ENSO impacts on Atlantic watersheds of South America

Impactos ENSO en cuencas atlánticas de Sudamérica

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ABSTRACT

Interannual changes in precipitation cause significant effects on the Pacific watersheds of South America. Large rivers flowing to the Atlantic Ocean as the Paraná and Uruguay are also influenced by ENSO-triggered floods causing significant impacts on the economies of Argentina, Brazil and Uruguay. At the same time, the floodplains of small rivers are also sensitive to strong ENSOs. Floods occur approximately simultaneously in subtropical watersheds of Brazil and high-latitude watersheds of North Patagonia. ENSO-triggered floods were recorded during the years 1941-42, 1982-83 and 1997-98. Several floods impacted along the Itajaí River affecting the higher (Blumenau city) and lower estuary (Itajaí city). The Guaiba River, at the headlands of Lagoa dos Patos, has repeatedly flooded Porto Alegre. At the Río de la Plata basin, significant increases in the discharges were assigned to the Paraná and the Uruguay rivers. The small basin of the Quequén Grande River without extended floodplains is subject to periodic failure of its margins. The Colorado River, the northern limit of Patagonia, is allochthonous and its watershed was artificial and progressively modified; the ENSO event of 1983 caused an increase in its salinity due to the sudden reactivation of the Desaguadero-Curacó system.

Keywords: floods; Atlantic rivers; Argentina; Brazil; Uruguay

RESUMEN

Los cambios interanuales en las precipitaciones causan significativos efectos en las cuencas pacíficas de Sudamérica. Los grandes ríos que fluyen hacia el Océano Atlántico como el Paraná y el Uruguay también son influenciados por estas inundaciones originadas por estos eventos ENSO causando significativos impactos en las economías de Argentina, Brasil y Uruguay. Asimismo, las planicies aluviales de los pequeños ríos también son sensibles a los ENSOs fuertes. Las crecidas ocurren casi simultáneamente en las cuencas subtropicales de Brasil como en las cuencas de altas latitudes de Patagonia. Inundaciones gavilladas por eventos ENSO fueron registradas en los años 1941-42, 1982-83 y 1997-98. Varias inundaciones afectaron al río Itajaí afectando las porciones más altas (Blumenau) y bajas del estuario (Itajaí). El río Guaíba, en las cabeceras de la Lagoa dos Patos, ha repetidamente inundado Porto Alegre. En la cuenca del Río de la Plata, incrementos significativos de su descarga fueron originados por los ríos Paraná y Uruguay. La pequeña cuenca del río Quequén Grande sin grandes planicies aluviales está sujeta a periódicos derrumbes de sus albardones. El río Colorado, límite norte de la Patagonia, es alóctono y su cuenca fue progresiva y artificialmente modificada; el ENSO de 1983 causó un aumento de su salinidad debido a la súbita reactivación del sistema Desaguadero-Curacó.

Palabras clave: inundaciones; ríos del Atlántico; Argentina; Brasil; Uruguay

1. Introduction

The International Geosphere-Biosphere Programme (IGBP) proposed to map the global land cover at a resolution of 1 km (Data and Information System, IGBP DIS) in order to estimate global fluvial discharges, and assuming similar annual discharges. However this last assumption is invalid for much rivers of South America. The distribution of annual rainfall has significant spatial and temporal variability either on the Pacific and Atlantic coasts. Some special atmospheric phenomena for this region are key determinants of climate variability in terms of temperature and precipitation. Among the most important, the passage of frontal systems in the region and the recurrence of El Niño-Southern Oscillation (ENSO) cycles account for a large proportion of total rainfall recorded, and producing direct effects on some basins (Isla *et al.* 2003, Bello *et al.* 2004, Compagnucci & Araneo 2007). Climate and land-use changes have also significant effects on floodplains colonised by agriculture (Wasson 1996). In this sense, it was estimated that 20% of global particulate river sediment is trapped in large reservoirs (Syvitski *et al.* 2005), but additional 23% is trapped in small dams (Vörösmarty *et al.* 2003). Some South American watersheds, comprising large areas extending from the Andes Cordillera towards the Atlantic Ocean, were physically affected even at estuarine areas and causing anomalous sea-level variations (Isla 2008). During January 2011, floods in Brazil have caused more than 800 deceases in small watersheds. Some of these impacts occurred by the urbanization of floodplains of small watersheds within Serra do Mar as the Panquequer River (Vieira & da Cunha 2008) or the small rivers surrounding Petrópolis (Palatinado, Quitandinha e Piabanha; Guerra *et al.* 2007).

