
1992	626495	9340205	9966700	0.07	0.94	0.06
1993	521303	6920295	7441598	0.08	0.93	0.07
1994	565867	8108149	8674016	0.07	0.93	0.07
1995	595502	8500628	9096131	0.07	0.93	0.07
1996	517471	6379839	6897310	0.08	0.92	0.08
1997	773723	13044626	13818350	0.06	0.94	0.06
1998	523279	6653444	7176724	0.08	0.93	0.07
Average	579743.3	8272826	8852570	0.07	0.93	0.07

Transport of sandy bed sediments at Aruana (reach 5). Gsf = bed load; Gss = suspended sand; Gs = total bed material transport (Gsf + Gss); the data in bold signify the decade average.

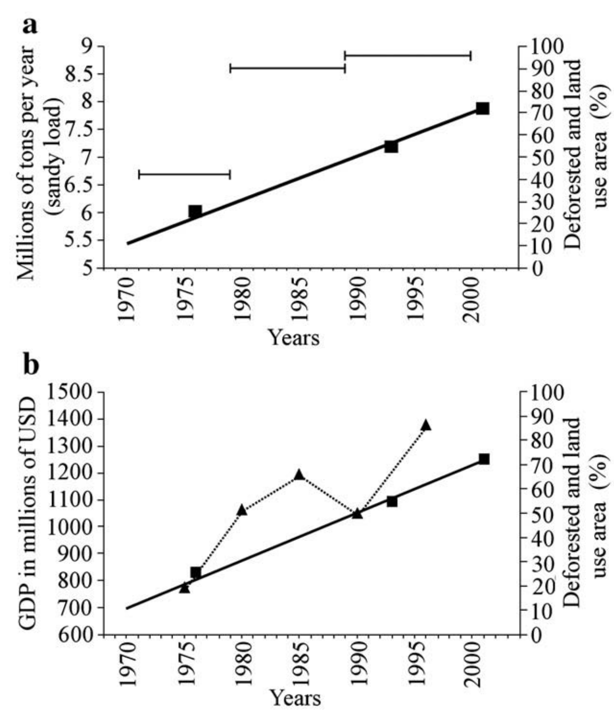

Fig. 15. a)Average total sand transport (bed and suspended loads) in millions of tons for the periods 1970–1979, 1980–1989 and 1990–1998 at Aruanã (indicated by horizontal bars) compared with the percent of basin deforestation and land use. b). Gross domestic product in millions of dollars of all the counties (municipal districts) of the Araguaia basin in the Goiás State. The increase of land use and deforestation is accompanied by the regional GDP growth.

Acknowledgments

We specially thank T. Dunne, J.C. Stevaux and L. Guimaraes Ferreira, for critical review and comments. This investigation was supported by CNPq-Brazil, CYTED Network XII-K. Vitae Foundation, Bi-national Project, PROSUL Program-CNPq-Brazil and project NASA-USA, Earth Science Enterprises, 2700-0087. We thank especially J. Huespe for taking part in the bathymetric survey, to M. Correntino and N. de Carvalho for providing important discussions and data of the Araguaia basin and to the Geological Survey of Brazil and ANA (Brazilian National Agency of Water) for providing hydrological data.

References

Ackers, P., White, W., 1973. Sediment transport: new approach and analysis. Journal of the Hydraulics Division HY11, 2041–2060.
Brown, C.B., 1950. Sediment transportation (Chap. XII). In: Rouse, H. (Ed.), Engineering Hydraulics. John Wiley and Sons, Inc., New York.
Castro, S., Borges de Campos, A., Oliveira, C.J., Silva, A., 1999. The upper Araguaia basin and the effects of human-induced erosion. Boletim Goiano de Geografia 19 (1), 128–139.
Gentry, A.H., Lopez-Parodi, J., 1980. Deforestation and increased flooding of the upper Amazon. Science 210, 1354–1356.
Einstein, H.A., 1950. The Bed-Load Function for Sediment Transportation in Open Channel Flows, United State Department of Agriculture, Soil Conservation Service, Washington, D.C., Technical Bolletin 1026, 1950.
Engelund, F., Hansen, E., 1967. A Monograph on Sediment Transport in Alluvial Streams, Teknisk Vorlan, Copenhage, Denmark, 1967.
Franco, S.M. 2003. O grande vale do Araguaia: transformações da bacia do Araguaia e Goiás. MSc thesis, Instituto de Estúdios Sócio Ambientais, Universidade Federal de Goiás, 1–382
Latrubesse, E., 2008. Patterns of anabranching channels: the ultimate end member adjustment of mega-rivers. Geomorphology 101, 130–145.
Latrubesse, E., Franzinelli, E., 2002. The Holocene alluvial plain of the middle Amazon River, Brazil. Geomorphology 44, 241–257.
Latrubesse, E., Stevaux, J.C., 2002. Geomorphology and environmental aspects of the Araguaia fluvial basin. Zeitschrift fur Geomorphologie 129, 109–127.
Laursen, E.M., 1958. The total sediment load of streams. Journal of the Hydraulic Division ASCE 84 (HY1 Proc. Paper 1530), 1–36.
Marinho, G.V., de Castro, S.S., de Campos, A.B., 2006. Hydrology and gully processes in the upper Araguaia river basin, Central Brazil. Zeitschrift fur Geomorphologie 145, 119–145.
Molinas, A., Wu, B.S., 2001. Transport of sediments in large sand bed rivers. Journal of Hydraulic Engineering 124 (80), 786–793.
Myers, N., Mittermeier, R., Mittermeier, C., Fonseca, G., Kents, J., 2000. Biodiversity hot spots for conservation priorities. Nature 403, 853–858.
Nordin, C.F., Meade, R., 1982. Deforestation and increased flooding in the upper Amazon. Science 215, 246–247.
Reid, L.M., Dunne, T., 1996. Rapid evaluations of sediment budgets. Geoecology paper. Catena Verlag, Reiskirchen, Germany.
Rijn, L.C. van, 1984. Sediment transport, part I: bed load transport. J. Hydr. Eng., ASCE 110 (10), 1431–1456.
Rijn, L.C. van, 1993. Principles of Sediment Transport In Rivers, Estuaries and Coastal Seas. Aqua Publications, Amsterdam, The Netherlands.