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Natural and human forcing in recent geomorphic change; case studies in the Rio de la Plata basin

Jaime Bonachea [a], Viola M. Bruschi [a], Martín A. Hurtado [b], Luis M. Forte [b], Mario da Silva [b], Ricardo Etcheverry [b], José L. Cavallotto [c], Marcilene F. Dantas [d], Osni J. Pejon [d], Lázaro V. Zuquette [d], Maria Angélica de O. Bezerra [e], Juan Remondo [a], Victoria Rivas [a], José Gómez-Arozamena [a], Gema Fernández [a], Antonio Cendrero [a,*]

[a] Universidad de Cantabria, Spain
[b] Universidad Nacional de La Plata, Argentina
[c] Servicio de Hidrografía Naval, Argentina
[d] Universidade de Sao Paulo (São Carlos), Brazil
[e] Universidade Federal de Mato Grosso do Sul, Brazil

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ABSTRACT

An analysis of geomorphic system's response to change in human and natural drivers in some areas within the Río de la Plata basin is presented. The aim is to determine whether an acceleration of geomorphic processes has taken place in recent years and, if so, to what extent it is due to natural (climate) or human (land-use) drivers. Study areas of different size, socio-economic and geomorphic conditions have been selected: the Río de la Plata estuary and three sub-basins within its watershed. Sediment cores were extracted and dated (^{210}Pb) to determine sedimentation rates since the end of the 19th century. Rates were compared with time series on rainfall as well as human drivers such as population, GDP, livestock load, crop area, energy consumption or cement consumption, all of them related to human capacity to disturb land surface. Data on river discharge were also gathered. Results obtained indicate that sedimentation rates during the last century have remained essentially constant in a remote Andean basin, whereas they show important increases in the other two, particularly one located by the São Paulo metropolitan area. Rates in the estuary are somewhere in between. It appears that there is an intensification of denudation/sedimentation processes within the basin.

Rainfall remained stable or varied very slightly during the period analysed and does not seem to explain increases of sedimentation rates observed. Human drivers, particularly those more directly related to capacity to disturb land surface (GDP, energy or cement consumption) show variations that suggest human forcing is a more likely explanation for the observed change in geomorphic processes. It appears that a marked increase in denudation, of a "technological" nature, is taking place in this basin and leading to an acceleration of sediment supply. This is coherent with similar increases observed in other regions.

1. Introduction

Since the 19th century, many authors have pointed out the growing role of humans in changes experienced by the planet; biosphere, hydrosphere, atmosphere/climate or processes affecting the surface of the lithosphere (Marsh, 1877; Thomas, 1956; Wolman and Schick, 1967; Costa, 1975; Dunne and Leopold, 1978; Goudie, 1993, 1995; WCED, 1987; Turner et al., 1990; Walling, 1996; Rawat et al., 2000; Turner, 2006; Slaymaker, 2000; UNEP, 2005, Naredo and Gutiérrez, 2005; Lu, 2005; IPCC, 2001, 2007; Bakker et al., 2008; Liverman and Roman-Cuesta, 2008; Slaymaker et al., 2009).

The important role played by "technological denudation" as well as human contribution to sediment generation was pointed out by several authors (Brown, 1956; Judson, 1983; Douglas, 1990; Hooke, 1994; Goudie, 1995; Phippen and Wohl, 2003; Gellis et al., 2004; Ruiz-Fernández et al., 2005; Syvitski et al., 2005; Cendrero et al., 2005; Rivas et al., 2006). The latter authors indicate that human mobilisation of rocks and unconsolidated materials could be one or two orders of magnitude greater than denudation/transport by natural processes. Also, that areas disturbed by excavation/accumulation, although relatively small, are significant contributors to sediment generation, perhaps the main one. According to Syvitski et al. (2005), human activities have increased global sediment transport by rivers by 2.3 +/− 0.6 Gt a^{-1} and at the

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* Corresponding author.
E-mail address: antonio.cendrero@unican.es (A. Cendrero).

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same time reduced flux to the oceans by 1.4 Gt a^{-1}, through retention in reservoirs.

The existence of a "geomorphic dimension of global change" was mentioned by Cendrero and Douglas (1996), to refer to the direct and indirect effect of human activities on earth surface processes. Remondo et al. (2005b) suggested a possible "global geomorphic change", initially on the basis of data from northern Spain that showed considerable increases of landslide activity during Holocene–present, not explained by changes in rainfall regimes, but coinciding with expansion of human activity.

A conceptual model was then proposed to express the possible relationship between human activity and geomorphic processes. It considers that a possible explanation of the data obtained could be a cause–effect sequence of relationships such as: drivers (population, technology, and wealth) — pressures on geomorphic systems (increased human activity and intervention on the territory) — impacts (land-use changes, resilience of surface layer, and behaviour of processes) — response of geomorphic systems (increased rates of geomorphic processes, landslides, denudation, and sedimentation). Of course, natural drivers, mainly rainfall, also play a role in geomorphic processes and their changes ought to be considered. Therefore, testing of the model includes assessing possible contributions of climate-related drivers. In this conceptual model drivers (human and natural) can be considered as independent variables, although strictly speaking only population and wealth are really independent (and not completely). Other human drivers and present climate variations depend on the former. The final dependent variable whose changes are being compared to drivers is sedimentation rate (itself dependent on runoff, slope movements, channel flow, all of which are influenced by both human and natural drivers).

The model assumes that human capability to affect land surface is determined by the number of people in a region and their economic and technological capacities. GDP (Gross Domestic Product) is an expression of such capability. Greater capability implies more intervention on, and modification of the surface layer. This could trigger a geomorphic response in the form of increased runoff, slope movements, denudation in general and, consequently, sedimentation. Sedimentation rate increase was indeed found in estuaries of northern Spain, with trends and magnitudes "grosso modo" comparable to those shown by landslides (Cendrero, 2003; Remondo et al., 2005b, Ródenas et al., 2004; Gelen et al., 2004; Pérez-Arlucea et al., 2005; Soto et al., 2006; Soto-Torres et al., 2007; Viguri et al., 2007; Irabien et al., 2008a, b; Cearreta et al., 2008; Bruschi et al., 2008).

Data on the frequency of geomorphic events at other scales (Fig. 1) and in other regions (Munich Re, 2005; Guzzetti and Tonelli, 2004; EM-DAT, 2005) are also consistent with the conceptual model. Disasters labelled by EM-DAT (www.em-dat.net) as "geologic" (earthquakes, tsunamis and volcanic eruptions) show an increase which we think could be more apparent than real and probably due to two factors: a) more complete compilation of data on disaster events in recent times; b) an increase in human exposure (more population and material elements) so that recent events would more likely produce damages and therefore be considered as "disasters". We assume that the increase in these disasters, which has been practically the same as that of GDP during the same period, could be due mainly to the latter factor. Strictly climatic disasters, such as droughts or windstorms, show a greater increase. This could be due to the factors commented as well as the effects of climate change. Finally that in the EM-DAT (www.em-dat.net) graph are named as "floods and related" (floods and wet mass movements) increase much more markedly. Our assumption is that this is probably reflecting the same factors as above plus the effects of geomorphic change.

According to Brierley and Stankoviansky (2003) «whether land-use change or climate change is the main trigger of accelerated erosion-accumulation processes in long term landscape evolution remains uncertain… however…it is clear that…land-use changes

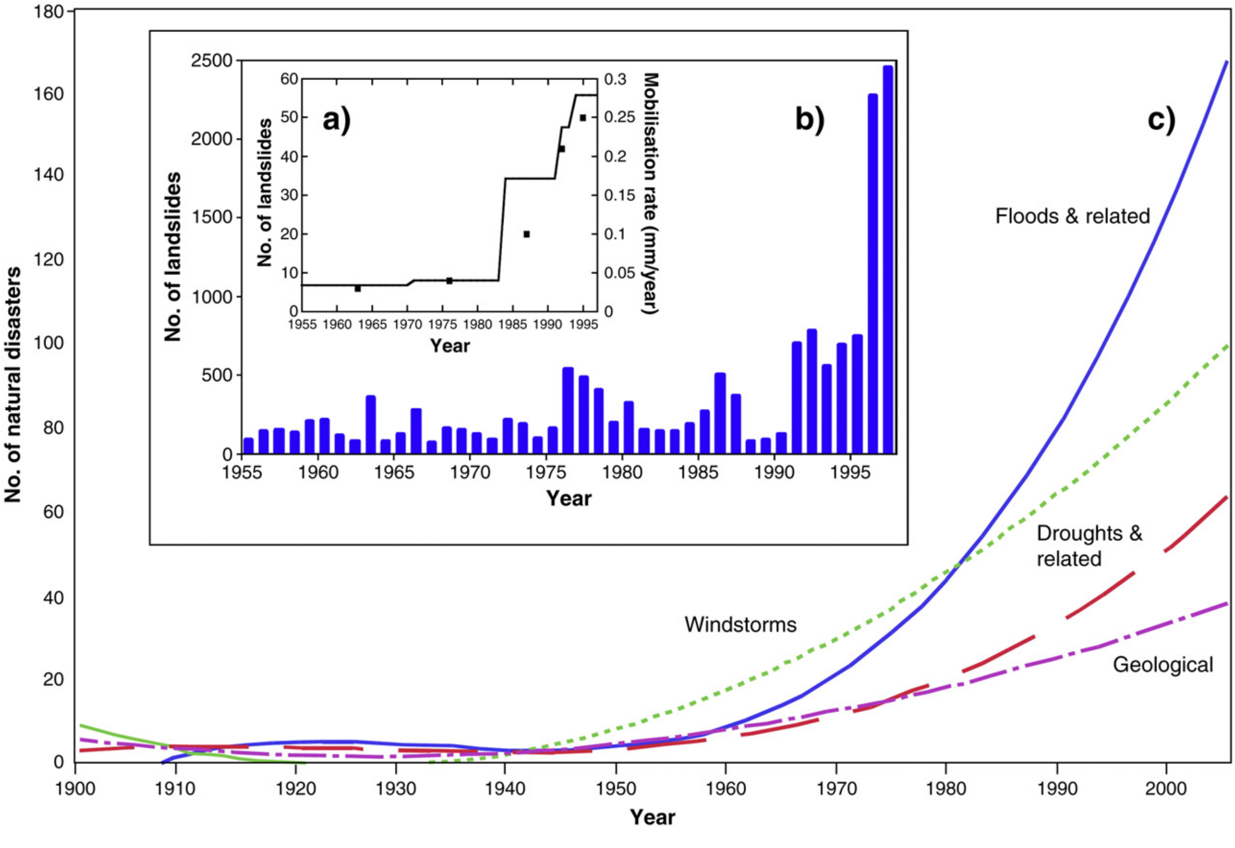
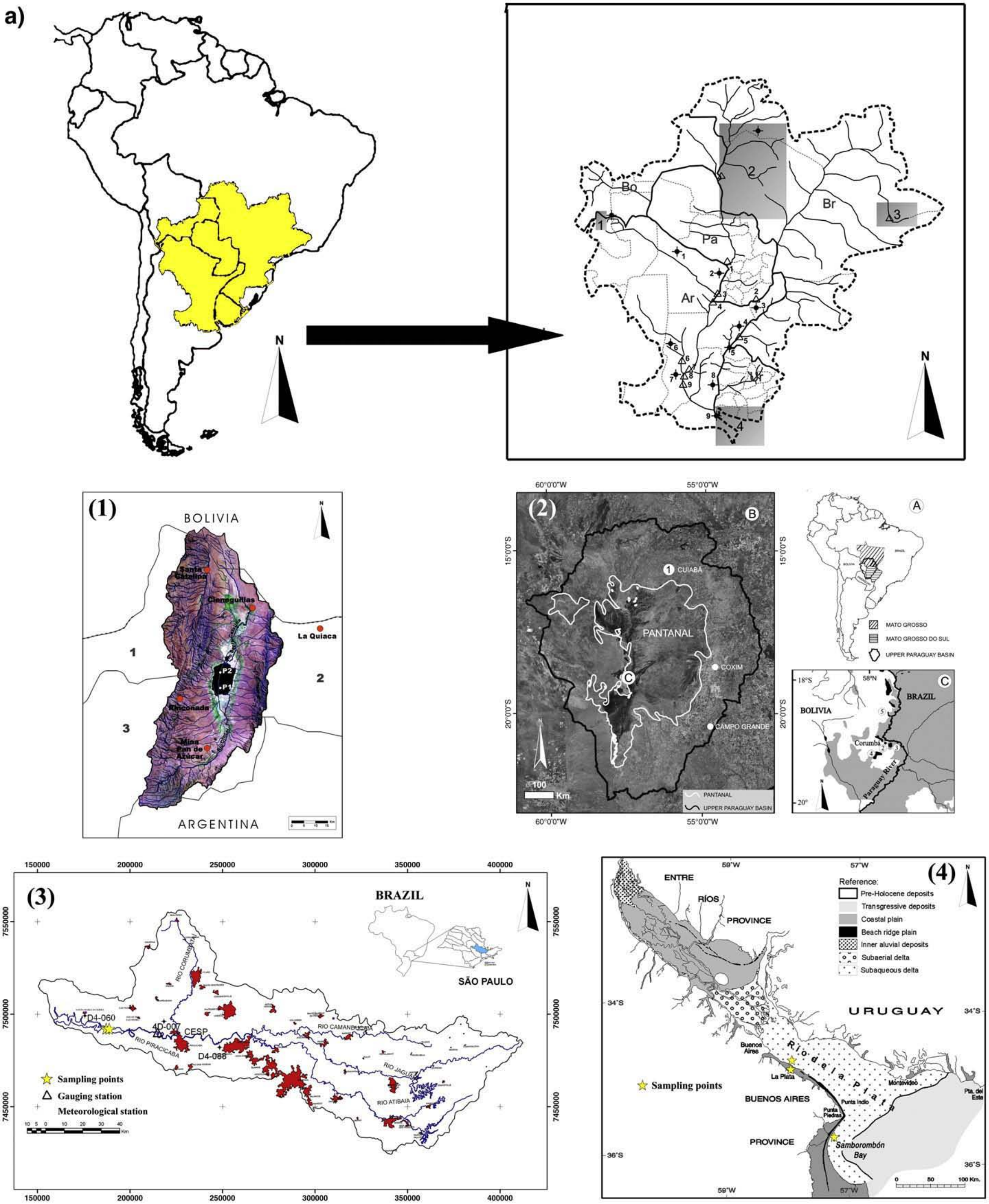


Fig. 1. Landslide frequency in the Deva valley, Spain (a) and in Italy (b). Frequency of natural disasters in the world (c). After Cendrero et al. (2006), with data from Guzzetti and Tonelli (2004), EM-DAT (2005) and Remondo et al. (2003).


a)
N
Bo
Br
Pa
Ar
1
2
3
4
(1)
BOLIVIA
Santa Catalina
Cieneguillas
La Quiaca
P2
P1
Rinconada
Mina Pan de Azúcar
1
2
3
ARGENTINA
(2)
60°0'0"W
55°0'0"W
15°0'0"S
20°0'0"S
B
CUIABA
PANTANAL
COXIM
C
CAMPO GRANDE
100 Km
PANTANAL
UPPER PARAGUAY BASIN
A
MATO GROSSO
MATO GROSSO DO SUL
UPPER PARAGUAY BASIN
C
18°S
58°N
BRAZIL
BOLIVIA
Corumbá
Paraguay River
20°
(3)
BRAZIL
SÃO PAULO
D4-060
4D-007
CESP
D4-086
RIO CORUMBATAI
RIO PIRACICABA
RIO CAMANDUCAIA
RIO JAGUARI
RIO ATIBAIA
Sampling points
Gauging station
Meteorological station
Km
150000
200000
250000
300000
350000
400000
7550000
7500000
7450000
(4)
ENTRE RÍOS PROVINCE
59°W
57°W
Reference:
Pre-Holocene deposits
Transgressive deposits
Coastal plain
Beach ridge plain
Inner aluvial deposits
Subaerial delta
Subaqueous delta
34°S
URUGUAY
Buenos Aires
La Plata
Río de la Plata
Montevideo
Pta. del Este
Sampling points
BUENOS AIRES PROVINCE
Punta Indio
Punta Piedras
Samborombón Bay
36°S
0 50 100 Km.

