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Avulsive Rivers in the Hydrology
of the Pantanal Wetland

**Mario Luis Assine, Hudson Azevedo Macedo, José Cândido Stevaux,
Ivan Bergier, Carlos Roberto Padovani, and Aguinaldo Silva**

Abstract This chapter presents and discusses the avulsive nature of the Pantanal rivers and shows how the ever-changing drainage network influences the surface hydrology and ecology. Besides, the systemic portrait here outlined provides new insights concerning the Pantanal hydrodynamics, in its particularities and as a whole system. A simple model of the avulsion process is illustrated, and several realistic examples of the processes leading to river avulsions are shown and discussed. The north-to-south flood-pulse wave due to the presence of bottlenecks is further described in detail. This systemic approach allows identifying that the fluvial "avulsive and bottleneck" dynamics seasonally affects both local and regional ecohydrological processes. Moreover, it shows that avulsive processes are commonplace in Pantanal, and changes in land use, particularly in river headwaters in the highlands, accelerate the avulsions, making the sustainable use of the Pantanal lowland areas difficult.

Keywords Flood dynamics, Fluvial avulsion, Fluvial bottlenecks, Fluvial megafans, Multichannel systems

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Contents

1   Introduction

The Pantanal wetland is located in the middle of South America in the upper portion of the La Plata Basin, where seasonal changes in rainfall largely control the annual flood pulse of river floodplains [1]. Inter-annual and inter-decadal fluctuations in intensity, duration, and magnitude of the flood pulse are modulated by global-scale phenomena as the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ) [2–5]. The convergence of airflows into the ITCZ overrides the opposite effects of wind patterns known as easterlies [6]. Rainfall quantity and distribution are usually affected by changes in sea surface temperature [7], which in turn influences the South American Monsoon System [8, 9].

The annual movement of the overhead sun causes the ITCZ to migrate northerly and southerly throughout the year, which affects wet climates in tropical latitudes. The Subtropical Atlantic Anticyclone shifts from S30° northward in the summer and produces NE-to-NW winds which push the continental equatorial air mass toward the Upper Paraguay Basin. Because of this phenomenon, the Pantanal region has a typical wet-dry climate whose rainfall regime is the most important climatic variable [10, 11]. Although temperature range can seasonally vary from $-1°C$ to $41°C$, the seasonal mean temperature is virtually constant and ranges between $20°C$ in July and $27°C$ in December, whereas rainfall is, in general, well marked seasonally [12, 13]. According to Garcia [10], other factors may also influence the regional climate, as the South Amazon humid air mass and the cold front of polar instability that reaches the SE and S portion of the Pantanal.

The Pantanal wetland is an immense lowland of approximately 150,000 km^2 (altitudes <200 m a.s.l.) located in the Upper Paraguay Basin (Fig. 1). The annual precipitation in river headwaters is not homogeneous but varies from 1,200 to 1,350 mm at north-northeast to 710–1,200 at the south-southwestern sector, with the lowest annual precipitation of 700 mm in the center of the Pantanal (Fig. 2). This precipitation/discharge dynamics largely relies on the "monsoon-like effect" produced by the altitudinal gradient between low- and highlands [14]. Also, the majority of the annual rainfall takes place from October to March, whereas July to September is the driest period [12].