These effects have significant correlation to climate variability. Not withstanding the interannual frequency of 3.5-6 years, there are increases in annual precipitation between 1950 and 1984 of rivers contributing to the Paraná River basin (Paraguay, Tieté, Pilcomayo and Bermejo; García *et al.* 2010). Climates of Southern Hemisphere and particularly in South America have not yet received much attention although they have demonstrated high variability (Neukom & Luterbacher 2011). The discharge of the Paraná River was correlated to cycles related to the motion of the Sun around the barycentre of the Solar System (Antico & Krohling 2011).

This paper is a first complete report about the long-term records of fluvial discharges of six major rivers of temperate South America to evaluate their hydrological response to the ENSO signal. These watersheds are very different in their extension (figure 1).

2. Methods

Monthly mean river discharges were compiled from different national agencies of Argentina and Brazil, and analyzed in order to identify former ENSO events (table 1).

The records spanned from southern Brazil to northern Patagonia considering specified ENSO years as 1941-1942, 1982-1983 and 1997-1998. Monthly discharges were selected as best records of their seasonal response than annual means. In some watersheds where dams have been constructed (Paraná, Uruguay, Colorado), only the discharge stations more distant from reservoirs were selected for the analysis in order to avoid temporal effects of reservoir storage. A Geographic Information System (Arc View) was used to select these stations and to interpret basin behaviours.

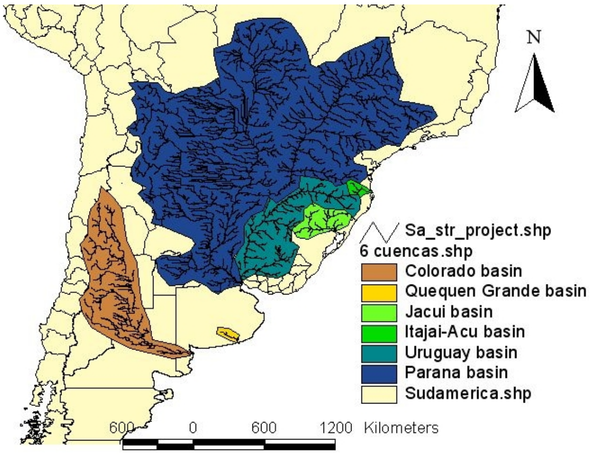

Figure 1: Location of Atlantic Mid-latitude watersheds (Itajaí-Açú, Jacuí, Uruguay, *Paraná, Quequén Grande and Colorado basins).*

Table 1: Maximum, mean and minimum discharges in m^3/s of the Itajaí-Açu, Jacuí, Uruguay, Paraná, Quequén Grande and Colorado rivers.

River at station, country	Qmax	Q mean	Qmin	Period	Reference
Itajaí-Açu at Blumenau, Bra	1000	228	80	1940-2003	Schettini & Toldo 2006
Jacuí at Pardo, Bra	7030	801	110	1940-2006	Vaz *et al.* 2006
Uruguay at Paso de los Libres, Arg	9484	4315	650	1909-2003	Evarsa 2006
Paraná at Timbres, Arg	20,905	15,306	9,577	1906-2004	Evarsa 2006
Quequén Grande at Quequén, Arg	1700	16	1.6	1986-2000	Teruggi *et al.* 2005
Colorado at Pichi Mahuida, Arg	252	131	40	1919-2004	Evarsa 2006

3. Results

Monthly records were analyzed in relation to history of the watershed and ENSO-triggered hydrological responses.