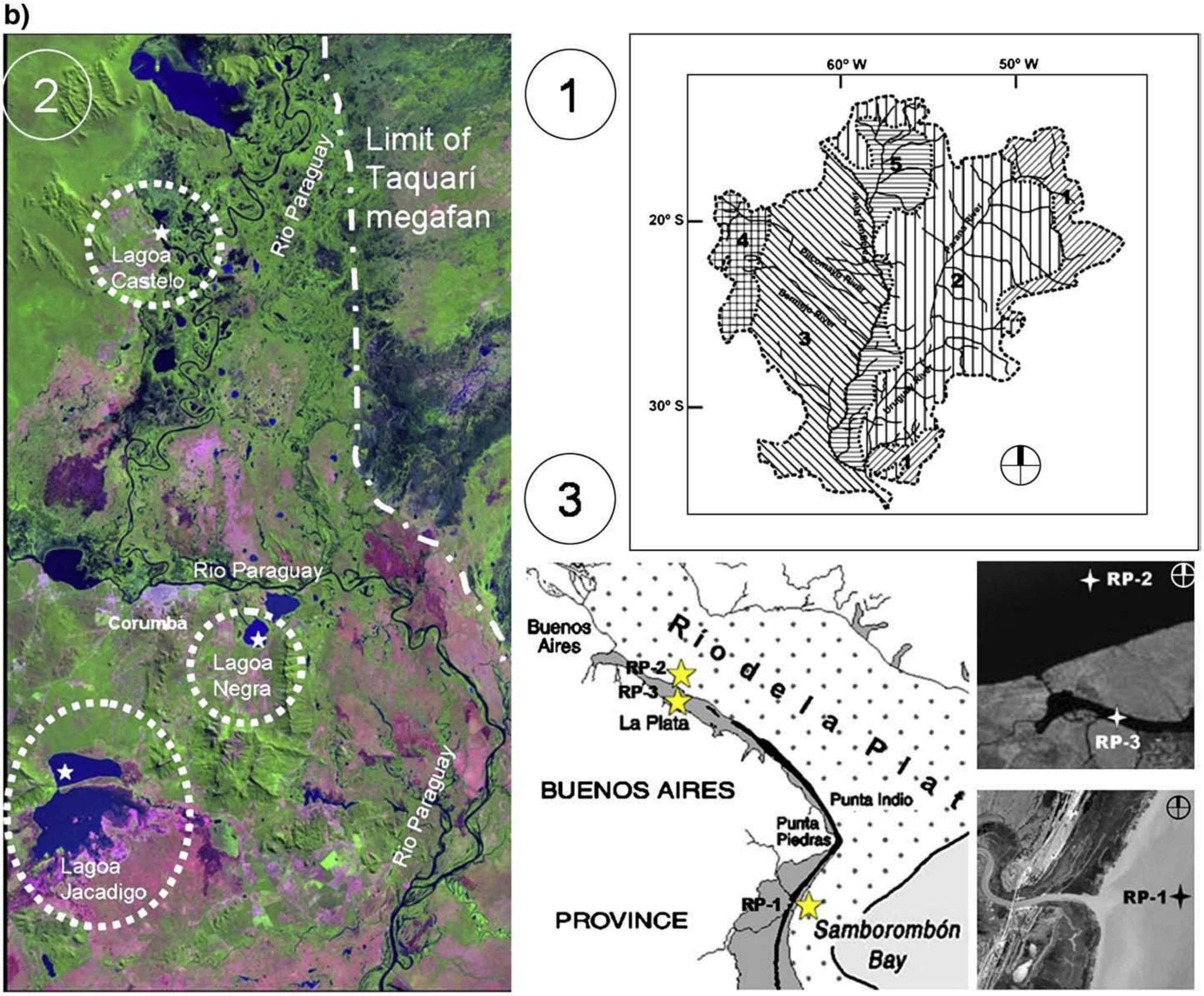


Fig. 2. a) Map of the Río de la Plata watershed, showing country and state/province borders and location of study areas. (1). Laguna de Pozuelos basin, showing the location of sampling points (P-1 and P-2) and the meteorological station nearest to the study area (La Quiaca) from which rainfall records were obtained. 1: Departamento de Santa Catalina. 2: Departamento de Yaví. 3: Departamento de Rinconada. (2). Pantanal basin. A. Location of upper Paraguay basin (Pantanal watershed), showing the limits of Mato Grosso and Mato Grosso do Sul states. B. The Pantanal and its watershed. C. Detail of the area where cores were extracted (1) Meteorological Station; 9th District, Instituto Nacional de Meteorologia — INMET). (2) Gauging Station, 6th District, Brazilian Navy, city of Ladário). (3) Core LN95/C1 (Lagoa Negra); (4) Core LJ95/C1 (Lagoa Jacadigo) and (5) Core LC95/C1 (Lagoa Castelo). (3). Barra Bonita basin. Sampling points, location of meteorological (4D-060 and 4D-088) and stream gauging stations (4D-007). (4). Río de la Plata estuary. Sampling points are indicated. b) (1) Main geologic units in the basin (after OEA, 1971 and Iriondo, 1996, 2000, 2005). (2) More detailed map of the Pantanal showing location of sampling sites. (3) Details of the Río de la Plata estuary areas showing location of sampling sites.

decrease the boundary resistance of landscape to change». These modifications might increase landscape sensitivity and the effects of relatively small climate changes.

Many other authors (among others, Judson, 1983; Hooke, 1999; Collins et al., 1997; Owens et al., 1999; Eriksson and Sandgreen, 1999; Knox, 2001; Cisternas et al., 2001; Macaire et al., 2002; Owens and Walling, 2002; Lang, 2003; Lespez, 2003; Schmitt et al., 2003; Glade, 2003; Ritchie et al., 2004; Gellis et al., 2004; Siakeu et al., 2004; Gámez et al., 2005; Keesstra et al., 2005; Pérez-Arlucea et al., 2005; Ramos-Scharrón and MacDonald, 2007; Kasai et al., 2005; Slaymaker et al., 2009) have shown that important modifications exist in denudation and sedimentation rates, at different temporal scales. All of them point out that land-use change is an important cause of variations observed in the magnitude of geomorphic processes.

If the working hypothesis implicit in the model is correct, we should expect to find the type of relationships outlined above in many other regions, because those drivers are growing practically all over the world. If the new evidence suggests that there is indeed an acceleration of geomorphic processes, this should be taken into consideration for the assessment of "hydrogeomorphic hazards" (floods and mass movements in which water plays a role), because future frequency (and therefore hazard or risk, Remondo et al., 2004, 2005a, 2008) might be greater than the one contemplated in scenarios based on past behaviour of those processes.

The general aim of this contribution is to test the validity of the hypothesis, formulated initially on the basis of landslide and hydrogeomorphic disaster data: There seems to be an increase in the rate of geomorphic processes in general that could be due mainly to growing land-surface modification caused by human activities. If this is so, the final expression of geomorphic processes, sediment generation and deposition, should show signs of acceleration, and its rates of change should resemble more closely human than natural drivers (hydroclimate). In other words, we are trying to determine whether as well as a climate change there is a geomorphic change that could have a global dimension and be reflected in the intensity or frequency of geomorphic processes and events.

2. Study areas

To test the model, a series of study areas was selected within the Río de la Plata basin (Fig. 2a, b), the third largest (3.1×10^6 km^2) basin in the world, after the Amazon and the Congo. This basin is shared by Brazil, Argentina, Paraguay, Uruguay and Bolivia, and concentrates over 75% of the GDP of these five countries. The first two countries account for about 75% of the basin's area and 90% of its population and GDP (Table 1). Population has increased about tenfold during the last century and this, together with the increase in "per capita" income, has led to a substantial growth of total Gross Domestic Product. GDP growth has been obviously coupled with increases in a variety of human activities that directly or indirectly produce physical changes in land surface. It was therefore expected that this should be reflected in an intensification of geomorphic processes and resulting sedimentation rates.

The basin is located between the high reliefs of the Andean orogen and the much lower South American platform. Its general geological characteristics (Fig. 2b) were described by OEA (1971) and Iriondo (1996, 2000). Five main units can be identified: 1. Brazilian Shield, to the NE, where gneisses and other metamorphic rocks predominate. They are covered by tropical, Quaternary loess. A similar unit appears to the SE of the Uruguay River. This area is a source of quartz and kaolinite. 2. Jurassic–Cretaceous unit, made up of basalts and sandstones which are bordered by two strips of Carboniferous rocks of glacial origin. The unit is covered by a thin veneer of aeolian deposits and is also a source of quartz and kaolinite. 3. Chaco-Pampa unit, formed basically by Quaternary sediments (fine sand, silt and clay, mainly illite) originated to the W and SW of the area. These sediments often contain soluble salts. Accordingly, the unit is a source of dissolved and suspended sediment. 4. Andean Cordillera, including the Sub-Andean Sierras, Bolivian highland and Argentine Puna. It is formed by a series of N–S mountain belts made up mostly of Tertiary, fine-grained sedimentary rocks. It is therefore a source of fine quartz and clay, which are transported by the Pilcomayo and Bermejo rivers. 5. Eastern plains. These are two areas located on the eastern side of the Paraguay–Paraná lineament. The one to the north (Pantanal de Matto Grosso) is formed by large alluvial fans. The southern area (Mesopotamia Argentina) is covered by several tens of metres of Quaternary fluvial, sandy–clayey sediments.

Altitude in the watershed is 1500–2000 m in the costal ranges of Brazil and exceeds 5000 m in the Andes. Climate ranges from arid in the NW to humid tropical with rainy summers in the N and NE, and subtropical-temperate with rainfall more evenly distributed throughout the year in the central and southern parts of the basin (Pampa and Delta areas). Annual rainfall ranges between <50 mm in parts of the Andean Cordillera (Argentina) and over 4000 mm in the Serra do Mar, upper Paraná (Brazil). Most of the basin receives 800–1400 mm/year. Accordingly land cover varies considerably, from nearly bare areas in the NW to dense forest in the north or prairies and cultivated land in most of the centre and SE. The intensity of human activities also varies widely, including nearly uninhabited areas in the Andean Plateau (Puna), rapidly growing megacities (São Paulo and Buenos Aires, which rank 7th and 17th respectively in the world; Forstall et al., 2009; http://www.citypopulation.de/index.html), or areas subject to intense farming activities, such as the Argentine Pampa or the Brazilian Planalto.

The three main rivers of the basin, Paraná, Paraguay and Uruguay, end in a prograding sedimentary complex developed in the inner part of the Río de la Plata, the "Paraná Delta". According to Sarubbi et al. (2004), the Paraná carries some 160.10^6 ton a^{-1} of sediment. Silt and clay as well as part of the fine sand (45.10^6 ton a^{-1} clay, 90.10^6 ton a^{-1} silt, 10.10^6 ton a^{-1} fine sand; about 90% of the total solid load) are transported as suspended load and the remaining 10% as bed load.

Several study areas were selected for sampling and analysis (Table 2, Fig. 2, Appendix A): 1. *Laguna de Pozuelos*, a 4000 km^2 endorheic basin where population is extremely low, economic activities are limited to sheep and llama farming and changed little during the century. 2. The *Pantanal*, the largest wetland of the world, with a basin of about 650,000 km^2 where human activities, especially in the surrounding highland ("planalto"), have increased significantly during the period considered. 3. *Barra Bonita*, an artificial reservoir (310 km^2) finished in 1963, with a basin of 12,450 km^2 in which a considerable expansion of farming and urban-industrial activities and infrastructure has occurred after construction of the dam. 4. Finally, the *Río de la Plata* estuary, covering some 35,000 km^2, with depths rarely reaching 10 m and sediments that are an extension of the subaerial delta, grading from sand in the proximal part to silt and clay in the distal one. If the model is correct, sedimentation rates should have remained stable (or varied according to rainfall changes) in area 1 and show increases in areas 2 and 3, particularly the latter. Rates in the estuary should also increase, presumably with trends somewhere between those in the areas indicated.

3. Methodological approach

The methodological approach was directly derived from the working hypothesis proposed, initially formulated on the basis of landslide and sedimentation rate data from small basins in Northern Spain. The approach used here tries to determine to what extent it provides a reasonable explanation for new data from a different area and at a very different scale. To that end, sedimentation rates (indiative of the intensity of geomorphic response) during the last century were determined in the three sub-basins selected and in the estuary itself. The assumption is that relative changes in sedimentation rates are, in a first approximation, indicative of changes in deposition in the different study areas. Those rates were compared with changes in human and natural drivers to determine to what extent process behaviour conforms to the expected pattern. To cover a variety of situations different environments (an isolated lake, floodplain lakes, a reservoir and an estuary) were selected for sampling.

Sediment cores were extracted by manual methods in all study areas (coordinates of sampling points are presented in Appendix A). Hand-driven PVC tubes were used to extract the cores in the Laguna de Pozuelos and Río de la Plata sampling areas. In Barra Bonita and the Pantanal the sampling device shown in Fig. 3 was used. Cores were cut into 1 cm thick slices and dated using the ^{210}Pb method (Koide et al., 1973; Appleby and Oldfield, 1978, 1983; Appleby et al., 1988; Shukla and Joshi, 1989; Bolívar et al., 1994; Appleby, 1998; Fuller et al., 1999; Sánchez-Cabeza et al., 2000; San Miguel et al., 2004). The analytical procedures used have been discussed in former contributions by some of the authors (Bezerra, 1999; Gelen et al., 2004; Ródenas et al., 2004; Soto et al., 2006; Cearreta et al., 2008; Irabien et al., 2008a,b). In some study areas, in which it was expected they could provide complementary age information, heavy-metal analyses were also carried out.

Drivers considered were rainfall and several indicators of the intensity of human activity, such as population, GDP, energy or cement consumption (Table 3). These reflect human capacity to act on and transform land surface through all kinds of activities. In particular, energy and cement consumptions are directly related to activities that imply excavation or modification of land surface (extraction of construction materials, expansion of urban-industrial areas and related infrastructure, and intensive agriculture). Certainly, none of those indicators is univocally and exclusively linked to the alteration

Table 1
Area (km^2) of the different sub-basins within the Plata watershed. Population and GDP data for the countries included in the basin. Census and GDP data from ECLAC, UN (www.eclac.org), years 2000–2004, depending on the country. Area data from Coronel and Menéndez (2006). Total values and percentage are presented. Note that: >90% GDP corresponds to Brazil + Argentina; >70% of the countries' GDP is within the Plata basin; >70% of Brazil + Argentina GDP is in the basin.

	Paraná	Paraguay	Uruguay	R. Plata	Basin area in each country	Population in basin $\times 10^6$	Country population (% in basin)	GDP[a] in basin $\times 10^6$ US$	Total GDP $\times 10^6$ US$ (% in basin)
Argentina	565,000	165,000	60,000	NA	920,000	29.10	36.26	234,868	271,809
	37.5%	15.0%	16.4%		29.7%	25.3%	80%	33.2%	86.4%
Bolivia	NA	205,000	NA	NA	205,000	3.66	8.30	9414	21,343
		18.7%			6.6%	3.2%	44%	1.3%	44.1%
Brazil	890,000	370,000	155,000	NA	1,415,000	73.78	169.80	409,934	644,476
	59.0%	33.9%	42.5%		45.7%	64.4%	43.5%	58.0%	63.6%
Paraguay	55,000	355,000	NA	NA	410,000	5.18	5.18	28,799	28,799
	3.5%	32.4%			13.2%	4.5%	100%	4.1%	100%
Uruguay	NA	NA	150,000	NA	150,000	3.00[b]	3.24	23,642	35,744
			41.1%		4.8%	2.6%[a]	92%[b]	3.4%	92%[b]
Total	1,510,000	1,095,000	365,000	130,000	3,100,000	114.84	222.78	706,657	992,172
	48.7%	35.3%	11.8%	4.2%	100%	100%	51.5%	100%	71.2%

NA: not applicable.

[a] Year 2000 value.

[b] Approximate value; limits with the Atlantic watershed slightly unclear.

Table 2
Characteristics of study areas.

Name	Basin area (km^2)	Altitude (m)	Rainfall (mm/year)	Present population	Human activity during last century
Laguna de Pozuelos	4000	3600–4808	350	<3000	Almost nil; stability
Barra Bonita	12,450	450–2060	1150–2000	4,258,000[a]	Urban-infrastructure, very intense growth
Pantanal	628,000	80–1400	800–1600	5,293,790[b]	Farming-urban, growth
Plata Basin	3.1×10^6	0–5000	<50–>4000	113,191,000[c]	All sectors, intense growth

[a] Population (2007) for the municipalities included within the basin. Data from IBGE (www.ibge.gov.br).

[b] Population (2008) for the states of Mato Grosso and Mato Grosso do Sul, more than half of which are within the watershed. Data from IBGE (www.ibge.gov.br).

[c] Population (2000) of Paraguay plus the states/provinces within the basin for Argentina, Brazil, Bolivia and Uruguay. Data from ECLAC (UN) (www.eclac.org).

of land surface and related intensification of processes such as landslides, surface runoff, denudation and sediment generation (for instance, certain forms of energy generation or cement consumption are not related to activities that directly modify land surface, although generally speaking the more extensive the land modification the greater the energy and cement consumptions).

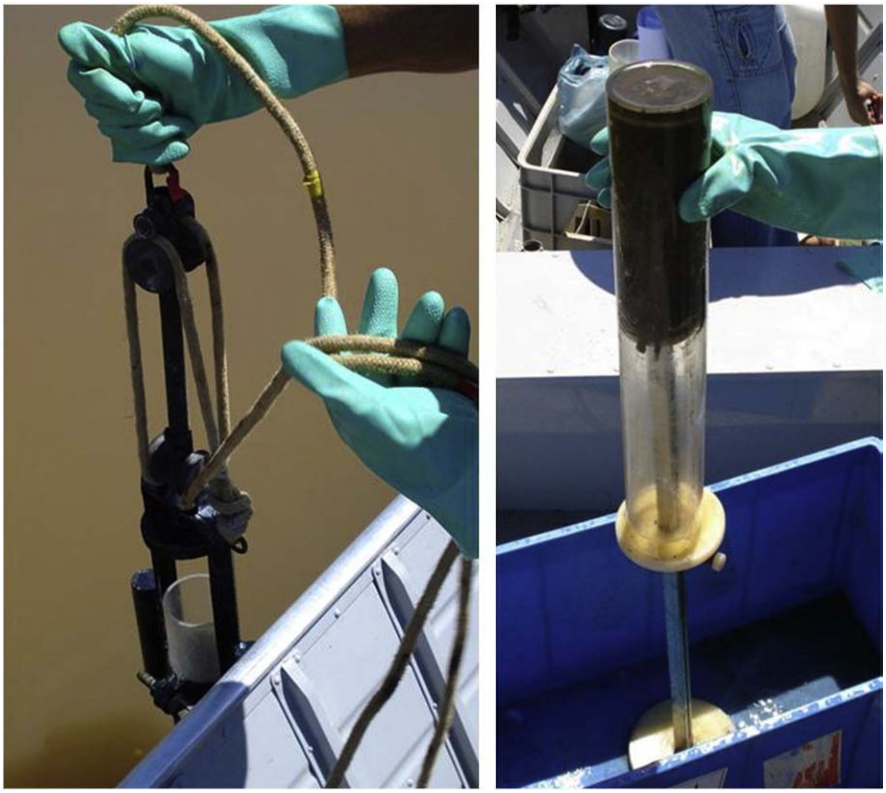


Fig. 3. Coring device used in the Pantanal and Barra Bonita areas. Left: device being lowered to extract the core. Right: PVC tube with core.

Table 3
Types of data gathered for the study areas and periods covered in each case.