This chapter provides insightful information interlinking climate, geology, and hydrology for better portraying and understanding the Pantanal dynamics in its particularities and as a whole system.
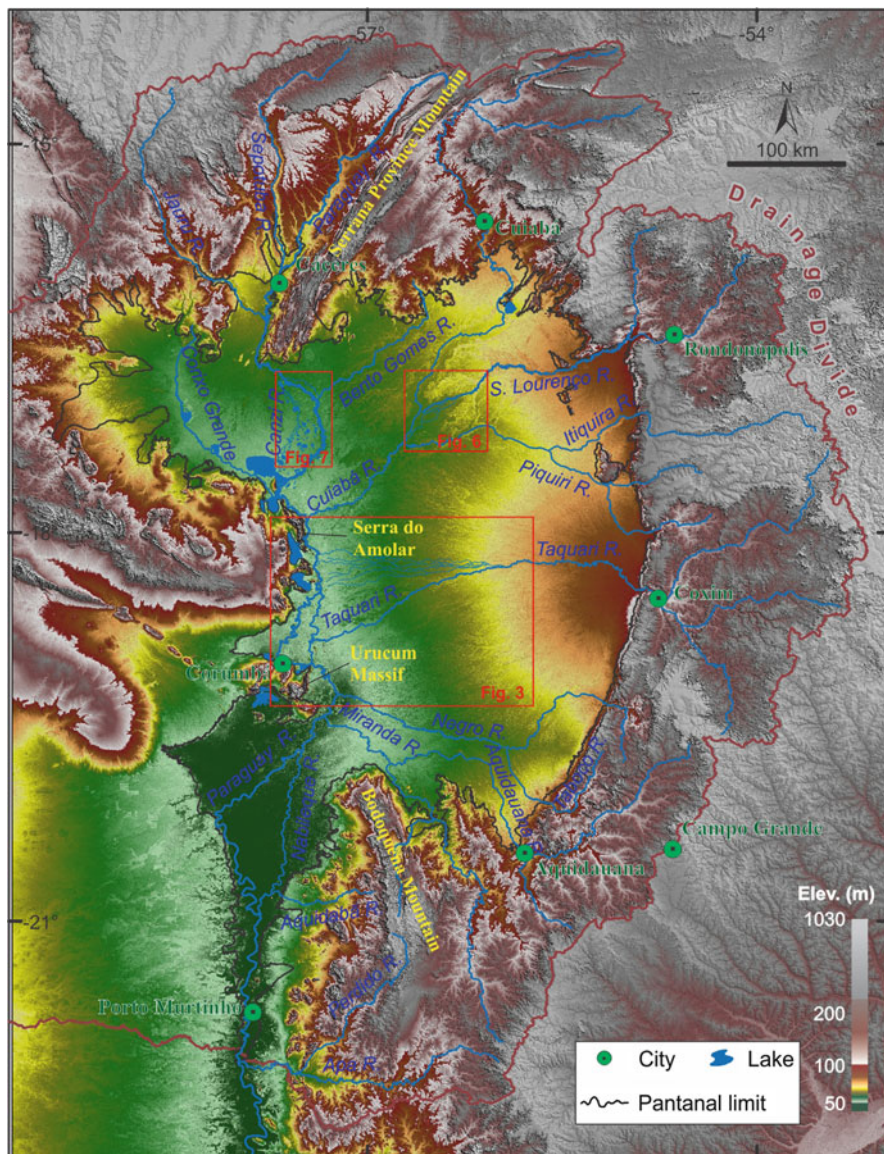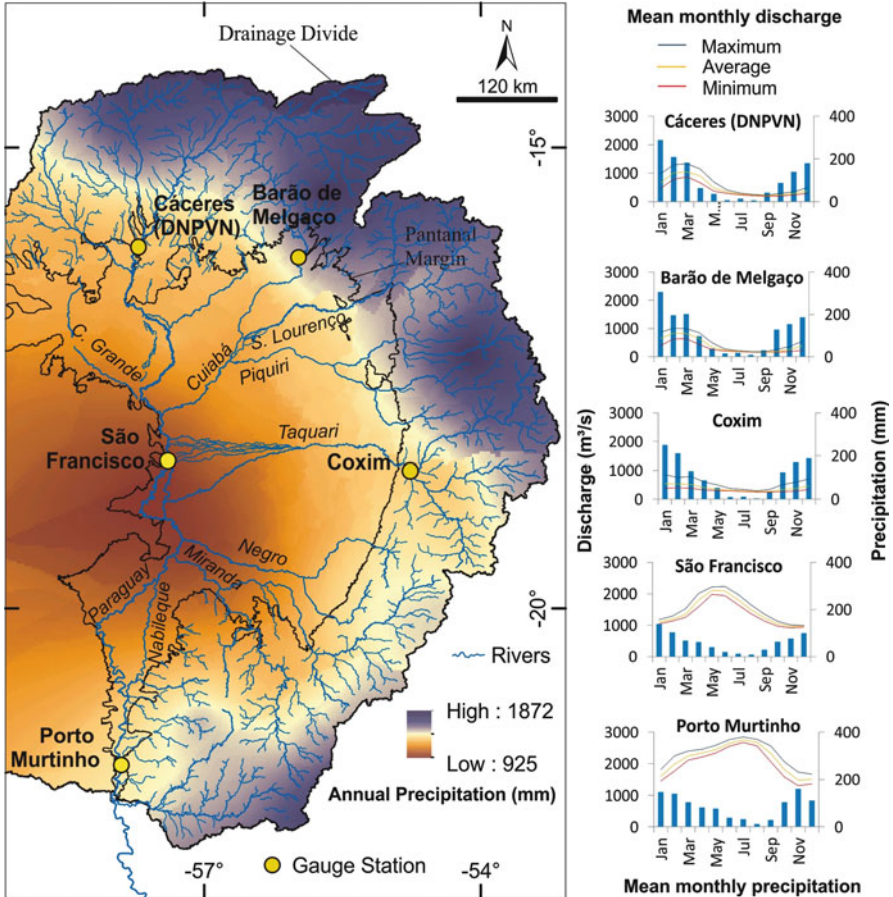
Fig. 1 Hypsometry and the drainage network of Upper Paraguay Basin, with indication of the Pantanal area (digital elevation model from Shuttle Radar Topographic Mission – SRTM)

Fig. 2 Hydrographs of some rivers of the Upper Paraguay Basin (monthly mean during the period 2003–2012). The annual precipitation map was obtained by the Kriging interpolation of data in the same period (Data source: ANA – Brazilian Agency of Water)

2 Avulsive Rivers in Distributary and Multichannel Systems

Rivers in the catchment area surrounding the Pantanal wetland are essentially bedrock rivers, which means watercourses formed by erosion of underlying rocks with valley. Many small stream rivers flowing into a large river (main stem) compose the tributary drainage networks, such as the drainage basins of the rivers Miranda, Aquidauana, Taquari, São Lourenço, Paraguay, and Cuiabá (see Fig. 1). Incision processes carve valleys and confine the flow in thalwegs. The sediment generated by erosion is transported downstream, with little and short-lived alluvial deposition along the valley.

The lateral slopes vanish when the confined rivers reach the Pantanal basin and the rivers develop into unconfined systems. Sedimentation takes place and the rivers turn into alluvial with poorly defined valleys with no apparent slopes. Sedimentation occurs due to the combination of valley unconfinement, sudden drop in the river gradient, and flow speed reduction. The unconfinement increases downstream with terrace slopes decreasing favoring overflow, crevassing, and channel splitting. Both channel bifurcation and sedimentation lead to changes in the position of channels, and, eventually, the main channel may fully change position and the river course shifts to another portion of the floodplain, a phenomenon termed *avulsion*.

The Pantanal is a large subsiding sedimentary basin that continuously creates accommodation space for deposition [15]. The rivers deposit sediments carried from the catchment-source area, filling portions of the basin, whereas other areas remain starved. Consequently, the river changes continually its position within the basin to distribute sediments all over the area, which means that the river behavior is avulsion dominated and the system is avulsive [16]. Fluvial avulsion is a step-by-step serial processing that abruptly shifts the river course.

Avulsive channel systems commonly lead to a fluvial distributary drainage pattern, characterized by networks of channels radiating from the apex of the system, with one or more perennial and many intermittent channels that are active only during floods. These systems are termed *fluvial megafans* and are distinguished from debris flow dominated alluvial fans not only because they are dominated by rivers, but also due to their large areas reaching 10^3–10^5 km^2 while alluvial fans are generally $<10^2$ km^2 [17]. The Kosi River system in India is an example of large fans since Gole and Chitale [18] reported records of river shifts of ~100 km from east to west across the fan surface, over a period of 230 years (1731–1963). The Kosi fan typifies braided river-dominated alluvial fans in the threefold classification of fluvial subaerial fans [19]. In this classification, the Okavango fan in Botswana is a suitable model for the second group of stream-dominated fans: the low sinuosity/meandering river-dominated fans.