3.1. The Itajaí-Açu watershed

The Itajaí-Açú River is located 100 km north of the city of Florianópolis, Brazilian state of Santa Catarina (figure 1). It has a drainage basin of 15,500 km^2. Its lower estuary morphology is very simple, being a meandering river, with marine influences extending 7 km upstream from the estuary. The middle estuary extends from the mouth to about 30 km upstream, with high salt stratification; the upper estuary extends up to 70 km from the mouth, where only tidal fluctuations are recorded. The lower and middle portion of this estuary was defined as a highly stratified/salt-wedge type (Schettini & Toldo 2006). The tidal regime is mixed with semi-diurnal dominance. Mean tidal range is about 0.7 m, varying from 0.4 to 1.2 m during neap and spring tidal periods, respectively. During periods of low discharge, tidal effects are found 70 km upstream, and behave synchronously as far as 55 km upstream. Storm surges play an important role and can reach up to 1 m height during the passage of cold fronts. Mean discharge is 228 ± 282 m^3s^{-1}, without any significant seasonal pattern. The discharge is predominantly low but with some peaks greater than 1,000 m^3/s, although in some years conditions typical of the tropics occur giving mean discharge of about 500 m^3/s during the summer (Schettini & Toldo 2006). The flow gauge at Blumenau (26º55'05"S; 49º03'55"W), 12 m above mean sea level (MSL), recorded floods in 1953, 1966 and 1984. The ENSO events of 1982-83 and 1997 also affected the basin but were less marked (figure 2a). However, the 1983 flood was strongly recorded at the Ituporanga flow gauge (27º23'55"S; 49º36'21"W).

3.2. The Jacuí River watershed

The Lagoa dos Patos is a large, shallow coastal lagoon fed by several rivers (Jacuí, Camaquá, Gravataí, Sinos, Sao Lourenço). The area of its watershed is estimated at 170,000 km^2 (Toldo *et al.* 2006). The lagoon has an area of 10,145 km^2, a mean depth of 6 m, and it receives large quantities of fresh water, although salinities of 3 psu are very common; residence time is about 108 days (Toldo *et al.* 2006). The Jacuí River originates in Passo Fundo and meets this large coastal lagoon at the neighborhood of Porto Alegre (Vaz *et al.* 2006) in a water body called the Guaiba Lake, with area 470 km^2. In May 1941, the Jacuí River was delivering 7030 m^3/s into this lake and the city of Porto Alegre was severely flooded (figure 2b). The Guaíba Lake level rose 4.5 m above normal, higher than the former floods of 1873 (3.5 m) and 1936 (3.22 m), and resulted in the construction of a protecting wall between the harbour area and the city centre and the formation of a series of polders along the lower Gravataí River (Menegat 2006).

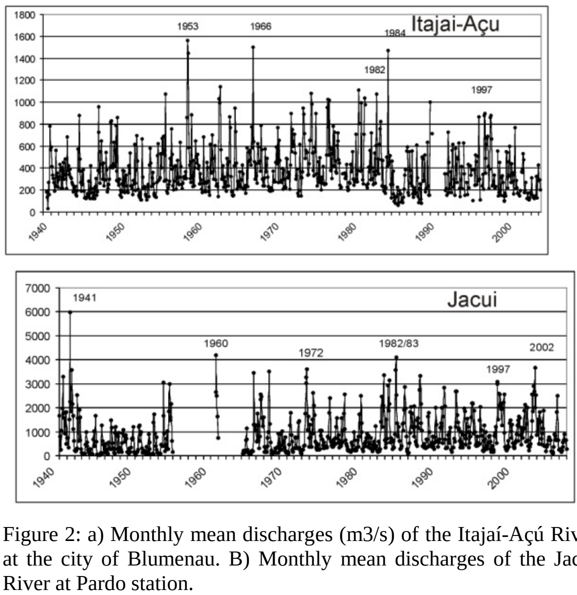

Figure 2: a) Monthly mean discharges (m3/s) of the Itajaí-Açú River at the city of Blumenau. B) Monthly mean discharges of the Jacuí River at Pardo station.

Floods were also recorded in 1941, 1960, 1972, 1982/83, 1997 and 2002 at the Pardo station (figure 2b) which is located (29º59'S; 52º22'W) at an altitude of 3 m above MSL; high discharges occurred usually in winter (July to August; Vaz *et al.* 2006). The Sao Jerónimo discharge station has a longer record (1928-2008) but with more gaps; however, this station clearly recorded the floods of 1928, 1941, 1965 and 1982-83. During the evaluation of this paper, the contribution of the Jacuí River to the Patos coastal-lagoon complex (involving Mirim and Mangueira lagoons) were also related to the precipitations in Porto Alegre, and analysed mathematically in terms of harmonics (Pasquini *et al.* 2012).