Study areas	Plata basin	Pozuelos	Barra Bonita	Pantanal
Sediment cores[a]	3	2	2	3
Annual rainfall	1906–2007	1904–2007	1950–2002	1912–2007
Freq. intense rains[b]	1903–2007	1904–2007	1950–2002	ND
River discharge	1904–2003	ND	1936–2003	1900–2008
Freq. intense flows	1904–2003[c]	ND	1936–2003	1900–2008[d]
Population	1900–2007	1702–2001	1950–2007	1950–2007[e] 1910–2007[f]
GDP	1900–2007	ND	1950–2000[g]	1950–2007[e]
Energy consumption[h]	1970–2007	ND	ND	ND
Cement consumption[i]	1960–2007	ND	ND	ND
Livestock load	1960–2007[j]	1937–2004[k]	ND	1970–2006[f]
Cultivated area	1960–2007[l]	ND	1960–2000	ND
Urban population	1950–2001	ND	1950–1991	1950–2001[e]

[a] Number of cores extracted is indicated.
[b] Only monthly data available for the periods indicated.
[c] Maximum and minimum daily discharge.
[d] River stage level.
[e] For the states of Mato Grosso and Mato Grosso do Sul.
[f] Only Mato Grosso do Sul. ND. No data available.
[g] For the state of Sao Paulo.
[h] Secondary energy consumption, Brazil + Argentina.
[i] Brazil + Argentina.
[j] Brazil + Argentina.
[k] Total for the "departamentos" including the basin.
[l] Brazil + Argentina.

There are other indicators of the intensity of geomorphic response that could be compared with natural and human drivers. These include, for instance, frequency of slope movements, occurrence of erosion landforms, erosion rates, river discharge, sediment load or frequency of flood events. The model proposed assumes that alteration of land surface by human activity increases the sensitivity — or reduces the resilience — of the surface layer (Cendrero et al., 2006) and increases runoff. This should produce more slope movements and erosion, as well as increased runoff, which should result in greater discharge (in particular minimum flows).

As it is not possible to obtain time series on all types of indicators for all study areas, a selection was made on the basis of study area characteristics and data availability (Table 3). This means, of course, that data resolution is not the same for all data sets. Some data refer to the whole basin and have one-year resolution (GDP, population, etc.). Other data, such as sediment dates and sedimentation rates obtained from them, correspond to specific points and their time resolution is lower. As the data are used to compare trends or relative changes during periods of 40–100 years, these differences can be considered as acceptable for an in initial test of the hypothesis, which is the aim of this contribution.

4. Results and discussion

Results obtained are presented and discussed first for individual basins. Considerations about the whole basin are made later. Analytical results for all cores dated are presented in Appendix A.

4.1. Laguna de Pozuelos

Two cores were extracted in this lake (Fig. 2a-1). Fig. 4 shows sedimentation rates obtained by ^{210}Pb dating, rainfall data, population and livestock census as well as heavy-metal content. Heavy-metal analyses were carried out for P 1 (southern part of the lake), not far from the mouth of the Río Cincel, which runs near the Pan de Azúcar polymetallic sulphide mine. The mine, intermittently exploited since colonial times, operated more intensely and continuously during the 20th century, with peaks in the forties and early seventies. In 1983 activity was very much reduced, closing down altogether in 1990. In the 1960s a spoil heap collapsed. We thought these events might have left some geochemical signature in the lake's sediments that could provide complementary age data.

Sedimentation rates obtained for both cores are fairly stable. The same stability is revealed by heavy-metal concentrations. In the case of Zn, Rb and V and to a lesser extent Cu and Ni, a decrease (except for a single Zn value) is observed at depths around 10 to 30 cm. This might reflect the decrease in mining activity between the peaks of the forties and seventies mentioned above, but it cannot be stated with certainty.

Population data presented were obtained from Gil-Montero (2004) and data on livestock load were provided by Drs R. Tecchi (Universidad Nacional de Jujuy) and Oscar Hugo Mendoza (INDEC, Jujuy). Those data refer to the municipalities ("departamentos") of Rinconada, Santa Catalina and Yaví (Fig. 2a-1) without specifying population or livestock in each village. Only a part of the three "departamentos" are within the basin and villages contained in the latter represent a small part of their population. In particular, the "Departamento de Yaví" has practically no population in the basin, only a couple of very small settlements and a few, disperse individual dwellings. Therefore, only data from Rinconada and Santa Catalina were used for the graph in Fig. 4A. Actually, less than 50% of the population in them lives within the basin but the general trend observed in these two municipalities reflects the trend within the former (personal communication by Drs R. Tecchi and Oscar Hugo Mendoza). Time series on livestock is incomplete, especially in the case of llama. Up to the 2002 census only animals within closed properties (which represent 50–60% of the total) were included. This explains an — apparent — increase observed in that year. In general, recent data obtained and direct observations in the field reveal very limited changes with respect to the situation observed during former works in the area (Ottonello et al., 1982; Cendrero et al., 1993).

Despite the limitations of data on human drivers, a couple of conclusions can be drawn from them. First, as indicated in the description of study areas, that potential human influence on geomorphic processes has been very small indeed throughout the period analysed, due to the low density of population within the basin and its limited economic activity. Secondly, that human influence does not show any sign of increase during the last century or so, but rather a certain decrease (presumably not very relevant either from the geomorphic point of view, given the very low human presence in the basin). Rainfall, be it expressed as total annual or monthly precipitation (rough proxy for high intensity episodes), does not show a clear trend of change, perhaps a very slight decrease since the middle of the century.

Thus, the general picture that emerges from data above is one of geomorphic stability, with no noticeable climate or human forcing or change in sedimentation rates.

4.2. Pantanal

In the case of the Pantanal sedimentation rate results (Fig. 5) correspond to cores taken from a former work by one of the authors (Bezerra, 1999) in three lakes in the SW part of the wetland, near the Paraguay River and connected to its dynamics (Fig. 2a-2 and b). Sedimentation rates are shown together with rainfall, river stage, livestock load, population and GDP data. Rainfall data (obtained from the Instituto Brasileiro de Meteorologia) are from the Cuiabá station. River stage data are from the 6th Brazilian Navy District gauging station in Ladário, on the Paraguay River, by the Pantanal outlet. The number of days during which river stage was equal or greater than 3.5 m is shown. This is the level at which the Paraguay overflows its left bank in Ladário. Population and GDP data are for the States of Mato Grosso and Mato Grosso do Sul, which include about 80% of the Pantanal basin. It has not been possible to obtain time series on the actual population within the basin, but it accounts for 55–60% of the total. Therefore, trends (not absolute values) for those two states can be used to reflect trends for the basin.

Results obtained show that sedimentation rates in the three lakes were below 0.2 cm/year up to the 70s. A marked increase took place after that date, particularly in Lagoa Castelo, with rates close to 0.8 cm/year at the end of the period. This lake is the one with the coarsest sediment, due to its connection through a channel (Fig. 2b) to the dynamics of the Paraguay River during the whole hydrologic year. Rates increased to just over 0.5 cm/year in the other two lakes, with finer-grained sediments and inflow limited to high-water periods. It is interesting to point out that rates in the Lagoa Negra increased at a later period than in the other two. This is explained by the fact that a dam and road started to be built in 1974 (work stopped in 1979 due to financial restrictions, and 1.2 km is still unfinished), partially restricting flow into the lake.

Rainfall and river stage data (Fig. 5) show that three main periods can be identified. The period ending in 1960, during which rainfall and maximum river stage were fairly high. A second period between 1960 and 1973 with somewhat lower rainfall, lower river stage and a drastic reduction in the number of days with water level above 3.5 m. Finally the period after 1973, when rainfall and river stage increased again, reaching levels similar to those of the initial period, and days

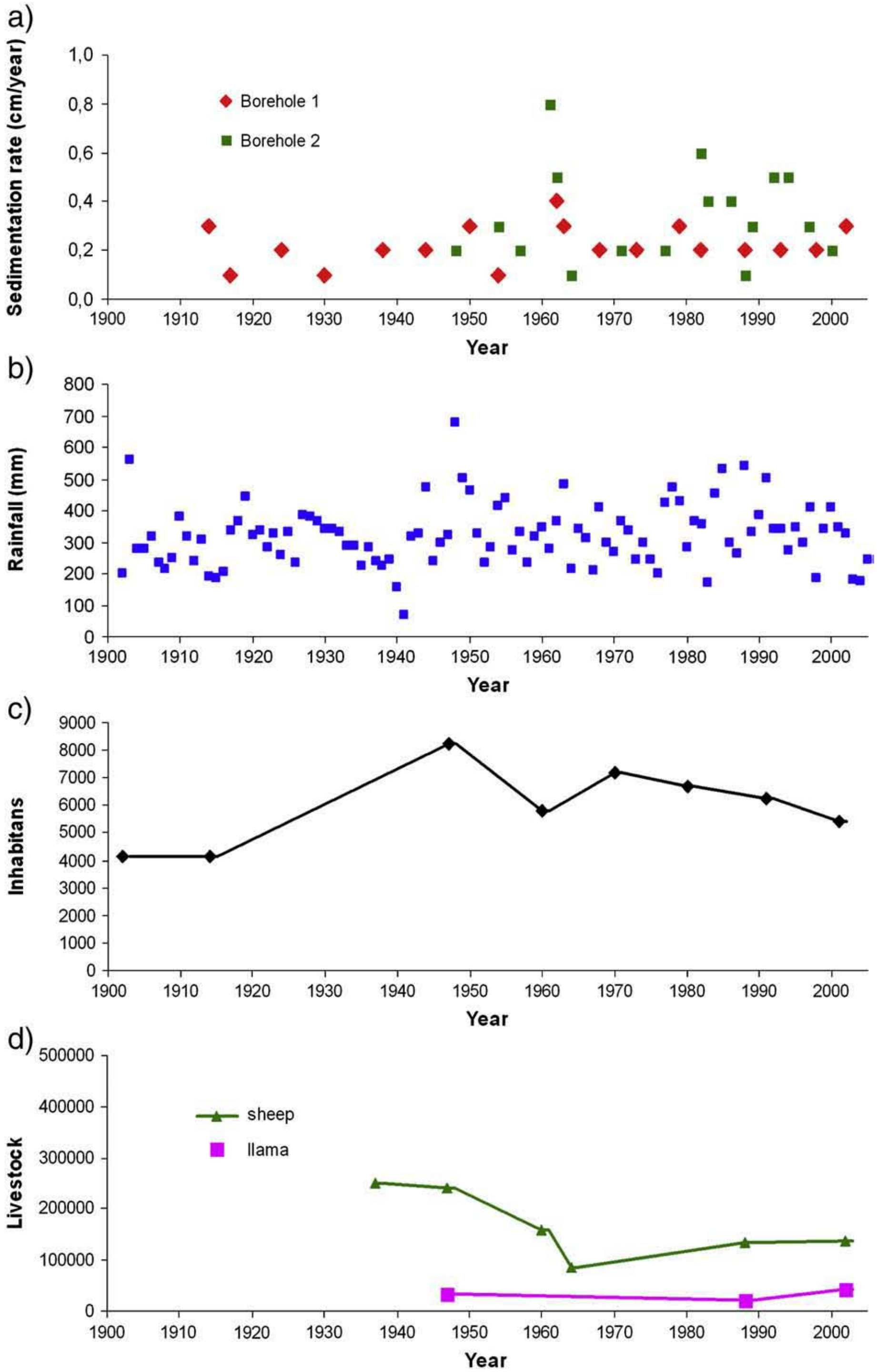


Fig. 4. a. Sedimentation rates obtained for the two cores from Pozuelos. b. Annual rainfall data (Servicio Meteorológico Nacional, Argentina, La Quiaca station). c. Population (Gil-Montero, 2004). d. Livestock data (provided by INDEC, Argentina). E. Heavy metal content of core P 1.

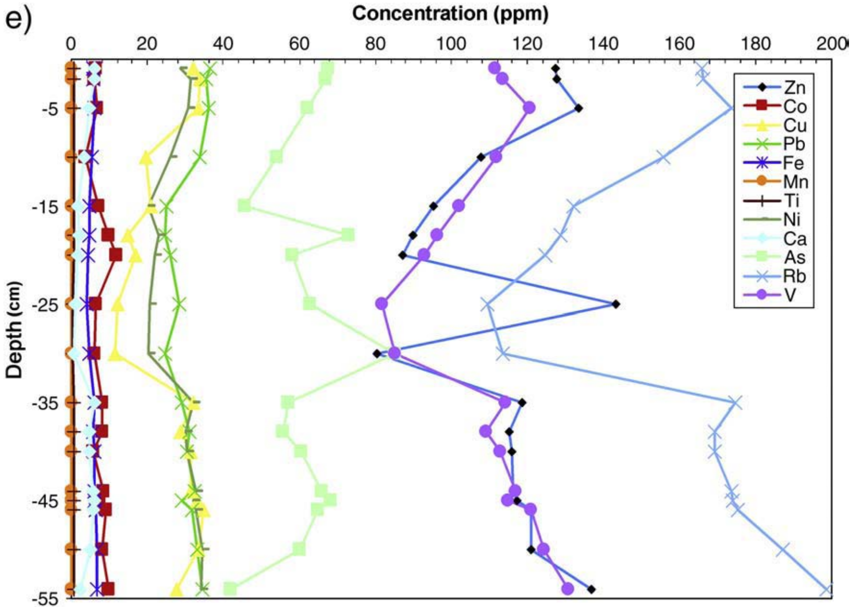


Fig. 4 (*continued*).

with water level above 3.5 m were clearly more frequent than during the initial period. Those data suggest that although rainfall must have had an influence on sedimentation rates, this was probably not the main factor contributing to their increase. Precipitation regime was not very different prior to 1960 and after 1974, whereas there were very important differences in sedimentation rates. Moreover, sedimentation rates were very similar during the period prior to 1960, with normal rainfall, and the 1960–74, lower-rainfall period.

The relationship between river stage and rainfall in this area has been discussed by Galdino et al. (1997), Collischonn (2001), Krepper and García (2004) and Diniz et al. (2008). The latter authors analysed rainfall data from the Cuiabá meteorological station and concluded that from the beginning of the 70s an important precipitation increase took place. This resulted, among other effects, in the great flooding of 1974 (water level reached 5.5 m, compared to the 1964–73 average of 2.0 m, and flooded area went from 6.770 km^2 in 1973 to 46.585 km^2 in 1974; PCBAP, 1997). After that date important changes took also place in the agricultural activities of the area. Cultivated pastures all over the basin increased considerably, at the expense of natural vegetation (Da Silva et al., 1998).

Human activities appear to have played a more important role than rainfall in sediment generation. During the 70s a series of government policies provided incentives for the development of the Pantanal and adjacent highland ("planalto"); different projects were implemented and an expansion of agriculture and livestock took place, with the consequent land-cover changes (Prance and Schaller, 1982; PCBAP, 1997; Cunha, 1998). From 1974 to present the basin, in particular the highland at the northern part where soils are very sensitive to erosion, has experienced important modifications caused by human activities. Collischonn (2001) and Tucci (2002) suggested that changes in the hydrologic regime could be related to those modifications. A few examples: area devoted to soya and cultivated pasture expanded very rapidly after 1980 (Collischonn, 2001); according the (IBGE, Instituto Brasileiro de Geografia e Estatística) cultivated pastures increased from 1285×10^6 ha in 1970 to 6×10^6 ha in 1990; area deforested in the Lagoa Negra basin went from 6% in 1965 to 38% in 1982, as a result of charcoal production for industry (Isquierdo, 1997). Livestock load (Fig. 5) grew by a factor of about 4.5.

Fig. 5 also shows that population and GDP grew very markedly during the 1950–2000 period, approximately by a factor of 9 and 30 respectively. Urban population growth has been particularly intense (Hany, 2005), with a multiplication factor of about 15 for the period 1950–2000 in Mato Grosso do Sul. Energy consumption also increased significantly, from 264,806 to 2,832,654 MWh during 1976–2000 (Empresa Energética de Mato Grosso do Sul; http//www.semac.ms.gov.br). Urban population and energy consumption are normally (although not exclusively) linked to activities affecting land surface, such as urban expansion, infrastructure development, mining and intensive agriculture. Land surface disturbed by the activities described could have increased its sensitivity to the effects of rainfall. The concurrence of both factors very likely produced an intensification of sediment generation and the observed augmentation of sedimentation rates. It is interesting to point out that the lake where sedimentation rates grew most is the one which, due to its connection with the Paraguay River, is more likely to reflect changes in the basin.

In summary, data available clearly show a 3–8 fold sedimentation rate increase in less than 30 years in the three lakes sampled. As suggested by the comparison between sedimentation rates prior to 1960 and after 1974 (with quite similar average precipitation regimes), that increase appears to be due essentially to a decrease in the resilience of geomorphic systems to the effects of rainfall, as a result of land surface disturbance produced in the basin by human activities, mainly those related to urban-infrastructure and farming expansion (as described above). As pointed out by several authors (Galdino et al., 1997; Collischonn, 2001; Tucci, 2002; Krepper and García, 2004; Diniz et al., 2008) changes in river stage, or number of days with water level above 3.5 m observed after 1973 are coherent with this interpretation, because they would be explained by increased runoff due to land-cover/use changes related to the activities described.

In a relatively close area but quite a different environment, similar sedimentation rate increases have been found by Godoy et al. (2002) in five out of seven cores from three lakes in the middle Taquarí. These authors also attribute the increase found to the expansion of agricultural activities since the seventies.

However, the results above must be considered with caution. Although it is true that those lakes show sedimentation rate increase, it is also true that sedimentation on floodplains can present high variability. More determinations are needed to establish whether the observed trends are general. Also, it must be pointed out that an alternative explanation is possible. That sector of the Paraguay River is near the Taquarí megafan, with channels that can change position significantly in a few decades. Channel migration towards a lake could imply greater sediment supply to it, even if sediment generation in the basin remained constant. This does not seem to have been the case, but it should not be discarded. The lakes are on the opposite side of the Paraguay (Fig. 2B) with respect to the Taquarí fan, and trends are quite similar in all of them, irrespective of distance from the latter. Also, as indicated above, the Taquarí itself seems to have experienced a significant increase in sediment yield (Godoy et al., 2002).