The importance of fluvial megafans was recently emphasized by Weissmann et al. [20] and Hartley et al. [21], although they chose the term "distributive" (instead of distributary) and have referred them as distributive fluvial systems (DFS). The use of satellite images was crucial to recognize where large distributary systems occur today worldwide, and how they are strongly influenced by climate to establish fluvial drainage patterns [17, 20, 21].

The distributary drainage network and the dimensions of the alluvial systems of the Pantanal Basin [22–24] are typical of fluvial megafans [15]. The Taquari megafan is unquestionably the most studied of them and the largest distributary fluvial system in the basin with ~50,000 km^2 [25–28].

All Pantanal megafans are depositional systems driven by avulsive rivers. Fluvial avulsion is frequently an autogenic phenomenon since it emerges exclusively from intrinsic factors related to the construction and abandonment of depositional fan lobes. Fluvial avulsion is hence discernible from stream piracy, in which a river captures an adjacent river because of regressive erosion processes

or crustal movements in active tectonic areas. Avulsion is very common because the rivers do not drift laterally and gradually in the plain, but shift suddenly to areas far from the active main channel. Shifts of the Taquari River course have been quite frequent in the modern distributary lobe. A remarkable avulsion took place during the 1990s in the lower course at the fringe of the Taquari megafan, in the locality named "Zé da Costa." The channel shifted 30 km northward its confluence in relation to its original mouth at Porto da Manga locality [25]. The avulsion was quick as time lapses only 10 years and the succession of events is very well documented in satellite images (Fig. 3).

An avulsion of greater magnitude has been evolving since the beginning of the 2000s near the apex of the modern fan lobe (Caronal farm), where the meander belt unconfines. Frequent overflow and many in the natural levees on the right margin of the Taquari River with drainage of sediment-laden waters have been diverting the flow to the floodbasin. The distributary channels distribute the sediments over a broad accumulating alluvial area where a new avulsion belt is under construction. The new channels divide into numerous channels with frequent rejoin characterizing an anabranching (multichannel) river system, but channels fade away downstream and the waters flow unconfined in an extensive floodbasin. Most of the river water is already flowing through those newly formed channels (Figs. 3 and 4), and the changing landscape has been documented by satellite images (e.g., [27]). The Taquari River can shift its course and abandon the main channel, changing its mouth a hundred kilometers toward north, as previously envisaged by Assine [25].

Avulsion commonly results from the association of many factors, and the triggering occurs during a discharge event of magnitude at or near the avulsion threshold [29]. Although there is no consensus on the causes that initiate the avulsions in the Taquari megafan, one of the most important causes for avulsion is the channel aggradation [25, 27, 30]. Zani et al. [28] pointed out that avulsions are occurring progressively closer to the apex (intersection point of the megafan) and suggested that the system is being filled in a toe-to-apex direction. Based in these observations, they concluded that the base level is above the longitudinal profile downstream of the intersection point, where accommodation space is available for in-channel sedimentation, which causes avulsion triggering.

Flow deceleration downstream of the intersection point results in the channel aggradation and riverbed shoal formation (Figs. 3 and 4). Progressively the channel belt becomes a few meters higher than the adjacent floodbasins because of the aggradation inside the channel and increasing height of marginal levees, causing the channel to lose capacity to convey flood discharge. Channel overflow and crevassing (*arrombados*) create favorable condition for avulsion, beginning with channel splitting. The process can be very rapid because the slope down to the adjacent floodbasin is higher, diverting the flow and causing the abandonment of the main channel (Fig. 5).

Avulsive river shifting in the modern distributary lobe of the Taquari River is a natural response of the system to accommodate sediment supply coming from the catchment area. In this context, channel aggradation has been likely intensified by land use (livestock and farming) in the basin highlands [31, 32]. Besides, river
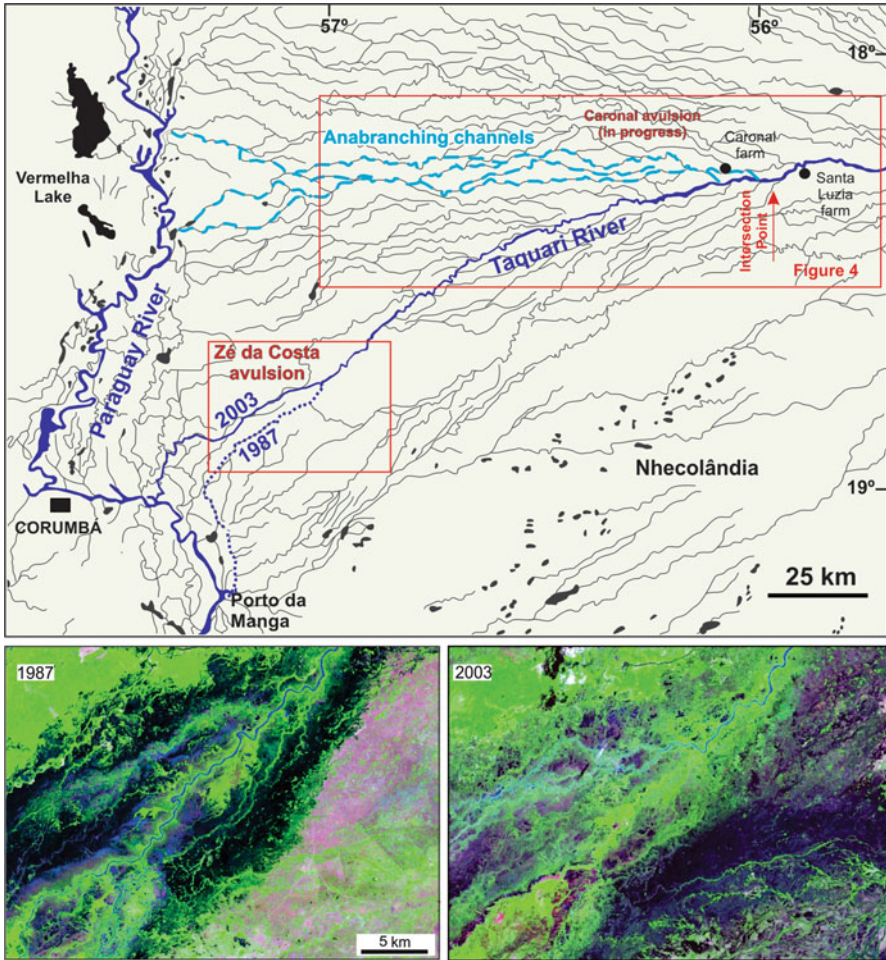
Fig. 3 Avulsions on the modern depositional lobe of the Taquari megafan (IP = intersection point). A large-scale avulsion is in progress at the apex near the intersection point of the megafan at the Caronal farm. The new distributary channels on the right margin of the river envisaged by Assine [23, 25] are now very active draining more the 70% of the river discharge and shifting approximately a hundred kilometers north from its confluence with the Paraguay River. The well-known "Zé da Costa" avulsion has occurred in a time lapse of two decades, as documented by multitemporal Landsat images taken in 1987 and 2003 (false-color composition R7G4B3)