3.3. The Uruguay River watershed

The Uruguay River crosses the Brazilian state of Rio Grande do Sul and forms the boundary between Uruguay and Argentina (figure 3a). It discharges with the Paraná River to the Río de la Plata after a narrow delta at Concepción del Uruguay. The Argentine Ministry of Public Works has measured its discharge since 1909 at Paso de los Libres (29º44'S; 57º05'W; 40 m above MSL). This station has a mean flow of 4315 m^3/s (Evarsa 2006) with high discharges during winter and spring and a peak discharge in November. The largest discharges were recorded in 1941, 1983 and 1997-98 (Nagy *et al.* 1998). Using data from several discharge stations in this basin, and an 11-year moving average, two interannual cycles of 6 and 3.5 years were discriminated (Krepper *et al.* 2003). Harmonic analysis shows a dry period during the 1950-1960 decade, recorded also at the Paraná watershed (Collischonn *et al.* 2001, Krepper *et al.* 2003).

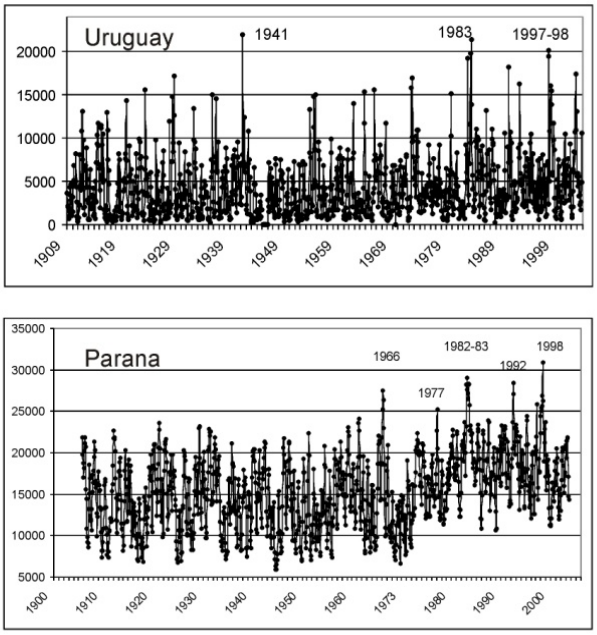

Figure 3: a) Monthly discharge of the Uruguay River at Paso de los Libres (29º44'S; 57º05'W). b) Monthly discharge of the Paraná River at Timbúes (32º39'30"S; 60º43'50"W).

3.4. The Paraná River watershed

The Paraná-Rio de la Plata system comprises a basin of 2.6 million km^2 and includes areas of Brazil, Paraguay, Bolivia, Argentina and Uruguay (figure 1; Depetris & Kempe 1990, Depetris *et al.* 1996) with an annual sediment load of about 150 million of tons (Orfeo & Steveaux 2002). The watershed discharges water precipitated both in the very high mountains and plateaus of Bolivia, and the lower hills of Serra do Mar (Brazilian states of Sao Paulo, Mato Grosso de Sul and Paraná). During the last decades, the upper Paraná and Paraguay rivers increased their discharges to the middle and lower Paraná; the contribution of the Paraguay River is increasing at a higher rate than the upper Paraná (Pasquini & Depetris 2010). This watershed has been altered by two large dams: Itaipú and Yaciretá-Apipé. The last one has signified significant effects at the level of the wetlands of Iberá (Canziani *et al.* 2006). However, significant changes in the watershed were assigned also to very modern tectonics and Quaternary climatic changes (Fortes *et al.* 2005). Some changes in the Upper Paraná were assigned to the reactivation of former faults (Fulfaro *et al.* 2005). Even the flood plains of the Upper Valley are dominated by sand (Santos 2005). The Upper Tieté River drains most of the Sao Paulo Metropolitan Region. This urban area occupied 190 km^2 in 1930 and in 2001 multiplied to 1900 km^2 causing significant floods in 1924, 1983, 1991 and 2005 (Steveaux *et al.* 2010). The urbanization of this upper valley implies several channelizations that rectified the meandering floodplain (Steveaux *et al.* 2010). In the Paraguay River, an anomalous dry period occurred during the 1960-1970 decade. This was not related to an ENSO signal but was found to correspond to other anomalies of the Congo River (Collischonn *et al.* 2001). Much of the suspended sediment transported to the Paraná basin originates from the Bermejo River (Drago & Amsler 1988).