4.3. Barra Bonita

Barra Bonita reservoir receives the waters of the Piracicaba and Tietê rivers, the latter including part of the São Paulo metropolitan area, the most dynamic conurbation of the country, in the wealthiest state. Two cores, a few hundred metres apart and some 50 km upstream from the dam, were extracted and dated in the branch of the reservoir fed by the Piracicaba basin (Fig. 2a-3). This basin includes nearly 4.5 million people (IBGE, 2006; Projeto Piracena, 2001) and hosts important urban-industrial centres, exploitations of construction materials, and intensive agriculture.

Results obtained are shown in Fig. 6. Sedimentation rates increased gently since the middle 80s and sharply after 2000, over a tenfold growth in about 20 years. Rainfall and river discharge records do not show variations that could justify the observed sedimentation rate increase (Fig. 6). High rainfall periods occurred in the area approximately every five years, with a fairly regular distribution throughout the time interval considered. The same lack of clear time trend is found when considering frequency of intense rainfall episodes. About 40 months with >300 mm and 11 with >400 mm rainfall have been registered during the period considered, but they are fairly evenly distributed, and do not show greater frequency in recent years (Dantas-Ferreira, 2008). High river discharge periods fairly closely reflect rainfall fluctuations. There is no increase in the frequency or intensity of rainfall or river discharge towards the end of the period analysed that could explain the sharp increase in sedimentation rates.

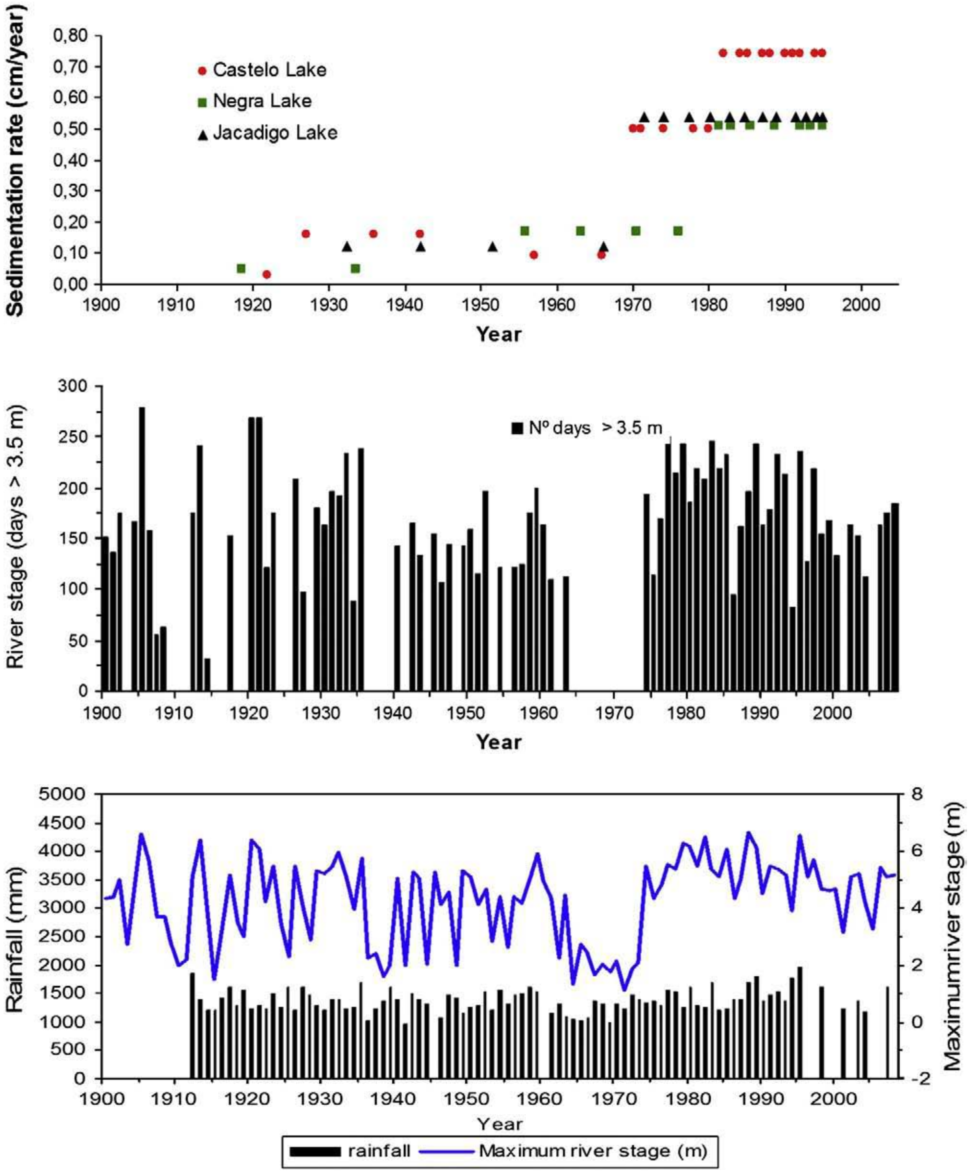


Fig. 5. Sedimentation rates obtained for three cores from the Pantanal. Rainfall (INMET, Cuiabá), maximum river stage in the year and number of days with river stage above 3.5 m (Brazilian Navy District, Ladário) are represented. Livestock data for Mato Grosso do Sul (data from IBGE). Population for Mato Grosso do Sul, 1910–2000 (1) (data from IBGE). Population (2) and GDP (3), 1950–2000, for Mato Grosso plus Mato Grosso do Sul (data from ECLAC, UN; http://www.eclac.org/).

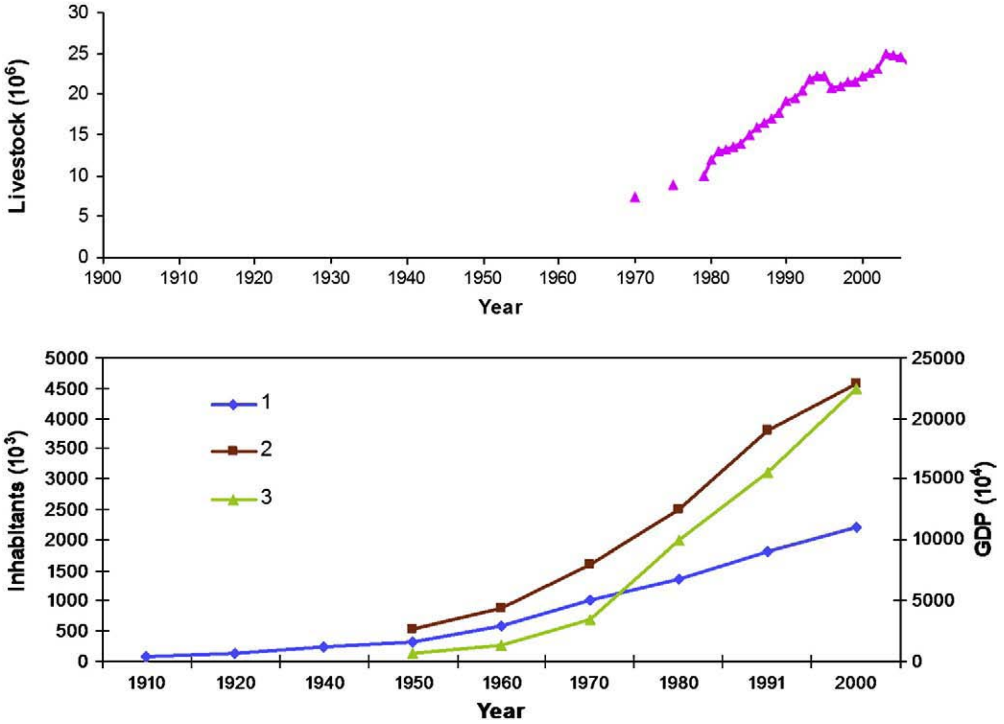


Fig. 5 (*continued*).

The situation is quite different with respect to human drivers. As indicated above, the Piracicaba basin is a highly populated and economically dynamic area (Projeto Piracena, 2001). Population within it (Fig. 6) grew by a factor of about 4.5 since 1960. Practically the whole increase corresponds to urban population. In 1950 urban population was slightly under 50% of the total, in 1991 it represented over 90% and in 2007 close to 95%. This, of course, implied a considerable urban-industrial and infrastructure expansion, activities which highly disturb land surface and contribute to sediment generation. No data are available on GDP for the basin for the same period, so that state data were used for Fig. 6, which show a 7.5 fold increase in the same period. Data at basin level are available since 1998 (IBGE, 2006) and they show that GDP within it increased twice as much as in the state, with a 100% increase since 2000. The significance of economic activities within the basin is shown by the fact that even though it represents less than 5% of the Sao Paulo state area, it concentrates around 20% of its GDP.

Other land-use changes related to specific activities that may have contributed to sediment generation have also taken place. Data for the basin (Projeto Piracena, 2001) are incomplete and cover only part of the period analysed. Nevertheless, with the information available it is possible to observe the main trends of change. Between 1970 and 1994 area covered by nearly natural vegetation (forest + pastures) in the Piracicaba basin decreased from about 515×10^3 ha to 212×10^3 ha. That is a reduction of approximately 60%. On the other hand cultivated areas increased by nearly 50% and urban areas were multiplied by a factor between 4 and 5 (the latter data were obtained from low-quality maps and are only approximate).

In the case of sugar cane, a radical transformation of land use has taken place since 1960 in Brazil in general and the basin in particular. Between 1960 and 2007 area devoted to sugar cane in Brazil increased from about 1.4 million to 7 million ha (FAOSTAT, 2007). The state of Sao Paulo concentrates more than 50% of the country's sugarcane. In the last 20 years this is the region where most of the expansion of sugar cane occurred by replacing pasture, and mostly in the western part of the state (Rudorff et al., 2004, Dantas-Ferreira, 2008). Sugar cane cultivation greatly increases erosion. Sparovek and Schnug (2001) estimated erosion rates in sugar cane fields are 15 times greater than in pasturelands. The effects of sedimentation related to sugar cane cultivation, were described by Fioro et al. (2000) in a reservoir built in 1978 in a small watershed in Piracicaba County, when sugarcane land cover was 25%. About 20 years later, sugarcane increased to 75% and the reservoir lost 50% of its water holding capacity due to sedimentation.

Finally another significant factor is the expansion experienced, in an area some 50 km upstream from the reservoir, by silt and clay exploitations for ceramic industries. Therefore, even though data available do not permit to determine exactly the extent of land-use transformations, it is obvious that the increase of activities which are potential generators of sediment has been considerable in the last few decades.

Thus, data available show that whereas natural drivers have not changed significantly after construction of the dam, human drivers did, and their increase took place in periods and with magnitudes that roughly match sedimentation rate increase.

4.4. *Río de la Plata estuary*

Three cores were extracted in the Río de la Plata (Figs. 2a–4, b and 7), one of them in the outer estuary, in the distal part of the submerged delta (RP-1; Samborombón Bay). The other two were obtained in the inner part, near the town and port of Ensenada, one in an area open to estuarine influence (RP-2) and the other (RP-3) in an inlet with restricted circulation in which estuarine influence is limited. It was expected that sedimentation rates should grow in RP-1 and RP-2, and remain more stable in RP-3.

Core RP-1 had some problems. Due to the very high water content of the sediment, a part of the samples in the upper levels was lost during processing and density values obtained for those levels are approximate. ^{210}Pb dates and sedimentation rates obtained from them have therefore a higher margin of uncertainty than in the other cases. Fortunately there was additional information that made it possible to obtain complementary age data and determine rates. The upper 3 cm of the core contained ^{7}Be, with a half life of 57 days. This indicates that material was deposited not more than 400 days (7 half-life periods) prior to analysis (July 2008) and that sedimentation rate during that period was 2.7 cm/year. Additionally heavy-metal (Fig. 8) and shell content in the sediment provided a clear date. There is an abrupt reduction of shell fragments, abundant in the lower part of the core, at 25 cm depth, which coincides with a marked increase in the content of most metals, followed by a gradual decrease. This change can be attributed to the construction, in 1987, of a new channel at the end of the Rio Salado. The artificial channel, with greater section and gradient, must have accelerated flow, sediment and heavy-metal supply. The natural river course crosses repeatedly several belts of Holocene estuary-margin deposits formed mainly by shell fragments ("cordones de conchilla" or beach ridges). The new channel cuts right across those belts, and is deeper than the natural one. Therefore, contact between water and shell fragments was very much reduced, and since that date they are carried to a very limited extent. The gradual decrease in heavy-metal concentration after that moment could only be due to two causes: decrease in heavy-metal supply or increase in sediment supply. We have investigated in environmental administration sources ("Secretaría de Política Ambiental y Desarrollo Sustentable de la Nación", SPAyDS) whether anti-pollution measures or technology changes in processes producing heavy-metal effluents were introduced after those dates, and they were not. Pollution-reduction programmes were approved recently ("Programa Federal de Producción Limpia y Consumo Sustentable", 2004, and "Plan Federal de Reconversión Industrial", 2008), but they are too recent to explain the change described.

Moreover, as Fig. 8 (please note that heavy-metal analyses were performed every 3, not 1 cm) shows, the decrease affected practically all metals, suggesting a general process rather than one affecting individual sources. Using the 1987 level as a reference, we can see that average sedimentation rates were approximately 0.3 cm/year for the period 1900–87, and 1.2 cm/year from 1987 to 2007 (when the core was extracted), with 2.7 cm/year during the last year. This coincides very well with the rates obtained by means of ^{210}Pb determinations.

Core RP-2 (Ensenada) presented a very irregular distribution of Pb along the profile (see Appendix A), suggesting it must have experienced mixing due to organic or human processes. It was therefore not possible

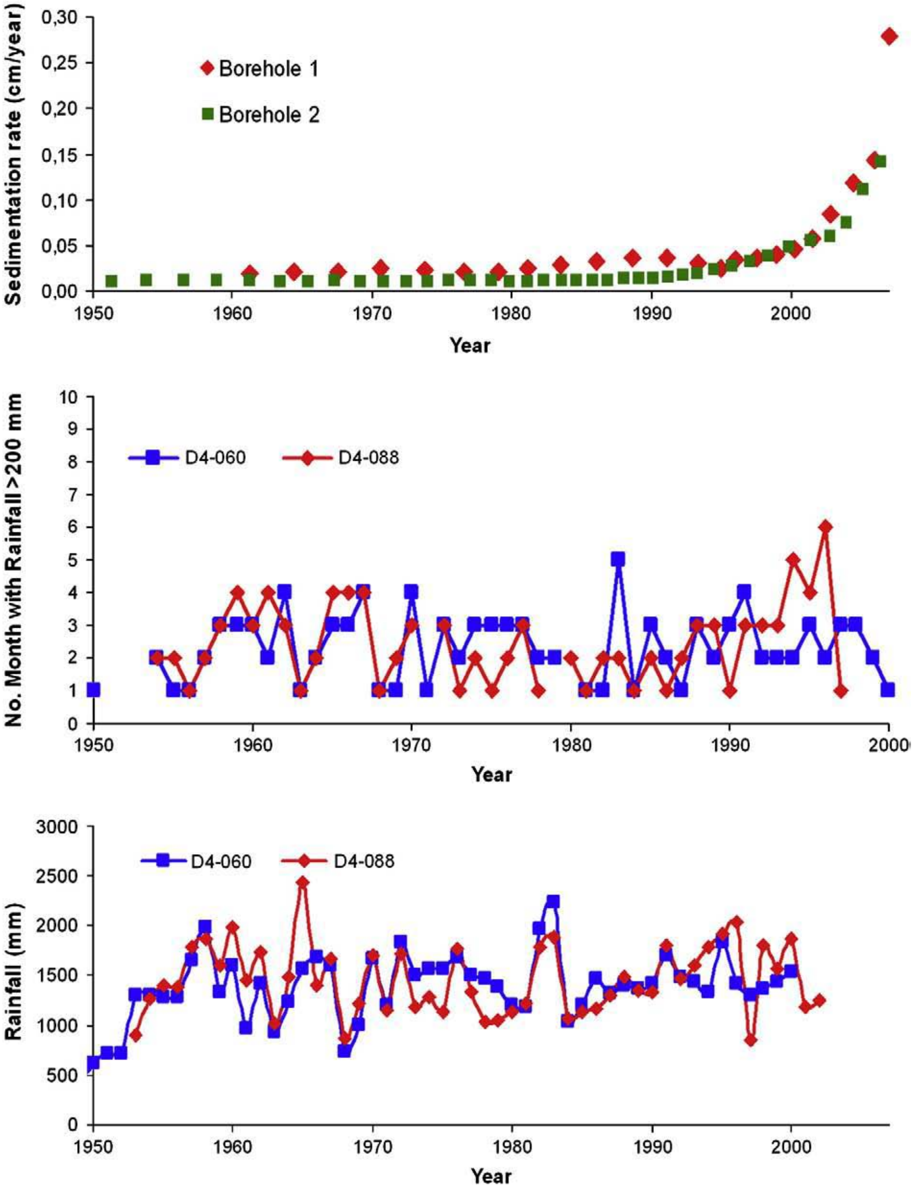


Fig. 6. Sedimentation rates obtained for 2 cores from Barra Bonita, compared with rainfall, river discharge, population of Piracicaba basin and GDP (state of São Paulo) data (Instituto Brasileiro de Geografia e Estatística-IBGE). D4-060 and D4-088, meteorological stations shown in Fig. 2a.