avulsions in lowlands may also result from increased rainfall since 1973, following a very dry decade.

Despite the recently anthropogenic interference, avulsion is a geomorphologic result of a natural depositional mechanism in fluvial megafans. The São Lourenço megafan gives us an important evidence of this natural behavior. The "Boca Brava" avulsion (Fig. 6) caused the abandonment of its former main channel, the "Braço do São Lourenço," and the confluence with Piquiri River and shifted the river to its
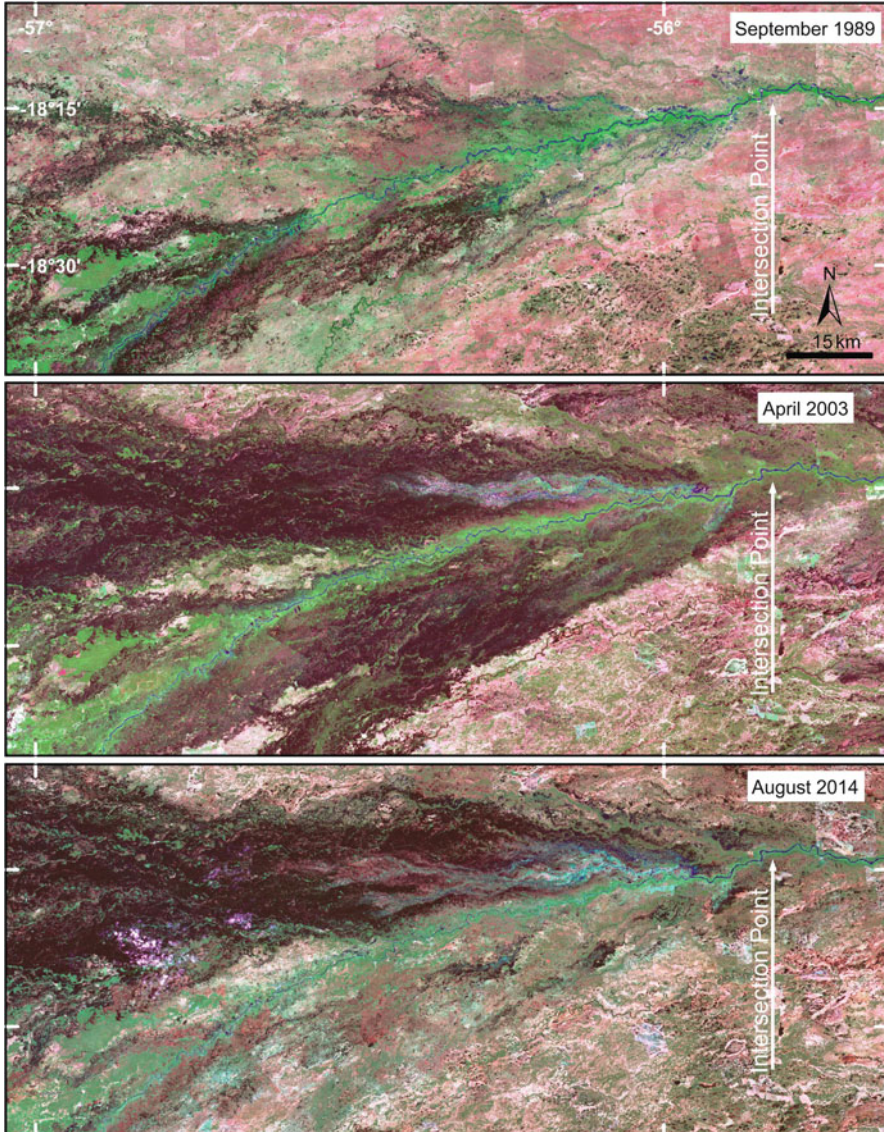
Fig. 4 Channel changes and the deposition of an avulsion belt associated with the Caronal avulsion as seen in multitemporal satellite images taken in 1989, 2003, and 2014. (Satellite images: 1989 TM5 R7G4B3; 2003 ETM+ R7G4B3; 2014 OLI R7G5B3)