Maximum discharge in the Río de la Plata can increase significantly during anomalous years, being a cause of severe natural disasters (Centro Estudios Sociales y Ambientales 2004). A statistical analysis disregarding its seasonal behavior, confirmed that the 1982-83 floods were the largest of the 1904-2004 period (Depetris 2007). These interannual effects can occur both in estuarine areas (Pousa *et al.* 2006, Meccia *et al.* 2009) and on the continental shelf (Piola *et al.* 2005). In the Paraná watershed, the ENSO-triggered flood volume of 1982-83 summed 547,000 hm^3 for the period October-March (figure 3b).

For the same period, the floods of 1992-93 yielded a total of 390,000 hm^3. During the floods of 1997-98, the flood volume was 431,000 hm^3 (Centro de Estudios Sociales y Ambientales 2004). Teleconnections between Buenos Aires sea level and the ENSO signal was already recognized considering a time lag of 5 months (Raicich 2005). At the Timbúes station (32º39'30"S; 60º43'50"W; 4 m above MSL) mean discharge is 15,306 m^{3}s^{-1}; high discharges occurs during autumn (March to May). It is more than 600 km from the nearest dam sited on the Paraná River (Yaciretá). Five major floods were recorded in this station in the last 40 years (figure 3b). The record indicates the floods were more significant since the late sixties, and that the Paraná had also experienced the low discharges in the decade 1960-1970 reported for the Paraguay River (Collischonn *et al.* 2001). Significant changes in land use (deforestation) within the basin can account for these ENSO-triggered floods.

3.5. The Quequén Grande River watershed

The Quequén Grande River is a small basin of 9,940 km^2 with an average discharge of only 16 m^{3}s^{-1} (Teruggi *et al.* 2005) and is free from impoundments. The watershed has its headlands in the Tandilia Range, and drains a plain dominated by silt with caliche indurated levels. From sedimentologic and geomorphological evidences, some creeks of the basin became non-operative as the Quequén River captured their upper watersheds increasing its depth towards the lower valley (Cortizo & Isla 2000, Isla *et al.* 2005). The river discharges into a meso-tidal estuary between the cities of Quequén and Necochea.

Two floods were recorded in recent years: 1986-87 and 1998 (figure 4a). The maximum discharge of the Quequén Grande River was 100 times greater than mean discharge. The floods of April 21-24, 1980 caused the collapse of the bridge between Quequén and Necochea cities.

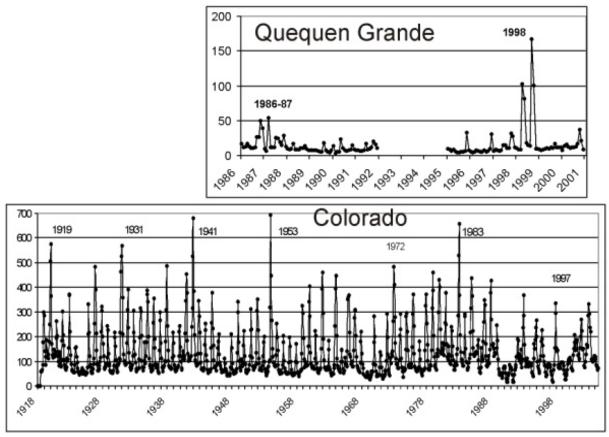

Figure 4: a) Monthly discharges of the Quequén Grande River at Quequén. B) Monthly discharges of the Colorado River at Pichi Mahuida (38º49'18"S; 64º58'43"W). In 1989, the reservoir of Casa de Piedra was still filling. The floods of 1997 were also recorded although without the influence of the Desaguadero-Curacó system.

3.6. The Colorado River watershed

The Colorado River originates in the Andes Cordillera from the joining of the Barrancas and Grande rivers at 834 m above mean sea level (MSL). Today, the watershed area is 34.000 km^2 (Blasi 1986), but historically it was significantly greater when the Colorado received overflows from the rivers Vinchina, Bermejo, Mendoza, Tunuyán, Diamante,Atuel, Desaguadero, Salado, Chadileuvú and Curacó (figure 1; Tapia 1935, Spalletti & Isla 2003). Dam construction on the rivers Jachal, San Juan, Mendoza, Diamante and Atuel reduced their contributions to the Desaguadero and Curacó rivers (Grondona1975). High inputs of water from the Andes have induced high levels of the Bebedero salt lake from the Upper Pleistocene to the recent past (González & Maidana 1998). During the XX century, some channels were dug (1920, 1928 and 1950) close to the delta to drain 90,000 hectares (Hernández & Levin 1985, Spalletti & Isla 2003).