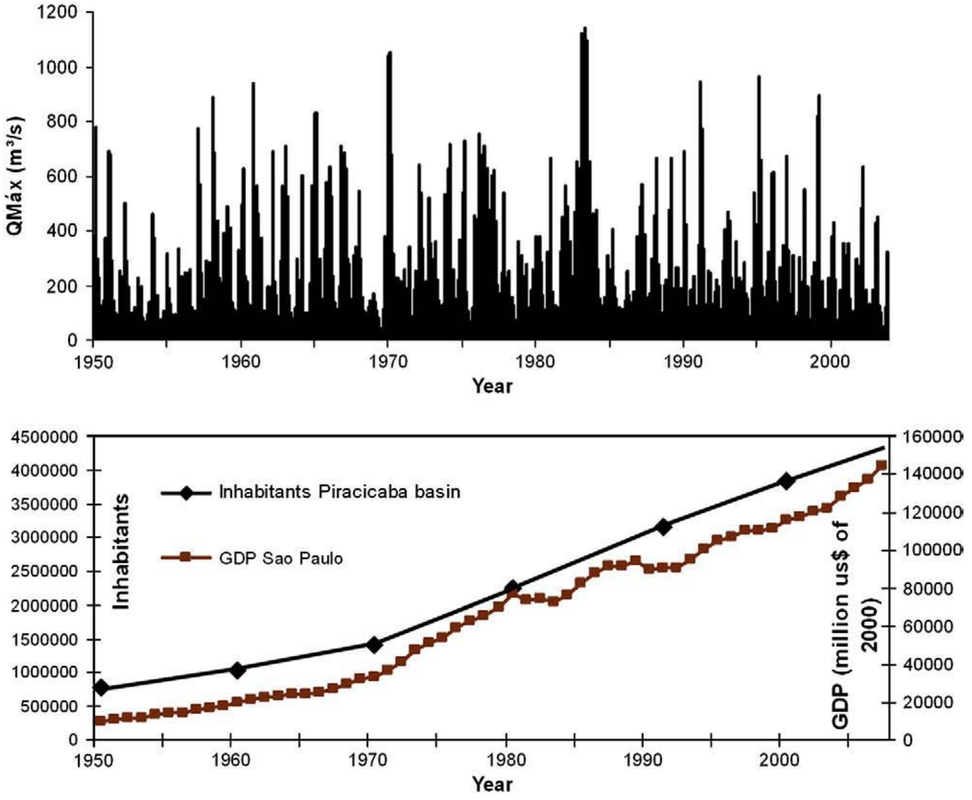


Fig. 6 (*continued*).

to use it for dating. The third core (RP-3, in the area with limited estuarine influence) yielded constant sedimentation rates (Fig. 7).

With the data above it appears that sedimentation in the outer delta increased markedly during the period analysed, particularly in the last 20 years, and showed no significant changes in the above-mentioned inlet near Ensenada. In principle, RP-1 should reflect the trend for the outer estuary, as it was extracted in an open site. On the other hand, RP-3 probably reflects local rather than general estuary trends. These results are coherent with the working hypothesis but, nevertheless, with the data so far obtained it is not possible to assess to what extent either trend is general or local. More cores should be dated.

Complementary information, obtained from the analysis of old maps, navigation charts, air photographs and satellite images of the Paraná Delta (Cavallotto, 1988; Cavallotto et al., 2005; Sarubbi et al., 2006; Forte et al., 2008), suggests that increase in sediment supply to the delta might well have been a general process. Area progradation of the delta is shown in Fig. 9. The general growth trend is linear, with an initial period (until 1969) showing increasing (exponential?) rates followed by a certain decrease and a new increase of the rates. Of course, area growth is only a rough indicator of volume growth (sediment supply and deposition). It is interesting to point out that until the late sixties there were very few dams in the basin. At that time dam construction increased very significantly, leading to the present number of about 130 large dams. Data on sediment loads in rivers upstream and downstream dams in different rivers in the region (Latrubesse et al., 2005; Syvitski et al., 2005; Bonetto et al., 2006; Stevaux et al., 2009; Amsler and Drago, 2009) show that reductions in sediment load are greater than 60%. In rivers from other parts of the world (Milliman and Meade, 1983; Meade and Parker, 1985; Meade et al., 1990; Milliman and Syvitski, 1992; Bobrovitskaya etal., 2003; Vörösmarty et al., 2003; Walling and Fang, 2003; Renwick et al., 2005a,b; Syvitski et al., 2005; Walling, 2006; Wang et al., 2007; Xu and Milliman, 2009) sediment load is reduced by factors between 2 and 200, normally 10–20.

As is well known, these reductions in sediment supply have led to retreat of beaches and deltas in different parts of the world (Mobarek, 1972; Poulos and Collins, 2002; Ericson et al., 2005; Syvitski and Saito, 2007; Zhang et al., 2008; El Banna and Frihy, 2009; Gamage and Smakhtin, 2009). It thus seems that sediment supply to the Paraná–Paraguay–Uruguay system probably increased during the second part of the century, because neither delta growth nor sedimentation rates experienced a reduction despite the fact that a large number of sediment traps were built. A cautionary comment: most dams in the Paraná and Paraguay basins have been built above the junction with the Bermejo, a very significant sediment contributor. Sedimentation rates registered, if general for the estuary, could mostly reflect changes in the latter basin.

Rainfall data from meteorological stations distributed throughout the basin (Figs. 2a and 7), show that rainfall (both annual total and months >200 mm) has experienced some variations during the period analysed, particularly after 1980, which are partly reflected by river discharge data. Three main periods can be identified from rainfall/discharge data. Up to 1950 there were relatively low rainfall, frequency of intense precipitation events (>200 mm/month) and river discharge. Between 1950 and 1980, during which both total annual rainfall and frequency of intense events increased but river discharge did not vary significantly. The last period, with slightly greater rainfall compared to the former one and a significant increase in river discharge.

According to Tucci and Clarke (1998), a considerable expansion of land devoted to farming started in the 50s, and has continued since. Different changes in river discharge have been observed (Halcrow, 1994; Paoli and Cacik, 2000; Menéndez, 2006). Mean discharge in the period after 1980 is 37% higher than in the period 1902–1970. Annual maxima and minima are also higher, and the frequency of exceptional floods has increased too. Out of the four floods with peak flow > 50,000 $m^3 s^{-1}$ (1905, 1983, 1992, and 1998), three correspond to that period. The increase in mean discharge has been attributed to greater runoff in the upper Paraná basin, explained only in part by increased rainfall, with land-use change as the most likely alternative cause. Greater frequency of exceptional floods seems to be attributable to climate conditions that have favoured the occurrence of very intense rainstorms. Minimum flow increase could be due to enhanced hydrologic response due to land-use change or to the regulatory effect of dams built in Brazil, essentially after the late 60s. In the case of the Uruguay River, Saurral et al. (2008) conclude that runoff is showing progressively shorter response times, which do not seem to correspond to precipitation but to land-use changes. Bevery et al. (2006) point out that river response exceeds rainfall increase; percent increase in river discharge in the period analysed doubles rainfall increase. Those results are coherent with data presented about sedimentation rates and with the model proposed.

On the other hand, all human drivers show very clear increases. A comment about some limitations of socio-economic indicators used is pertinent here. It has not been possible to obtain time series on most of those indicators which strictly refer to the basin. But what is needed for testing the model are trends (relative variation), not absolute values. Fig. 10 presents a comparison between population and GDP trends for the five basin countries, Brazil + Argentina, and states/provinces (Brazil/Argentina) within the Río de la Plata basin. As indicated above, these two countries account for over 90% of the basin's GDP, and slightly less in the case of population. Also, their joint population and GDP are concentrated in the basin (over 60 and 70% respectively; Table 1). Thus, the general variation of socio-economic parameters in the two countries can be considered to adequately reflect trends within the basin. Fig. 10 shows very clearly that Brazil + Argentina trends are practically the same as the other two. Multiplication factors in both cases are around 3 for population and 6–7 for GDP, respectively.

Fig. 11 shows the variation of the socio-economic parameters considered and Table 4 summarises growth factors for different periods (determined by the length of time series obtained). Clearly, drivers with the greatest growth factors are the ones in principle more directly related to human capacity to disturb land surface: GDP, energy or cement consumption. Considering the period after 1960, for which information is available on all indicators (1970 in the case of energy consumption), it can be seen that growth factors of the latter three parameters are quite similar to those of sedimentation rates obtained in the different study areas (with the logical exception of Laguna de Pozuelos).

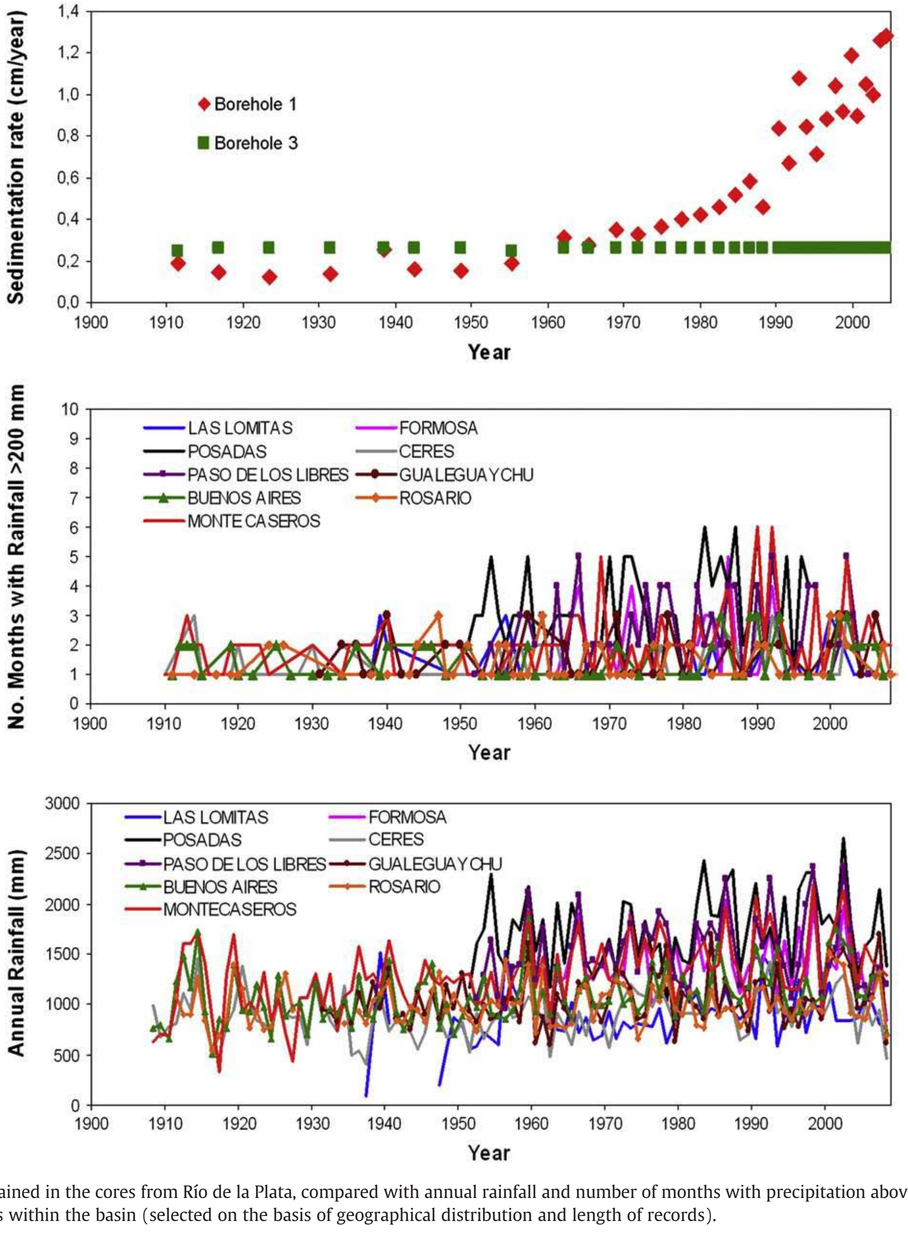


Fig. 7. Sedimentation rates obtained in the cores from Río de la Plata, compared with annual rainfall and number of months with precipitation above 200 mm, and river discharge data for representative stations within the basin (selected on the basis of geographical distribution and length of records).

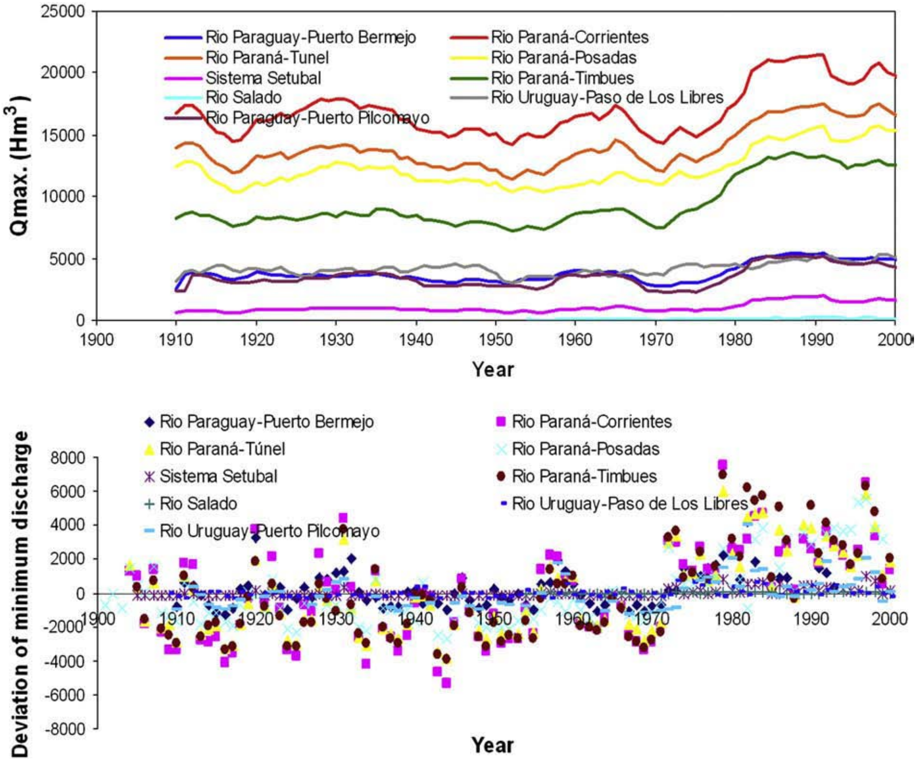


Fig. 7 (*continued*).

Economic growth related to farming activities has increased anthropogenic pressures, through deforestation, overgrazing and poor farm management practices in general. Deforestation in the basin exceeds 26% and unsuitable practices have been identified in more than 60% of farmlands (Tucci and Clarke, 1998, Grau and Brown, 2000; OAS-UNEP, 2005; Viglizzo and Frank, 2006; Boletta et al., 2006; Gaviño-Novillo et al., 2007; Izquierdo and Grau, 2009). Those activities seem to be the drivers that enhanced erosion and mass wasting processes and led to greater sediment generation.

But, as indicated above, sediment supply to the Paraná comes mainly from the W–NW part of the basin, in particular the upper Bermejo River, a tributary to the Paraguay River, itself the main tributary to the Paraná (Brea et al., 1996, 1999a,b,c). Therefore, comparison between sedimentation rates and human drivers could be more appropriate if only that part of the basin (which coincides essentially with the Argentine part) were considered. Fig. 12a, shows trends for human drivers in the provinces within the basin, and Fig. 12b the ones for the provinces of Salta and Jujuy, roughly

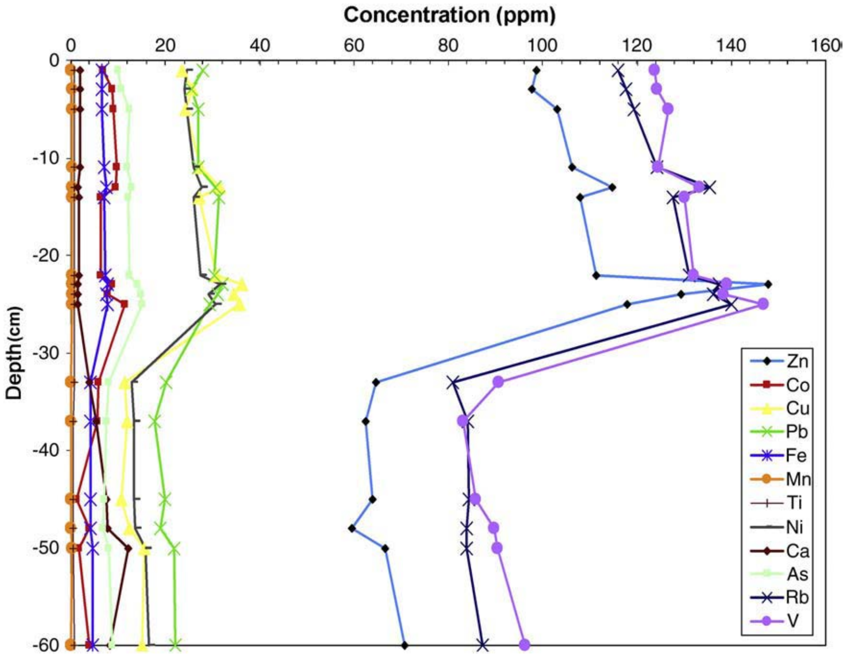


Fig. 8. Heavy metal composition in core RP 1 (please note that heavy metal analyses were performed for 3 cm thick layers, not 1 cm as in the case of ^{210}Pb determinations).