present course and actual confluence with the Cuiabá River [33]. The shift took place between 1890 and 1915 [33] and indicates that avulsions in the Pantanal are commonplace, independently of accelerated sedimentation due to anthropogenic activity, which became much more intense with agricultural and ranching practices
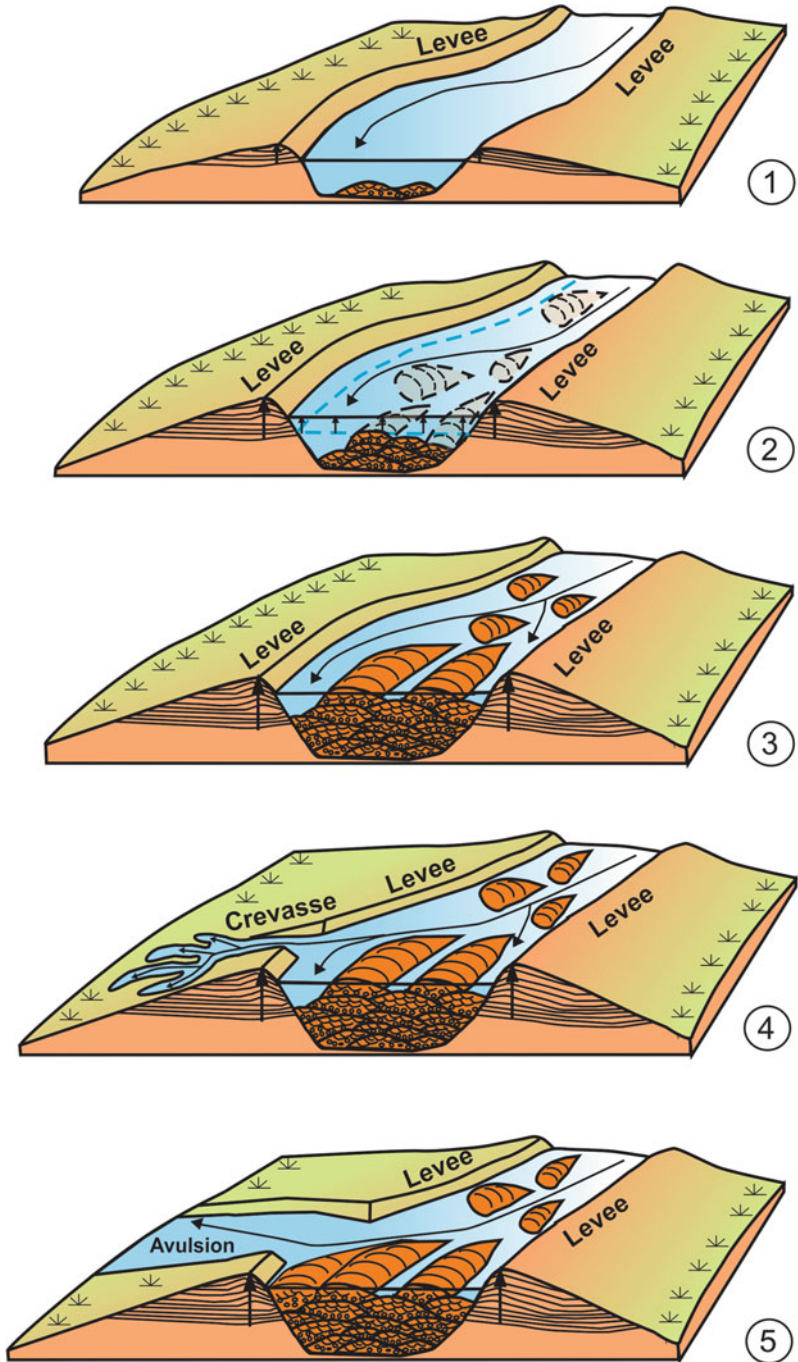
Fig. 5 Schematic evolution of the phenomenon of channel splitting and avulsion of the Taquari River [26]: (*1*) the channel steadily rises in relation to its adjacent areas due to the levees built through subsequent seasonal flood overflows. (*2*) The riverbed rises through sediment aggradation
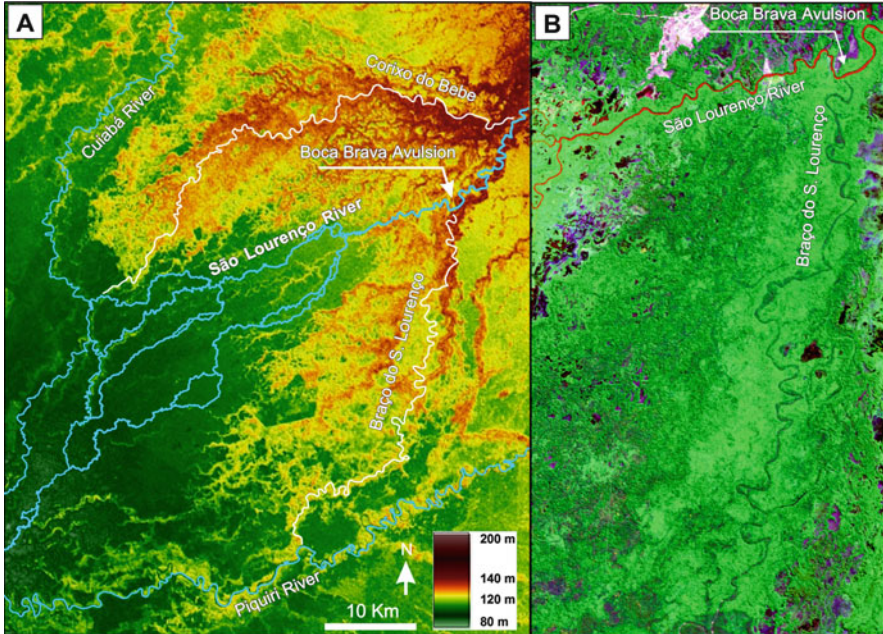
Fig. 6 Avulsion and establishment of distributary channels in the modern depositional lobe of the São Lourenço megafan. *Left-sided* image is SRTM data, and the *right-sided* image is a box section obtained by false-color band composition of Landsat TM data, GeoCover, RGB742, 1990

after the 1970s. The time span (<25 years) is similar to the rate of recent avulsions observed in the Taquari megafan [25]. The abandoned "Braço do São Lourenço" channel now behaves solely as an intermittent stream flowing during wet seasons, but remains a prominent morphologic feature on the landscape. Nowadays, sedimentation on the active depositional lobe of the "São Lourenço" megafan occurs in its most distal position, between the "Corixo do Bebe" and the "Braço do São Lourenço" abandoned lobes, an area with available accommodation space where river splits into two or more distributary channels, each one presenting many divides and rejoin (Fig. 6).