The station at Pichi Mahuida (38º49'18"S; 64º58'53"W; 122 m above MSL) is about 210 km from the dam at Casa de Piedra. It has a mean discharge of 130.70 m^3s^{-1}; maximum discharges occur during the summer (November to January). Six major floods have been recorded on this river, in 1919, 1931, 1941, 1953, 1972 and 1983 (figure 4b). The Casa de Piedra dam was begun in 1983 and six years later the reservoir was completely flooded. In 1984 the excess water delivered by the Desaguadero-Curacó system to the Colorado was estimated to be in the ratio 72/28 (Colorado/Curacó) and this therefore explains the episodic increase in salinity of the Colorado River (Hernández & Levin 1985).

4. Discussion

In the last years, ENSO phenomena affected significantly and almost simultaneously Western and Eastern South America. Anomalous monthly rainfalls were also recorded in Rocha, Uruguay, in 1941, 1959, 1986 and 1998 and recorded in the sediments of the Blanca shallow lake (García-Rodríguez *et al.* 2002). Interannual precipitation variability associated with ENSOs had different consequences for soybean yields depending on crop growth-stage (Podestá *et al.* 1999, Peñalba *et al.* 2007). Some basins without discharge to the ocean in Central Argentina, located in the Arid South American Diagonal, are particularly subject to water excesses delivered during ENSOs (Isla *et al.* 2003). The Caribbean and Pacific deltas of Colombia were also particularly affected by ENSO phenomena (Restrepo & López 2008). Interannual sea-level changes in the South China Sea were also assigned to ENSO effects (Rong *et al.* 2007).

ENSO floods affect the fish communities at low-lying plains of eastern South America.

During high discharges of the Lagoa dos Patos, migratory fishes could not enter the estuary due to the persistent ebb flow (Schroeder & Castello 2010). In the low-relief area of the Salado Basin, Buenos Aires Province, recent floods produced significant changes in the pond dynamics with significant effects on the fish communities (Rosso 2008, Rosso & Quirós 2008).

The floods of 1941-42 were recorded simultaneously in the watersheds of the Jacuí, Uruguay and Colorado rivers, but was not observed in the Paraná River. The more recent ENSO-triggered floods of 1982-1983 and 1997-98 caused severe consequences in some cities (figure 5a) and severe damages to their facilities (figure 5b). Dealing about sediment fluxes, although they were globally estimated based on annual estimations of large rivers (Wilkinson & McElroy 2007), little efforts were paid to the temporal variations in river loads (Syvitski *et al.* 2005). Only in Brazil, an inventory of fluvial sediment production orientated to forecast the operability of hydroelectric reservoirs (Campagnoli 2006). At the same time, there is a lack of future projections about water scarcity in South America (Revenga 2005), and these annual variations mean an extra effort for good estimations. Although ENSOs have been more frequent and intense in the last years, they were smaller in amplitude and less frequent during the mid-Holocene in South America (Clement *et al.* 2000).

Figure 5: a) Blumenau is a city dominated by German immigrants into the Santa Catarina State of Brazil. It was flooded during the ENSO of 1982-1983. Both benchmarks close to the top of this house indicate the level reached during the maximum flood. To improve the economy, the citizens obtained permission to held annually the Oktoberfest festival. Every October is a reminder of the ENSO of 1983. b) The floods of 1980 (April 21-24) caused the collapse of one of the bridges of the Quequén Grande River between Quequén and Necochea cities.

5. Conclusions

1. The six basins considered, Itajaí-Açu, Jacuí, Uruguay, Paraná, Quequén Grande and Colorado, extending from 26 to 38° S, have been critically affected by floods delivered by strong ENSO phenomena in the last years. The most significant floods were recorded in 1941-42, 1982-83 and 1997-1998.

2. Most the impacts were caused by the urbanization of floodplains and channelisation of former meandering reaches.
3. In the Colorado River, the 1983 flood caused the temporal reactivation of the Desaguadero-Curacó system, causing an increase in the salt content towards the inlet.

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