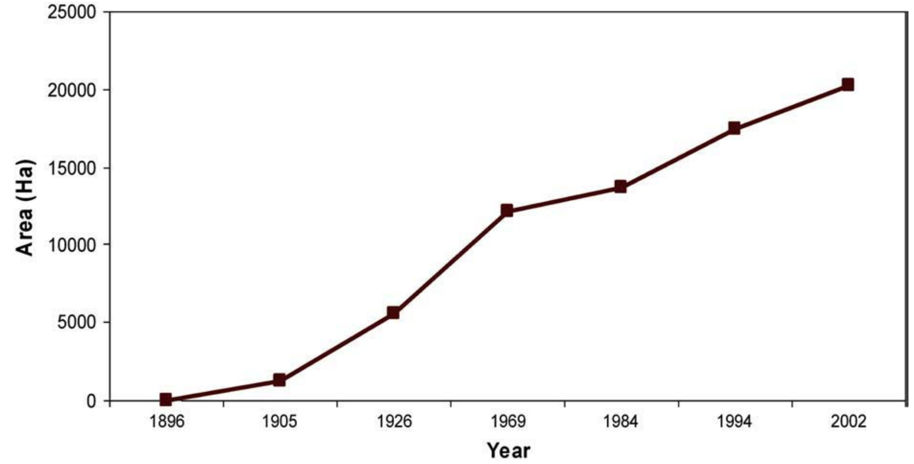


Fig. 9. Area progradation of the Paraná Delta.
After Forte et al. (2008).

coincident with the upper part of the former basin. The picture is not very different from the one previously obtained; if anything, socio-economic indicators at this scale show an even faster growth than at national level.

We are well aware of the limitations inherent to the analysis presented here. Data so far available are clearly not sufficient to consider the model proposed as valid, among other reasons because of the different resolutions of the various types of data used. They must be considered to represent only an initial, rough characterisation of the processes analysed in the basin, but they are reasonably coherent among themselves and with the model. The stability of sedimentation rates in Pozuelos is logical because neither natural nor human drivers show significant changes. Similarly, the fact that rates grew more markedly in Barra Bonita than in the Pantanal can be explained by the

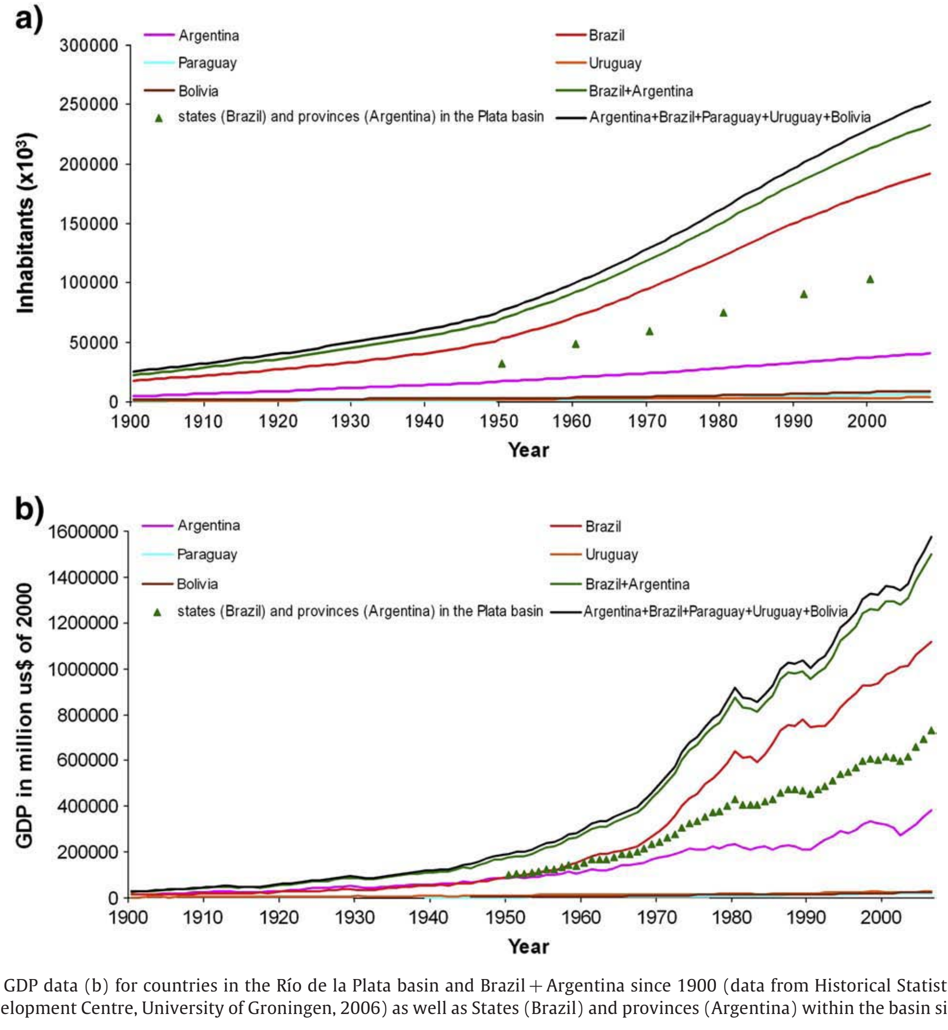


Fig. 10. Population (a) and GDP data (b) for countries in the Río de la Plata basin and Brazil + Argentina since 1900 (data from Historical Statistics for the World Economy. Groningen Growth and Development Centre, University of Groningen, 2006) as well as States (Brazil) and provinces (Argentina) within the basin since 1960 (data from ECLAC, UN; in year 2000 US).

fact that in the latter human influence is much stronger, and exerted to a great extent through activities that disturb land surface much more intensely (extraction of construction materials, urban-infrastructure development, and sugar cane cultivation), thus significantly contributing to sediment generation. These activities were also significant within the Pantanal watershed, but here land-use changes related to vegetation clearing for cattle breeding seem to have been an important factor too.

One implication of the model proposed is that, other factors being equal, there should be a relationship between the intensity of human influence and sediment generation in different basins; in other words, the more intense the former the greater the latter. The present analysis focuses on the relative variation of sedimentation rates (comparison should be made with absolute sediment yield) at specific points, and deals with study areas that differ not only in the degree of human pressure, but also in their physical characteristics. It therefore cannot be used to test this prediction. It would be interesting to analyse different basins to attempt establishing the relative contribution of different landscape evolution drivers (relief, tectonics, hydroclimate, and human activity; Summerfield and Hulton, 1994; Hovius, 1998; Summerfield, 2000, Turner, 2006; Slaymaker et al., 2009) to sediment generation, using GDP km^{-2} as an indicator of "human geomorphic pressure".

The Río de la Plata is a basin of considerable dimensions that can be considered to much better reflect possible global behaviour than the small basins for which the model was initially conceived. Thus, even though data presented cannot be interpreted as representative of processes for the whole basin, it does not appear unreasonable to think that the model could be valid at basin or larger levels. Results obtained in different parts of the world (Varekamp, 1991; Huh and Chen, 1999; Benoit et al., 1999; Cisternas et al., 2001; Kotarba et al., 2002; Cundy et al., 2003) also suggest that sedimentation rate increase is a fairly general phenomenon, perhaps of global extent.

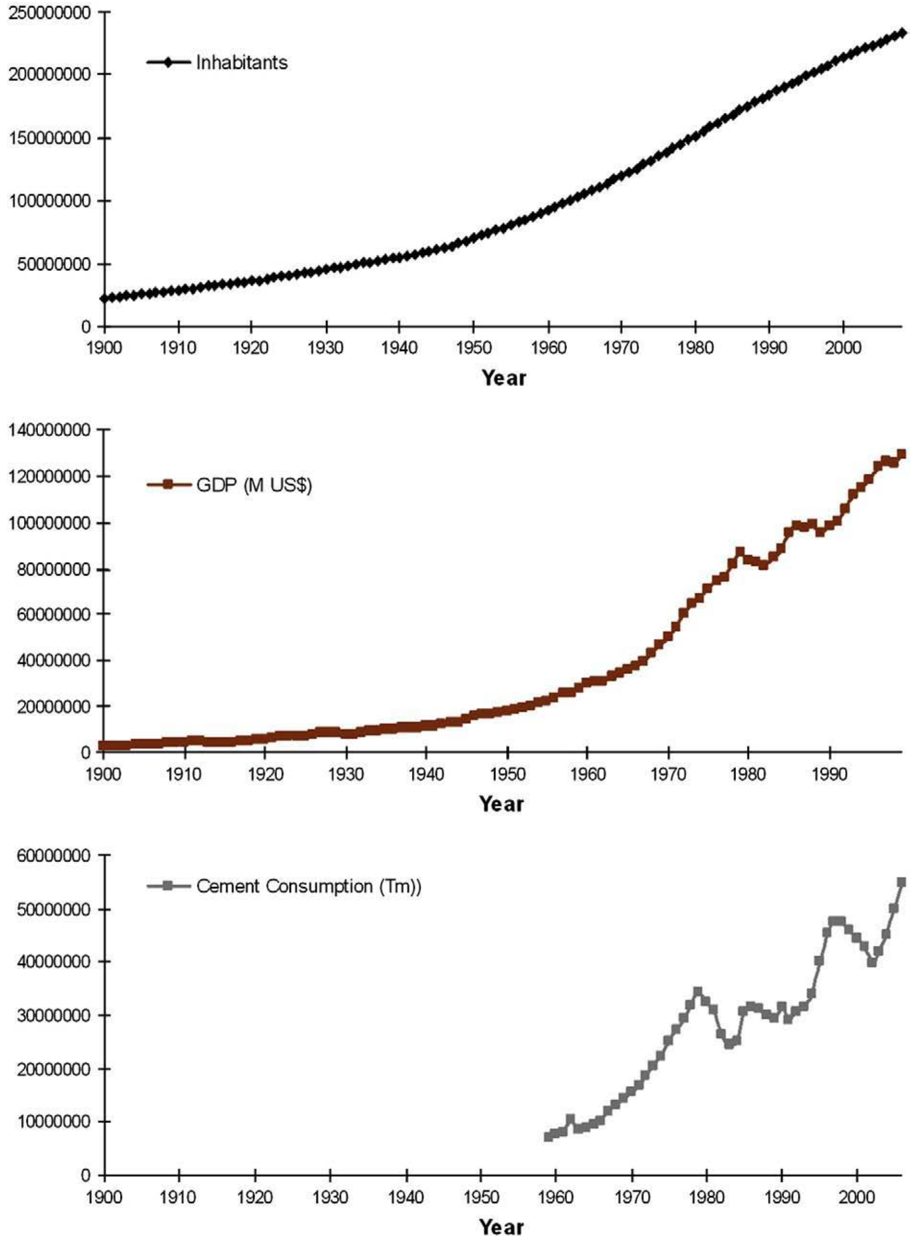


Fig. 11. Data on socio-economic drivers for the Plata basin. Population, GDP (data from ECLAC, UN; Historical Statistics for the World Economy. Groningen Growth and Development Centre, University of Groningen, 2006), cement consumption (Asociación de Fabricantes de Cemento Portland de Argentina and Associaçao Brasileira de Cimento Portland), energy (ECLAC, UN), crop area and livestock load (data from FAO).

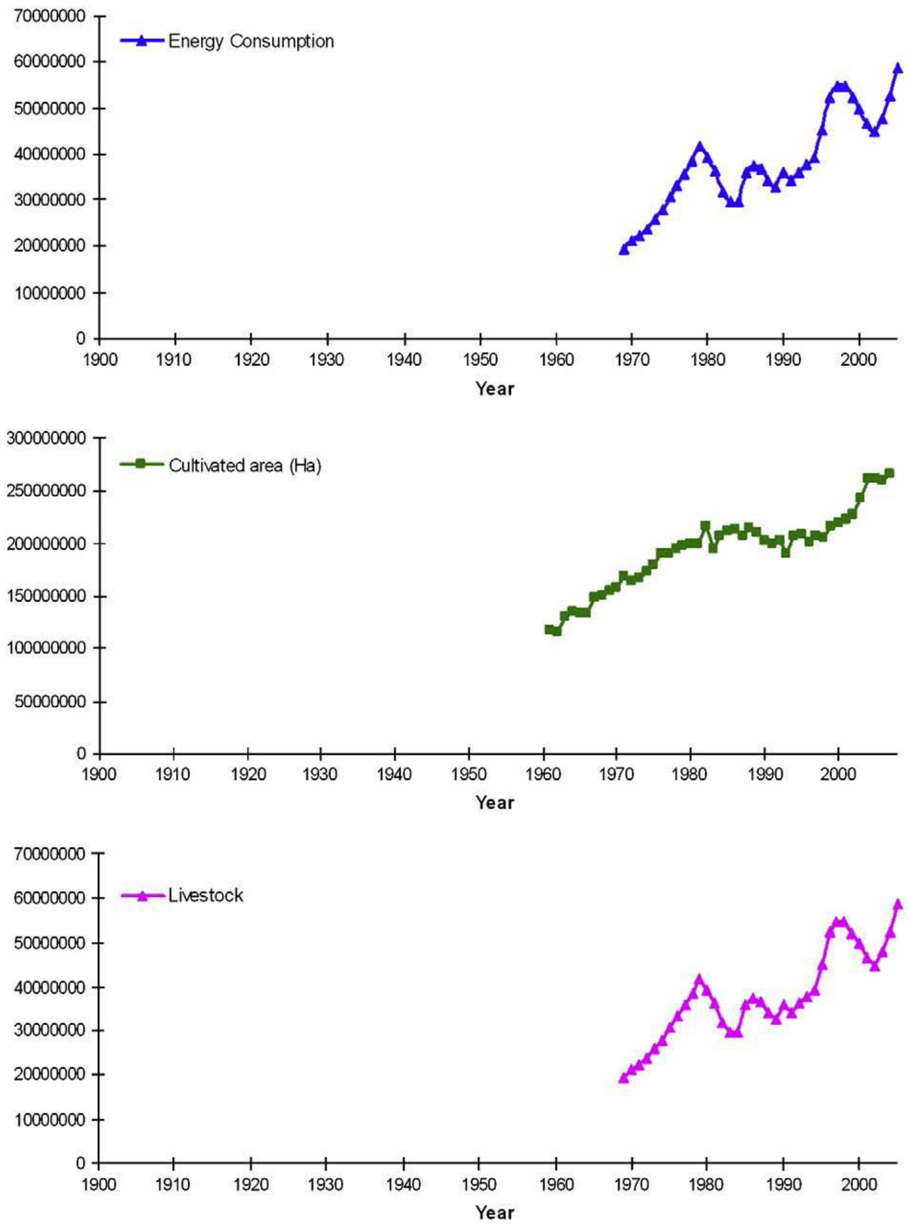


Fig. 11 (*continued*).

5. Conclusions

Some interpretations coherent with data so far available can be advanced. We take them as hypotheses that deserve further testing.

Sedimentation rates (and therefore, denudation) show signs of acceleration in the basin and some significant sub-basins within it. Increases observed in sedimentation rates are roughly one order of magnitude within a century. That augmentation can hardly be

Table 4
Growth factors for human drivers considered in the Plata basin.

Period	Population	Urban population	GDP	Crop area[a]	Livestock[a]	Energy consumption[b]	Cement consumption[c]
1900–2005	10[d]	ND	57[d]	ND	ND	ND	ND
1960–2005	2.2[e]	3.7[e]	5[f]	2.2	1.6	ND	6.4
1970–2005	1.8[e]	2.4[e]	3[f]	1.7	1.4	3.6	3.1

[a] Brazil + Argentina; 1961–2005 data from FAO (www.fao.org/corp/statistics).

[b] Secondary energy consumption, Brazil + Argentina; data from ECLAC, UN (www.eclac.org).

[c] Brazil + Argentina; data provided by the "Asociación de Fabricantes de Cemento Portland de Argentina" (Anuario Estadístico, 2007) and Associaçao Brasileira de Cimento Portland (http//www.abcp.org.br). ND: no data available.

[d] Data for Argentina and Brazil (Historical Statistics for the World Economy, 2006).

[e] Provinces (Argentina) and states (Brazil) within the basin; 1960–2001 data from ECLAC, UN (www.eclac.org).

[f] Brazil + Argentina (ECLAC and Historical Statistics for the World Economy, 2006; Angus Maddison).

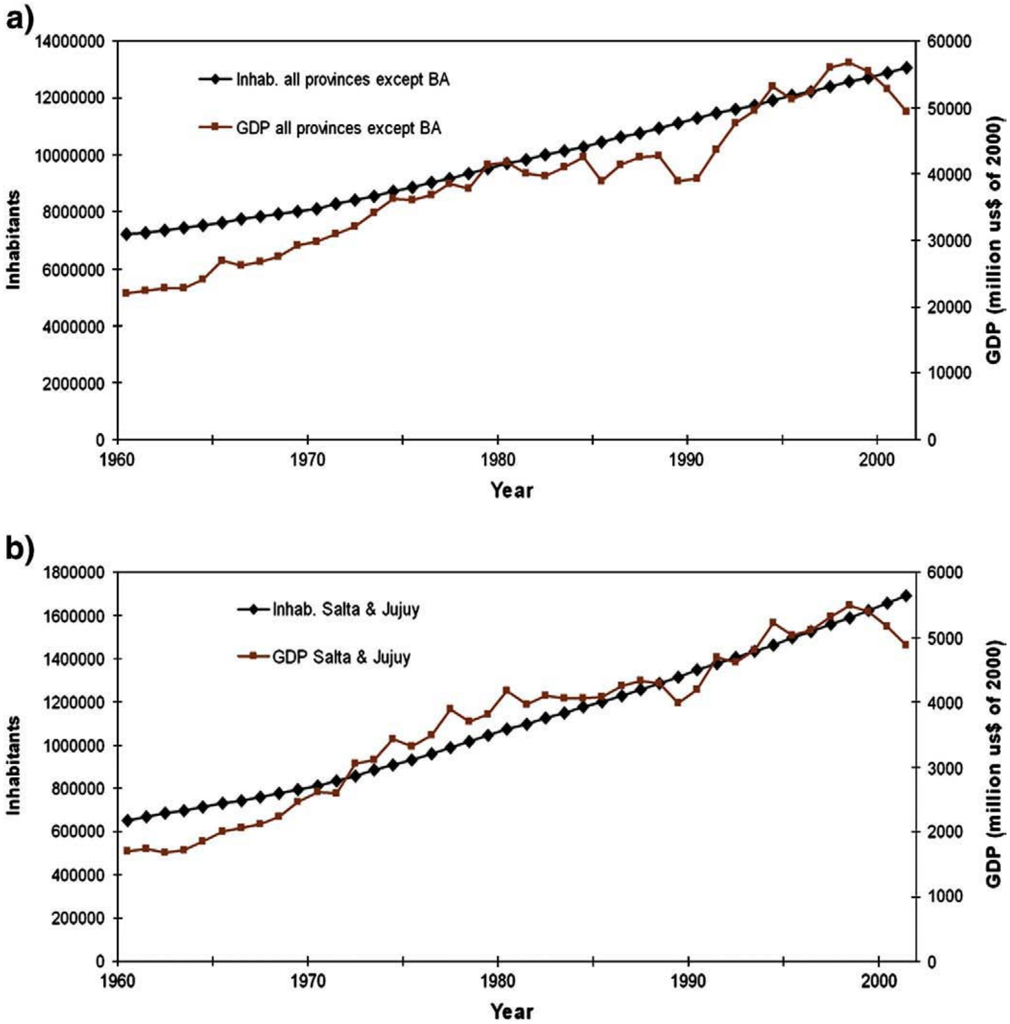


Fig. 12. a. Population and GDP data for Argentine provinces (except Buenos Aires) in the W part of the basin, where most sediment is generated. b. Population and GDP data for Salta and Jujuy (upper Bermejo basin).
Data from ECLAC.

attributed to rainfall change, which in the southern part of South America shows an increase of around 6–8% during the same period (IPCC, 2007). On the other hand, it agrees with the findings of Spencer et al. (2009), who point out the significance of human drivers of landscape change in most environments or biomes of the world.