The Paraguay River itself has been building a large megafan at the river entrance into the northwestern border of the Pantanal. The drainage pattern is distributary on the modern depositional lobe, and the Taiamã Island resulted from the split off and rejoin of the main channel [35]. Minor avulsions have commonly occurred in this

Fig. 5 (continued) in the channel and in the marginal levees. (*3*) Following the silting process of the channel, the sand bars emerge even in flood times, causing reduction in channel capacity of water retaining. (*4*) Sooner or later, a seasonal flood induces the crevassing of the marginal levee and the splitting of the channel. (*5*) The water flow is steadily diverted to the new channel and, finally, the river changes its course with the abandonment of the main channel
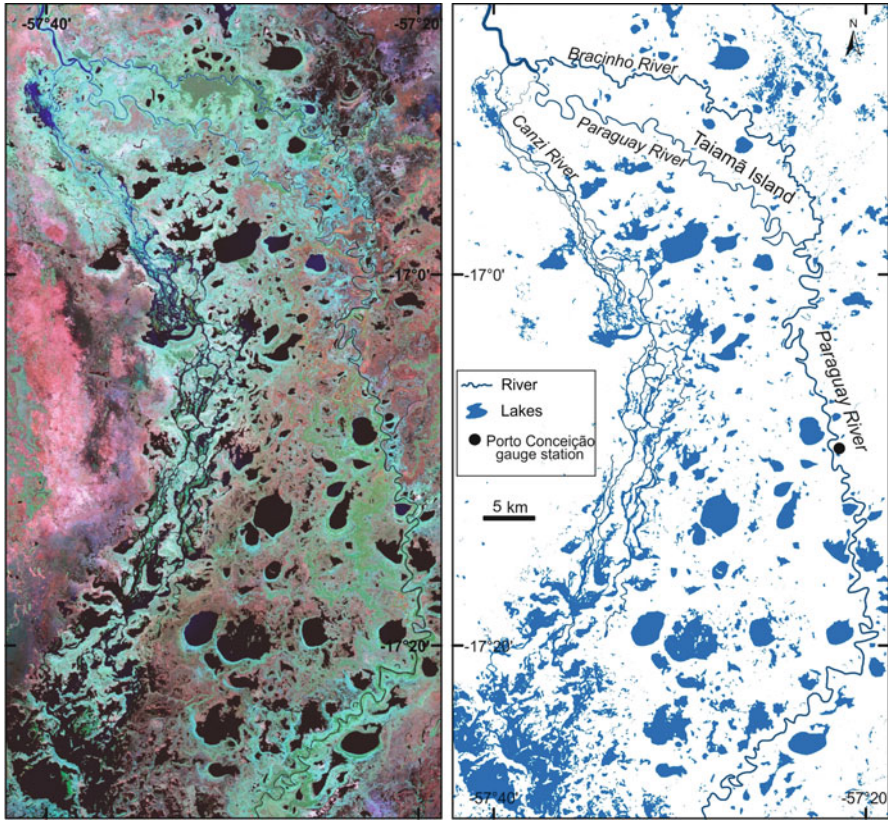
Fig. 7 Avulsion in progress on the right margin of the Paraguay River upstream of the Taiamã Island. Waters from the diverting channels are contributing to form the anabranching channels of the Canzi River

modern distributary lobe, as indicated by many abandoned channels within the floodplain. Emphasis must be addressed to an important avulsion in progress upstream of the Taiamã Island, where water is flowing out from the channel through some crevasses on the right margin of the Paraguay River. This pattern suggests a probable abandonment of the present channels of the Paraguay River and a future attachment of the Taiamã Island to the floodplain (Figs. 7 and 8).

Successive dividing and rejoining results in an anabranching fluvial pattern, which characterizes many reaches of modern depositional lobes of Taquari and São Lourenço River megafans. The Cuiabá River also exhibits anabranching channels in the modern depositional lobe, but differently from the former, it presents important reaches characterized by the existence of multiple small channels in the upper megafan setting [36].

Multiple dividing and rejoining river channels encompass a wide variety of river patterns, referred elsewhere as *braiding*, *anastomosing*, or *anabranching* which can
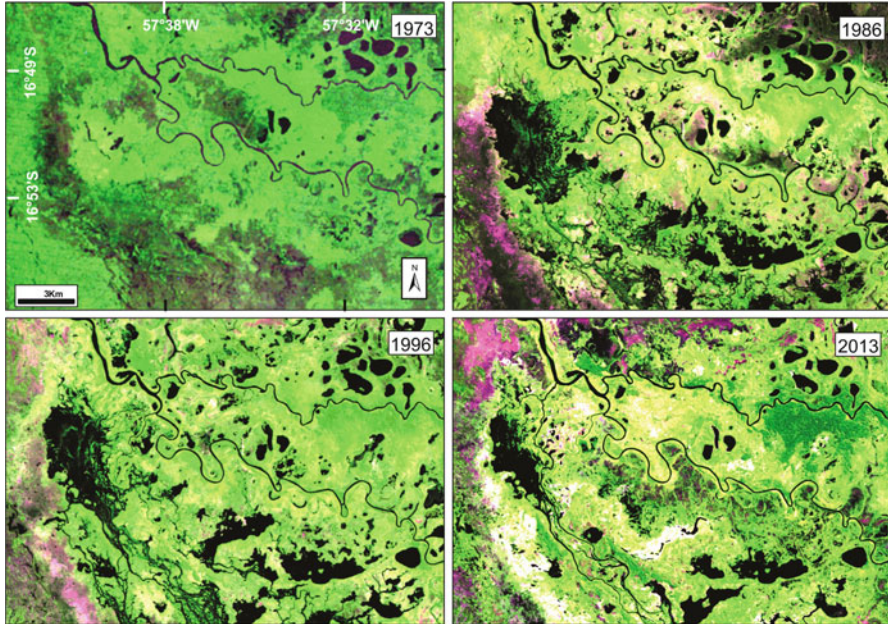
Fig. 8 Crevassing and diverting channels on the right margin of the Paraguay River as seen in multitemporal satellite images (Landsat 1 MSS, RGB475, August 1973; Landsat TM5, RGB547, October 1986; Landsat TM5, RGB547, July 1996; and Landsat 8 OLI, RGB657, June 2013