Potential drivers related to the modification of land surface by human activities (especially those related to excavation/construction and others that normally imply land disturbance) show, at sub-basin and general basin levels, growth patterns and magnitudes that roughly resemble those of sedimentation rates. Data obtained here suggest that, although the importance of agriculture as a land transformation force seems to be clear (Lambin and Geist, 2006), mining, quarrying, urban expansion and infrastructure development could perhaps represent greater contributions to sediment generation.

Data on rainfall/river discharge and analyses carried out by different authors indicate that the enhanced hydrologic response of some rivers within the basin cannot be satisfactorily explained by rainfall variations only, and that increased runoff due to land surface changes is probably playing a role too. Increases of both sediment generation and hydrologic response are indicative of an intensification of geomorphic processes. It is thus not unreasonable to think that other expressions of geomorphic activity, such as landslides or floods, might have increased in a similar way. It has been generally accepted (Dunne and Leopold, 1978) that hydrologic and geomorphic effects of land-use changes are confined to small basins, but results obtained here indicate that might not be necessarily so and agree with findings presented by Latrubesse et al. (2009) for another large river in South America.

However, as commented above caution should be taken to draw conclusions from the results presented. Data are still limited and perhaps that explains such a good fit with the hypothesis. Analysis of results from northern Spain (Irabien and Velasco, 1999; Bruschi et al., 2008) shows that, although most of them agree with the model, sedimentation rates in some cores did not increase significantly. It would be worth gathering additional data on these processes, for particular sub-basins and the whole Plata basin as well as other basins, to determine to what extent they conform to the suggested pattern. Also, a greater number of cores should be dated to make sure that the increase found in sedimentation rates in the points studied also exists in other parts of deposition areas of the basins. If the hypothesis is confirmed, it would help to better assess frequency trends of hazards related to those processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scitotenv.2010.03.004.

References

Amsler ML, Drago EC. A review of the suspended sediment budget at the confluence of the Paraná and Paraguay Rivers. Hydrol Process 2009. doi:10.1002/hyp.7390.

Appleby PG. Dating recent sediments by Pb-210. Problems and solutions. Proc. 2nd NKS/EKO-1 Seminar, Helsinki, Finland, 2–4 April 1997; 1998. p. 7-24.

Appleby PG, Oldfield F. The calculation of ^{210}Pb date assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 1978;5:1–8.

Appleby PG, Oldfield F. The assessment of ^{210}Pb date from sites with varying sediment accumulation rates. Hydrobiologia 1983;103:29–35.

Appleby PG, Nolan PJ, Oldfield F, Richardson N, Higgitt SR. Pb-210 dating of lake sediments and ombrotrophic peats by gamma assay. Sci Total Environ 1988;69:157–77.

Bakker MM, Govers G, van Doorn A, Quetier F, Chouvardas D, Rounsevell M. The response of soil erosion and sediment export to land-use change in four areas of Europe: the importance of landscape pattern. Geomorphology 2008;98:213–26.

Benoit G, Rozan TF, Patton PC, Arnold CL. Trace metals and radionuclides reveal sediment sources and accumulation rates in Jordan Cove, Connecticut. Estuaries 1999;22(1):65–80.

Bevery H, Doyle M, Barros V. Tendencias regionales de la precipitación. In: Barros V, Clarke R, Silva Días P, editors. El Cambio Climático en la cuenca del Plata, Proyecto SGPII 057: Trends in the hidrological cycle of the Plata basin: Raising awareness and new tools for water management. Buenos Aires: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); 2006.

Bezerra MAO. Uso de multi-traçadores na reconstrução do Holoceno no Pantanal Matogrossense, Corumbá, MS. Tese de Doutorado, Programa de Pós-graduação em Ecologia e Recursos Naturais. Universidade de São Carlos (Brazil); 1999.

Bobrovitskaya NN, Kokorev AV, Lemeshko NA. Regional patterns in recent trends in sediment yields of Eurasian and Siberian rivers. Global Planet Change 2003;39:127–46.

Boletta PE, Ravelo AC, Planchuelo AM, Grilli M. Assesing deforestation in the Argentine Chaco. For Ecol Manage 2006;228:108–14.

Bolívar JP, García-Tenorio R, García-León M. A generalized transmission method for gamma-efficiency determinations in soil samples. Nucl Geophys 1994;8(5):485–92.

Bonetto AA, Castello HP, Wais IR. Stream regulation in Argentina, including the superior Paraná and Paraguay rivers. Regulated Rivers Res Manage 2006;1:129–43.

Brea J, Busquets M, Spalletti P. Estudio sedimentológico preliminar de la Cuenca Inferior del Río Bermejo. Evaluación del impacto de las presas de la Alta Cuenca del Río Bermejo en la morfología del tramo inferior. Informe LHA 131-01-96. INCYTH-COREBE, Argentina; 1996.

Brea J, Spalletti PD, Spalletti L, Rafaelli S. Generación y transporte de sedimentos en la Alta Cuenca del río Bermejo. Impacto en la Hidrovía, Delta del Paraná y Río de la Plata. Producción de sedimentos en la Alta Cuenca del río Bermejo. Informe LHA 177-02-99. PEA-FMAM-OEA-PNUMA. INA. Ezeiza, Argentina; 1999a.

Brea J, Busquets M, Spalletti P. Generación y transporte de sedimentos en la Alta Cuenca del río Bermejo. Impacto en la Hidrovía, Delta del Paraná y Río de la Plata. Informe LHA 177-04-99. PEA-FMAM-OEA-PNUMA. INA. Ezeiza, Argentina; 1999b.

Brea J, Busquets M, Spalletti P. Análisis de la dinámica fluviomorfológica del río Bermejo Inferior. Informe LHA 178-02-99. PEA-FMAM-OEA-PNUMA. INA. Ezeiza, Argentina; 1999c.

Brierley GJ, Stankoviansky M, editors. Special issue geomorphic responses to land use changes, 51. Catena; 2003. p. 173–347.

Brown H. Technological denudation. In: Thomas WL, editor. Man's role in changing the face of the earth. Chicago: Univ. of Chicago Press; 1956. p. 1023–32.

Bruschi VM, Bonachea J, Remondo J, Rivas V, Gómez J, Salas L, et al. Existe un cambio geomorfológico global acoplado a la actividad económica? In: Cendrero A, Gómez J, Fernández PL, Quindós L, Ródenas C, Saiz C, editors. Contribuciones científicas en memoria del Profesor Jesús Soto. Santander: Ediciones de la Universidad de Cantabria; 2008. p. 31–54.

Cavallotto JL. Evolución holocena de la llanura costera del margen sur del Río de la Plata. Rev Asoc Geol Argent 2002;57(4):376–88.

Cavallotto J.L. Morfología y dinámica sedimentaria del Río de la Plata. Informe Final de Beca de Estudio. C.I.C-S.H.N. Buenos Aires, 1988, 87 pp.

Cavallotto JL, Violante RA, Colombo F. Evolución y cambios ambientales de la llanura costera de la cabecera del Río de la Plata. Rev Asoc Geol Argent 2005;60(2): 353–67.

Cearreta A, Alday M, Irabien MJ, Etxebarría N, Gómez J. Modern conditions and recent environmental development in the Muskiz estuary; historical disturbance by the largest oil refinery in Spain. J Iberian Geol 2008;34(2):191–203.

Cendrero A, Díaz de Terán JR, González D, Mascitti V, Rotondaro R, Tecchi R. Environmental diagnosis for planning and Management in the high Andean region: the Biosphere Reserve of Pozuelos, Argentina. Environ Manage 1993;17(5):683–703.

Cendrero A. De la comprensión de la historia de la tierra al análisis y predicción de las interacciones entre seres humanos y medio natural. Madrid: Real Academia de Ciencias Exactas, Físicas y Naturales; 2003. p. 77.

Cendrero A, Douglas I. Earth surface processes, materials use and urban development; project aims and methodological approach. Abstracts with programs, GSA Annual Meeting, Denver: A-79; 1996.

Cendrero A, Remondo J, Rivas V. Influencia humana sobre los procesos geológicos superficiales; consecuencias ambientales. In: Naredo JM, Gutiérrez L, editors. La incidencia de la especie humana sobre la faz de la Tierra (1955–2005). Granada: Universidad de Granada - Fundación César Manrique; 2005. p. 261–306.

Cendrero A, Remondo J, Bonachea J, Rivas V, Soto J. Sensitivity of landscape evolution and geomorphic processes to direct and indirect human influence. Geogr Fis Geodin Quatern 2006;29:125–37.

Cisternas M, Araneda A, Martínez P, Pérez S. Effects of historical land use on sediment yield from a lacustrine watershed in central Chile. Earth Surf Proc Land 2001;26:63–76.

Collins AL, Walling DE, Leeks GJL. Use of the geochemical record preserved in floodplain deposits to reconstruct recent changes in river basin sediment sources. Geomorphology 1997;19:151–67.

Collischonn W. Simulação hidrológica em grandes bacias. Tese de doutorado, Instituto de Pesquisas Hidrológicas. Universidade Federal do Rio Grande do Sul, Porto Alegre; 2001. p. 194.

Coronel G, Menéndez A. Fisiografía e hidrología de la Cuenca del Plata. In: El cambio climático en la cuenca del Plata, Barros V, Clarke R, Silva-Díaz P, editors. Report of project SGP II 057: Trends in the hydrological cycle of the Plata basin: Raising awarenes and new tools for water management. Buenos Aires: CONICET; 2006. p. 49–64.

Costa JE. Effects of agriculture on erosion and sedimentation in the Piedemont Province, Maryland. Geol Soc Am Bull 1975;86:1281–6.

Cundy AB, Croudace IW, Cearreta A, Irabien MJ. Reconstructing historical pollution trends in heavily-modified, contaminated estuaries: studies from Bilbao, Southampton Water, Sicily and the Westerschelde. Appl Geochem 2003;18(2):311–25.

Cunha SB. O custo ambiental da hidrovia Paraguai-Paraná. Ciênc Hoje 1998;23(135): 74-135.

Da Silva JSV, de Abdon MM, Boock A, da Silva MP. Delimitation of the Brazilian Pantanal and its sub-regions. Braz J Agric Res 1998;33:1703–13.

Dantas-Ferreira M. Proposta de índice para processos erosivos acelerados a partir de levantamento e diagnóstico geológico-geotécnico de áreas degradadas. Tese de Doutorado. EESC/USP; 2008. p. 447.

Diniz GL, Fonseca M, Campelo Jr JH. Análise harmônica do regime de precipitação em duas localidades da baixada cuiabana. Biomatemática 2008;18:37–48.

Douglas I. Sediment transfer and siltation. In: Turner BL, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB, editors. The Earth as transformed by human action. Cambridge, U.K.: Cambridge University Press; 1990. p. 215–34.

Dunne T, Leopold LB. Water in environmental planning. N. York: Freeman; 1978.

El Banna MM, Frihy OM. Human-induced changes in the geomorphology of the northeastern coast of the Nile delta, Egypt. Geomorphology 2009;107:72–8.

EM-DAT. The OFDA/CRED International Disaster Database www.em-dat.net- Université Catholique de Louvain-Brussels, Belgium, 2005.

Ericson JP, Vörösmarty CJ, Dingman SL, Ward LG, Meybeck M. Effective sea-level rise and deltas: causes of change and human dimension implications. Global Planet Change 2005;50:63–82.

Eriksson MG, Sandgreen P. Mineral magnetic analyses of sediment cores recording recent soil erosion history in central Tanzania. Paleogeogr Paleoclimatol Palaeoecol 1999;152:365–83.

FAOSTAT. Food and Agriculture Organization of the United Nations, Statistical Databases 2007. http://apps.fao.org.

Fioro PR, Dematte JAM, Sparovek G. Cronologia e impato ambiental do uso da terra na Microbacia Hidrográfica do Ceveiro, em Piracicaba, SP. Pesqui Agropecuaria Bras 2000;35:671–9.

Forstall RL, Greene RP, Pick JB. Which are the largest? Why lists of major urban areas vary so greatly. Tijdschr Econo Soc Geogr 2009;100:277–96.

Forte LM, Cavallotto JL, Hurtado MA, Muntz D, Etcheverry R, Cendrero A. Las ciudades como escenario del cambio geomorfológico global; comparación de la evolución histórica del Gran Buenos Aires y el delta subaéreo del Paraná. Actas XVII Congreso Geológico Argentino, Jujuy; 2008. p. 467–8.

Fuller CC, van Geen A, Baskaran M, Anima R. Sediment chronology in San Francisco Bay, California, defined by 210Pb, 234Th, 137Cs and 239, 240Pu. Mar Chem 1999;64(1–2): 7-27.

Galdino S, Clake RT, Padovani CR, Soriano BMA, Vieira LM. Evolução do regime hidrológico na planície do baixo curso do rio taquari-Pantanal. Anais do XII Simpósio Brasileiro de Recursos Hídricos. Vitória: ES; 1997. p. 383–90.

Gamage N, Smakhtin V. Do river deltas in east India retreat? A case of the Krishna Delta. Geomorphology 2009;103:533–40.

Gámez D, Vázquez-Suñé E, Simó JA, Salvany JM, Carrera J. Variación de las tasas de sedimentación en el Complejo Detrítico Superior del Delta del Llobregat (Barcelona): su relación con causas eustáticas, climáticas y antrópicas. Geogaceta 2005;38:175–8.

Gaviño-Novillo M. Bermejo River Basin Case Study. UNESCO-IHP, (ISI - LAC). Document prepared by ISI LAC, 1º Fieldtrip - ISI Scientific Advisory Committee (SAC), Buenos Aires 2007. In http://www.irtces.org/isi/isi.

Gelen A, Soto J, Gómez J, Díaz O. Sediment dating of Santander Bay, Spain. J Radioanalytical Nucl Chem 2004;261:437–41.

Gellis AC, Ellevein A, Aby S, Pavich MJ, Bierman PR, Clapp EM. Modern sediment yield compared to geologic rates of sediment production in a semi-arid basin; New

Mexico: assessing the human impact. Earth Surf Proc Land 2004;28(11): 1359–72.

Gil-Montero R. Población, medio ambiente y economía en la Puna de Jujuy, Argentina, siglo XIX-XX. Rev Demogr Hist 2004:185–208 XXII-I.

Glade T. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 2003;51(1):97-314.

Godoy JM, Padovani CR, Guimarães JRD, Pereira JCA, Vieira LM, Carvalho ZL, et al. Evaluation of the siltation of River Taquari, Pantanal, Brazil, through ^{210}Pb geochronology of floodplain lake sediments. J Braz Chem Soc 2002;13(1):71–7.

Goudie A. Human influence in geomorphology. Geomorphology 1993;7:37–59.

Goudie A. The changing Earth. Rates of geomorphological processes. Oxford: Blackwell; 1995.

Grau A, Brown AD. Development threats to biodiversity and opportunities for conservation in the mountain ranges of the upper Bermejo River Basin, NW Argentina and SW Bolivia. AMBIO J Hum Environ 2000;29:445–50.

Guzzetti F, Tonelli G. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. Nat Hazards Earth Syst Sci 2004;4:213–32.

Halcrow SW. Estudio de Regulación del Valle Aluvial de los ríos Paraná y Uruguay para el Control de las Inundaciones. Anexo B: Hidrología. Covenio S.W. Halcrow-Facultad de Ingeniería y Ciencias Hídricas. Santa Fé, Argentina: Universidad Nacional del Litoral; 1994. Technical Report.

Hany FE. Corumbá, Pantanal de Mato Grosso do Sul: periferia ou espaço central? Rio de Janeiro, Programa de Mestrado em Estudos populacionais e Pesquisas Sociais, Escola Nacional de Ciências Estatísticas - ENCE, IBGE; 2005. 149 pp.

Historical Statistics for the World Economy. Groningen Growth and Development Centre, University of Groningen 2006. http://www.ggdc.net/.

Hooke RL. On the efficacy of humans as geomorphic agents. GSA Today 1994;4(9): 224–5.

Hooke RL. Spatial distribution of human geomorphic activity in the United States: comparison with rivers. Earth Surf Proc Land 1999;24:687–92.

Hovius N. Controls on sediment supply by large rivers. In: Shanley KW, McCabe DJ, editors. Relative role of eustasy, climate and tectonics in continental rocks. TucsonSoc Econ Paleont Mineral; 1998. p. 3-16.

Huh CA, Chen HY. History of lead pollution recorded in East China sediments. Mar Pollut Bull 1999;38(7):545–9.