be referred altogether as *multichannel rivers* [37]. Despite the differences in channel style, multichannel rivers are present in the Pantanal wetland, not only in the fluvial megafans, but also along the Paraguay River main stem. The Paraguay flows from its catchment at north to the exit of the Pantanal wetland, crossing a heterogeneous floodplain and collecting the waters from the whole basin. Multi-channels are present in many geomorphic zones of the floodplain, and their importance to the Pantanal hydrology is presented in the following section.

3   Depositional Tract and Surface Hydrology Dynamics

Flowing from southward along the western margin of Pantanal wetland, the Para-guay River is the mainstem river of a depositional tract composed of many fluvial megafans and interfan systems, lakes, and swamp areas (Fig. 9; see [15]). Accord-ingly, the drainage system is very complex due to the coexistence and interaction of these different systems. Within the Pantanal, the drainage networks display channel bifurcations and avulsions in the megafan distributary systems, and multichannel reaches are frequent in the modern megafan depositional lobes, as well as in the Paraguay River mainstem plains. These peculiarities cause a very complex flood
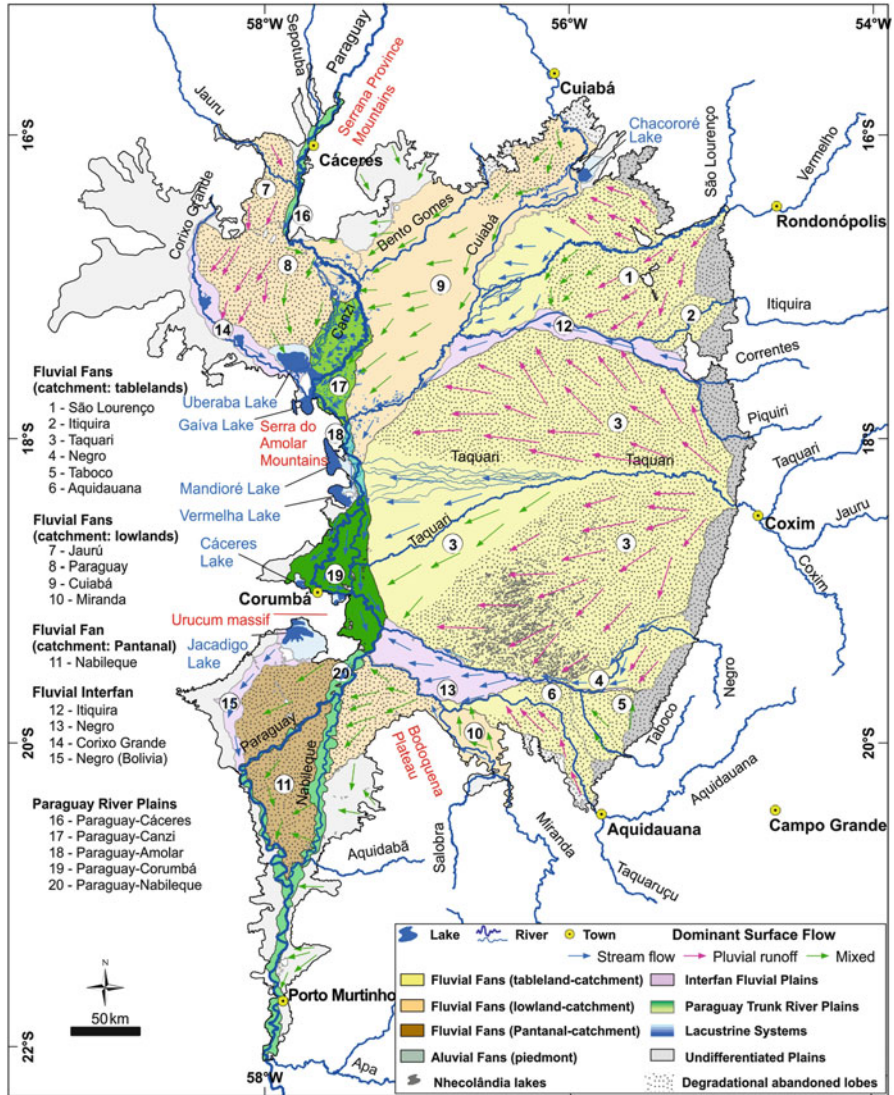
Fig. 9 The Pantanal alluvial depositional system tract with drainage pathways (streamflow, pluvial runnof, and mixed flow) [33]

regime within the Pantanal wetland with ecological and socioeconomic implications.

The hydrology of the Upper Paraguay Basin is very complex [38]. Rivers in the catchment area have comparable regimes with strong direct in-phase correlation between rainfall and discharge (Fig. 2), but in the fluvial megafans, the peak of fluvial discharge occurs one to two months after maximum rainfall. In the fluvial

megafans, meander belts are confined in the upper fan and the river works as a bypass transporting water from the catchment area directly to the modern lobes, and the abandoned lobes do not receive water from the river. In the abandoned lobes, the surface runoff is essentially pluvial during floods and sustained by subsurface return flow (throughflow) after flood peaks. Outflow of the ground in springs is the source of water to many small streams (named "corixos") that drain the surface of abandoned lobes following the wet season. Some of these abandoned lobes, especially those of the megafans situated on the south portion of the Pantanal (Aquidauana, Miranda, and Nabileque), are characterized by mixed surface runoff because there are contributions of pluvial water as well as sheet flow from unconfined fluvial waters (Fig. 9).