IBGE (Instituto Brasileiro de Geografia e Estatística) http://www.ibge.gov.br.

IPCC. Climate change 2001: the scientific basis. Cambridge: Cambridge University Press; 2001.

IPCC. Climate change 2007: synthesis report. Cambridge: Cambridge University Press; 2007.

Irabien MJ, Velasco F. Heavy metals in Oka river sediments (Urdaibai National Reserve, northern Spain): lithogenic and anthropogenic effects. Environ Geol 1999;37:54–63.

Irabien MJ, Cearreta A, Leorri E, Gómez J, Viguri JA. A 130-years record of pollution in the Suances estuary (southern Bay of Biscay); implications for environmental management. Mar Pollut Bull 2008a;56:1719–27.

Irabien MJ, Rada M, Gómez J, Soto J, Mañanes A, Viguri JA. An assessment of anthropogenic impact in a Nature Reserve. The Santoña marshes, northern Spain. J Iberian Geol 2008b;34(2):235–42.

Iriondo M. Estratigrafía del Cuaternario de la cuenca del Uruguay. XIII Congreso Geológico Argentino. Actas IV, Buenos Aires; 1996. p. 15–25.

Iriondo M. Características geológicas y geomorfológicas. In: Tomo I, Schreider M, Paoli Cy, editors. El río Paraná en su tramo medio. Contribución al conocimiento y prácticas ingenieriles en un gran río de llanura. Santa Fe, Argentina: Universidad Nacional del Litoral987-508-121-3; 2000.

Iriondo M. El Complejo Litoral en la desembocadura del río Paraná. In: de Barrio, Etcheverry, Caballé, Llambías, editors. Relatorio del XVI Congreso Geológico Argentino: "Geología y Recursos Minerales de la Provincia de Buenos Aires" (cap. XV), La Plata; 2005. p. 255–64.

Isquierdo SW. Análise integrada da sub-bacia da lagoa Negra - MS: um ensaio de cartografia temática com aplicação do SIG. Dissertação (Mestrado em Geografia Física)-Departamento de Geografia, Universidade de São Paulo. São Paulo; 1997. 171 pp.

Izquierdo AE, Grau HR. Agriculture adjustment, land-use transition and protected areas in Northwestern Argentina. J Environ Manage 2009;90:858–65.

Judson S. Erosion of the land, what's happening to our continents? In: Tank RW, editor. Environmental geology. New York: Oxford Univ. Press; 1983. p. 184–97.

Kasai M, Brierly GJ, Page MJ, Marutani T, Trustrum NA. Impacts of land use change on patterns of sediment flux in Weraamaia catchment, New Zealand. Catena 2005;64 (1):27–60.

Keesstra SD, van Huissteden J, Vandenberghe J, Van Dam O, de Gier J, Pleizier ID. Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes. Geomorphology 2005;69:191–207.

Knox J. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. Catena 2001;42(2–4):193–224.

Koide M, Bruland K, Goldberg ED. Th-238/Th-232 and Pb-210 geochronologies in marine and lake sediments. Geochim Cosmochim Acta 1973;37:1171–87.

Kotarba A, Lokas E, Wachniew P. Pb-210 dating of young Holocene sediments in high-mountain lakes of the Tatra Mountains. Geochronometria 2002;21:73–8.

Krepper CM, García NO. Spatial and temporal structures of trends and interannual variability of precipitations over the La Plata Basin. Quatern Int 2004;114:11–21.

Lambin EF, Geist HJ, editors. Land-use and land-cover change: local processes and global impacts. Berlin: Springer-Verlag; 2006.

Lang A. Phases of soil erosion-derived colluviation in the loess hills of south Germany. Catena 2003;51:209–21.

Latrubesse EM, Stevaux JC, Sinha R. Tropical rivers. Geomorphology 2005;70(3–4): 187–206.

Latrubesse EM, Amsler ML, de Morais RP, Aquino S. The geomorphological response of a large pristine alluvial river to tremendous deforestation in the South American Tropics: the case of the Araguaia River. Geomorphology 2009;113:239–52.

Lespez L. Geomorphic responses to long-term land use changes in eastern Macedonia (Greece). Catena 2003;51:181–208.

Liverman DM, Roman-Cuesta RM. Human interactions with the earth system: people and pixels revisited. Earth Surf Proc Land 2008;33:1458–71.

Lu XX. Spatial variability and temporal change of water discharge and sediment flux in the Lower Jinsha tributary: impact of environment changes. River Res Appl 2005;21 (2–3):229–43.

Macaire JJ, Bellemlih S, Di Giovanni C, De Luca P, Visset L, Bernard J. Sediment yield and storage variations in the Négron river catchment (South western parisian basin, France) during the Holocene period. Earth Surf Proc Land 2002;27:991-1009.

Marsh GP. The Earth as modified by human action (a new edition of Man and Nature). New York: Scribner, Armstrong & Co; 1877.

Meade RH, Parker R. Sediment in rivers of the United States. National Water Summary 1984. USGS Water-Supply PaperWashington: U.S. Geological Survey; 1985. p. 49–60.

Meade RH, Yuzuk TR, Day TJ. Movement and storage of sediment in rivers of the United States and Canada. In: Wolman MG, Riggs HC, editors. Surface water hydrology. The Geology of North AmericaColorado: Geological Society of America Boulder; 1990. p. 255–80.

Menéndez A. Tendencias hidrológicas en la cuenca del Plata. In: Barros V, Clarke R, Silva Días P, editors. El Cambio Climático en la cuenca del Plata, Proyecto SGPII 057: Trends in the hidrological cycle of the Plata basin: Raising awareness and new tools for water management. Buenos Aires: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); 2006.

Milliman JH, Meade RH. World-wide delivery of river sediment to the oceans. J Geol 1983;91:1-21.

Milliman JH, Syvitski JPM. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J Geol 1992;100:325–44.

Mobarek IE. The Nile Delta coastal protection project. Proceedings of the 13th ASCE Coastal Engineering Conference 1972. Vancouver, Canada; 1972. p. 1409–26.

Munich Re http://www.munichre.com/ 2005.

La incidencia de la especie humana sobre la faz de la tierra (1955–2005). In: Naredo JM, Gutiérrez L, editors. Colección Economía y Naturaleza. Universidad de Granada - Fundación César Manrique; 2005.

OAS-UNEP. Organization of American States. Office for Sustainable Development and Environment, UNEP. Water Project Series, Number 1. Bermejo River Basin. Implementation of the Strategic Action Programme for the Binational Basin of the Bermejo River 2005. In http://www.cbbermejo.org.ar.

OEA. Organización de Estados Americanos. Cuenca del Río de La Plata. Estudio para su planificación y desarrollo. Inventario de la información básica sobre recursos naturales. Organización de los Estados Americanos; Oficina de Desarrollo Regional; Unidad de Recursos Naturales, 1971. Washington, D.C.

Ottonello M, Reinoso G, Ruthsatz B. Environment, human settlement and agriculture in the Puna de Jujuy, Argentina; a case study of land change. Mt Res Dev 1982;2(1):111–26.

Owens PN, Walling DE. Changes in sediment sources and floodplain deposition rates in the catchment of the river Tweed, Scotland, over the last 100 years: the impact of climate and land use change. Earth Surf Proc Land 2002;27:403–23.

Owens PN, Walling DE, Leeks GJL. Use of floodplain sediment cores to investigate recent historical changes in overbank sedimentation rates and sediment sources in the catchment of the river Ouse, Yorkshire, U.K. Catena 1999;36:21–47.

Paoli C, Cacik P. Régimen de crecida y análisis de caudales máximos. In: Paoli C, Schneider M, editors. El río Paraná en su tramo medio. Santa Fé, Argentina: Centro de Publicaciones de la Universidad Nacional del Litoral; 2000. p. 109–71.

PCBAP. Plano de Conservação da Bacia do Alto Paraguai. Ministério do Meio Ambiente, Programa Nacional do Meio Ambiente, Brasília, 1997.

Pérez-Arlucea M, Nombela M, Rubio B, Filgueira M, Méndez G, Clemente F. Hydrology, sediment yield, erosion and sedimentation rates in the estuarine environment of the Ría de Vigo, Galicia, Spain. J Mar Syst 2005;54(1–4):209–26.

Phippen SJ, Wohl E. An assessment of land use and other factors affecting sediment loads in the Rio Puerco watershed, New Mexico. Geomorphology 2003;52:269–87.

Poulos SE, Collins MB. Fluviative sediment fluxes to the Mediterranean Sea: a quantitative approach and the influence of dams. Geol Soc Lond 2002;191:227–45.

Prance GT, Schaller GB. Preliminary study of some vegetation types of the Pantanal, Mato Grosso, Brazil. Brittonia 1982;34(2):228–51.

Projeto Piracena 2001. www.cena.usp.br/piracena.

Ramos-Scharrón CE, MacDonald LH. Measurement and prediction of natural and anthropogenic sediment sources, St. John, U.S. Virgin Islands. Catena 2007;71:250–66.

Rawat JS, Rawat G, Rai SP. Impact of human activities on geomorphic processes in the Almora region, Central Himalaya, India. In: Slaymaker O, editor. Geomorphology, human activity and global environmental change. Chichester: Wiley; 2000. p. 285–99.

Remondo J, González-Díez A, Díaz de Terán JR, Cendrero A, Fabbri A, Chung CF. Validation of landslide susceptibility maps; examples and applications from a case study in northern Spain. Nat Hazards 2003;30:437–49.

Remondo J, Bonachea J, Cendrero A. Probabilistic landslide hazard and risk mapping on the basis of occurrence and damages in the recent past. In: Lacerda WA, Ehrlich M, Fontoura SA, Sayao ASF, editors. Landslides; evaluation and stabilization. New York: Balkema; 2004. p. 125–30.

Remondo J, Bonachea J, Cendrero A. Landslide risk modelling at basin scale; from susceptibility to quantitative risk assessment. Landslides 2005a;2:321–8.

Remondo J, González-Díez A, Soto J, Díaz de Terán JR, Cendrero A. Human impact on geomorphic processes and hazards in mountain areas. Geomorphology 2005b;66: 69–84.

Remondo J, Bonachea J, Cendrero A. Quantitative landslide risk assessment and mapping on the basis of recent occurrences. Geomorphology 2008;94:496–507.

Renwick WH, Carlson KJ, Hayes-Bohanan JK. Trends in recent reservoir sedimentation rates in Southwestern Ohio. J Soil Water Conserv 2005a;60(2):72–9.

Renwick WH, Smith SV, Bartley JD, Buddemeier RW. The role of impoundments in the sediment budget of the conterminous United States. Geomorphology 2005b;71: 99-111.

Ritchie JC, Finney VL, Oster KJ, Ritchie CA. Sediment deposition in the flood plain of Stemple Creek watershed, northern California. Geomorphology 2004;61:347–60.

Rivas V, Cendrero A, Hurtado M, Cabral M, Giménez J, Forte L, et al. Geomorphic consequences of urban development and mining activities; an analysis of study areas in Spain and Argentina. Geomorphology 2006;73(3–4):185–206.

Ródenas C, Gómez J, Soto J. Medida de ^{210}Pb para datación de sedimentos en estuarios. Rev Investig Pesque 2004;1E:1–6.

Rudorff B.F.T., Berka L.M.S., Moreira M.A., Duarte V., Rosa V.G.C. Estimativa de área plantada com cana-de-açúcar em municípios do estado de Sao Paulo por meio de imagens de satélites e técnicas de geoprocessamento: ano safra 2004/2005. INPE-11421-RPQ/762 2004. Sao Paulo, Brazil.

Ruiz-Fernández AC, Páez-Osuna F, Urrutia-Fucugauchi J, Preda M. ^{210}PB geochronology of sediment accumulation rates in Mexico City Metropolitan Zone as recorded at Espejo de los Lirios lake sediments. Catena 2005;61:31–48.

San Miguel EG, Bolívar JP, Garcia-Tenorio R. Vertical distribution of Th-isotope ratios, ^{210}Pb, ^{226}Ra and ^{137}Cs in sediment cores from an estuary affected by anthropogenic releases. Sci Total Environ 2004;318(1–3):143–57.

Sánchez-Cabeza JA, Ani-Ragolta I, Masqué P. Some considerations of the ^{210}Pb constant rate of supply (CRS) dating model. Limnol Oceanogr 2000;45(4):990–5.

Sarubbi A, Pittau MG, Menéndez AN. Delta del Paraná: avance del frente e incremento areal. INA. Proyecto LHA 235 Informe LHA 05-235-06, 2006.

Sarubbi A, Pittau M, Menéndez A. Delta del Paraná: Balance de Sedimentos. Informe LHA 02-235-04. INA. Buenos Aires, Argentina; 2004.

Saurral RI, Barros VR, Lettenmaier DP. Land use impact on the Uruguay River discharge. Geophys Res Lett 2008;35:L12401. doi:10.1029/2008GL033707.

Schmitt A, Dotterweich M, Schmidtchen G, Bork HR. Vineyards, hopgardens and recent afforestation: effects of late Holocene land use change on soil erosion in northern Bavaria, Germany. Catena 2003;51:241–54.

Shukla BS, Joshi SR. An evaluation of CIC model of Pb-210 dating sediments. Environ Geol Water Sci 1989;14(1):73–6.

Siakeu J, Oguchi T, Tatsuto A, Esaki Y, Jarvie HP. Change in riverine suspended sediment concentration in central Japan in response to late 20th century human activities. Catena 2004;55(2):231–54.

Slaymaker O, editor. Geomorphology, human activity and global environmental change. Chichester: Wiley; 2000.

Slaymaker O, Spencer T, Embleton-Hamann C, editors. Geomorphology and global environmental change. Cambridge: Cambridge U. Press; 2009.

Soto J, Gómez J, Viguri J, Cendrero A, Irabien MJ, Yusta I, et al. Increase of sedimentation rates in an estuarine system. Contrib Educ Environ Prot 2006;7:35–40.

Soto-Torres J, Soto-Velloso JA, Ródenas G, Gelen A, Díaz O, Viguri J, et al. Estimación de las tasas de erosión en torno a la bahía de Santander, España. Cienc Tierra Espacio 2007;7:1031–6.

Sparovek G, Schnug E. Temporal erosion-induced soil deghradation and yield loss. Soil Sci Am Soc 2001;65:1479–86.

Spencer T, Slaymaker O, Embleton-Hamann C. Landscape, landscape-scale processes and global environmental change: synthesis and new agendas for the twenty-first century. In: Slaymaker O, Spencer T, Embleton-Hamann C, editors. Geomorphology and global environmental change. Cambridge: Cambridge U. Press; 2009. p. 403–23.

Stevaux JC, Martins DP, Meurer M. Changes in a large regulated tropical river: the Paraná River downstream from the Porto Primavera Dam, Brazil. Geomorphology 2009. doi:10.1016/j.geomorph.2009.03.015.

Summerfield MA, editor. Geomorphology and global tectonics. Chichester: John Wiley; 2000.

Summerfield MA, Hulton NJ. Natural controls of fluvial denudation rates in world drainage basins. J Geophys Res 1994;99(B7):13871–83.

Syvitski JPM, Saito Y. Morphodynamics of deltas under the influence of humans. Global Planet Change 2007;57:261–82.

Syvitski JPM, Vörösmarty CJ, Kettner AJ, Green P. Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. Science 2005;308:376–80.

Thomas WL, editor. Man's role in changing the face of the Earth. Chicago: The University of Chicago Press; 1956.

Tucci CEM. Impactos da variabilidade climática e do uso do solo nos recursos hídricos. Brasília: Agência Nacional de Águas; 2002. p. 150.

Tucci CEM, Clarke RT. Environmental issues in the La Plata basin. Water Resour Dev 1998;14:157–74.

Turner II BL. Land change as a forcing function in global environmental change. In: Geist HJ, editor. Our Earth's changing land: an encyclopedia of land-use and land-cover change, vol 1. Westport: Greenwood Press; 2006.

Turner BL, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB, editors. The earth as transformed by human action. Cambridge: Cambridge University Press; 1990.

UNEP. GEO Yearbook 2004-05. United Nations Environment Program. Oxford: Oxford Univ. Press; 2005.

Varekamp JC. Trace element geochemistry and pollution history of mudflat and marsh sediments from the Connecticut coastline. J Coast Res 1991;S1-11:105–23.

Viglizzo EF, Frank FC. Land-use options for Del Plata basin in South America: tradeoffs analysis based on ecosystem service provision. Ecol Econ 2006;57:140–51.

Viguri JR, Irabien MJ, Yusta I, Soto J, Gómez J, Rodríguez P, et al. Physico-chemical and toxicological characterisation of the historic estuarine sediments; a multidisciplinary approach. Environ Int 2007;33:436–44.

Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM. Anthropogenic sediment retention: major global impact from registered river impoundments. Global Planet Change 2003;39:169–90.

Walling DE. Erosion and sediment yield in a changing environment. In: Branson J, Brown AG, Gregory KJ, editors. Global continental changes: the context of palaeohydrology, 115. Geological Society: Special Publication; 1996. p. 43–56.

Walling DE. Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology 2006;79:192–216.

Walling DE, Fang D. Recent trends in the suspended sediment loads of the world's rivers. Global Planet Change 2003;39:111–26.

Wang H, Yang Z, Saito Y, Liu JP, Sun X, Yang W. Stepwise decrease of the Huanghe (Yellow River) sediment load (1950–2005): impacts of climatic change and human activities. Global Planet Change 2007;57:331–54.

WCED World Commission on Environment and Development). Our common future. Oxford: Oxford Univ. Press; 1987.

Wolman MG, Schick AP. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Water Resour Res 1967;3(2):451–64.

Xu K, Milliman JD. Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three George Dam. Geomorphology 2009;104:276–83.

Zhang S, Lu XX, Higgitt DL, Cheng-Tung AC, Jingtai H, Huiguo S. Recent changes of water discharge and sediment load in the Zhujiang (Pearl River) Basin, China. Global Planet Change 2008;60:365–80.