In general, the fluvial fans of the Pantanal have a concave-down morphology that favors the water dispersion, preventing water retention. The Taquari and São Lourenço megafans exemplify the morphological control on water transfer (Fig. 10). In the upper portion of the fan, the river is normally incised and runs in a narrow meander belt entrenched on their ancient lobes. The active lobes have a grossly triangular shape with the vertex toward the fan apex. Sedimentation processes are very active in these sites, avulsion being the main fluvial phenomenon of sediment dispersal. Following avulsion, the river becomes unconfined and the waters flow radially by a system of distributary and anabranching channels.

The hydrographs of the Taquari and São Lourenço rivers show that during mid-lower water level, the flow occurs only in the channel, both for the incised and anabranching reaches (Fig. 10). As these rivers do not receive any tributary along the fan, the discharge measured in the upper, mid, and lower gauge stations are practically the same. However, during the flood pulse, the gauge stations in the anabranching reach of both rivers show an impressive loss of water for secondary anabranching channels. Differently from common fluvial basins, the channel belt in the uppermost portions of the fluvial plain is a bypass and works as a "drainage divide" for surface runoff. The Hortonian flow lines drawn over the topographic maps of the Taquari and São Lourenço fluvial fans indicate a dispersive trend of water from the channel belt toward the fan fringes (Fig. 10).

The Paraguay River collects water from multichannel streams present in the modern distributary lobes of fluvial megafans and from streams of interfan fluvial plains, each one with very different hydrological functioning. Hydrographs along the Pantanal mainstem river display an opposite behavior relatively to the rivers in the catchment area (Fig. 2). Whereas the fluvial discharge in the catchment area (Cáceres, Barão de Melgaço, and Coxim stations) varies in phase, in São Francisco and Porto Murtinho stations, respectively, at the center and at the end of the Paraguay River plain, the discharge varies out of phase with local rainfall.

The historical gauge station series of the Pantanal rivers vary in data extension, continuity, and quality. Collischonn et al. [39] identified for the Ladário gauge station – the longest historical series constructed since 1900 – a period of low hydrometrical level from 1962 to 1973 followed by the present period of high hydrometrical level. An expedite hydrological comparison between dry and humid periods measured for eleven gauge stations along the Paraguay River shows a
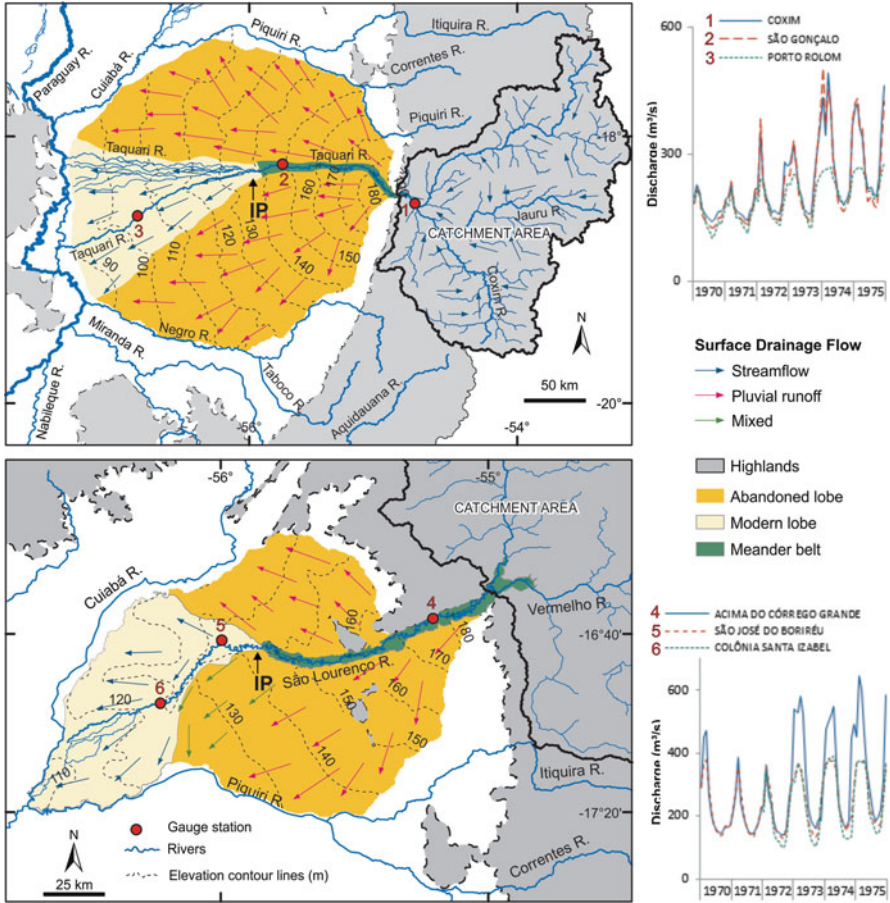
Fig. 10 Surface hydrology of the two large Pantanal megafans: Taquari (*upper*) and São Lourenço (*lower*). Both megafans are characterized by similar morphology and surface hydrology. Water from catchment areas reach the modern depositional lobes through feeder channels confined in meander belts entrenched in the upper fan (IP = intersection point). Abandoned lobes in both systems do not receive water from the catchment nor directly from the feeder channel, and most of the flooding comes from pluvial runoff. The rivers lose water to the floodplain in the modern depositional lobes, especially during rainy years, as occurred in 1974–1978 when the monthly mean discharge was higher than previous years. Hydrographs presented on the right refer to gauge stations: Coxim (*1*), São Gonçalo (*2*), Porto Rolom (*3*), Acima do Córrego Grande (*4*), Colônia Santa Izabel (*5*), and São José do Borireu (*6*)

difference from 81% in the annual average discharge at Porto Murtinho gauge station (Fig. 11). The intense land-use change in the Pantanal highlands during the last four decades also contributes to significant changes in the ecohydrology [40] of the Pantanal. Forest suppression in highlands for crop and livestock [41–45] is responsible for increasing river discharge while reducing evapotranspiration and
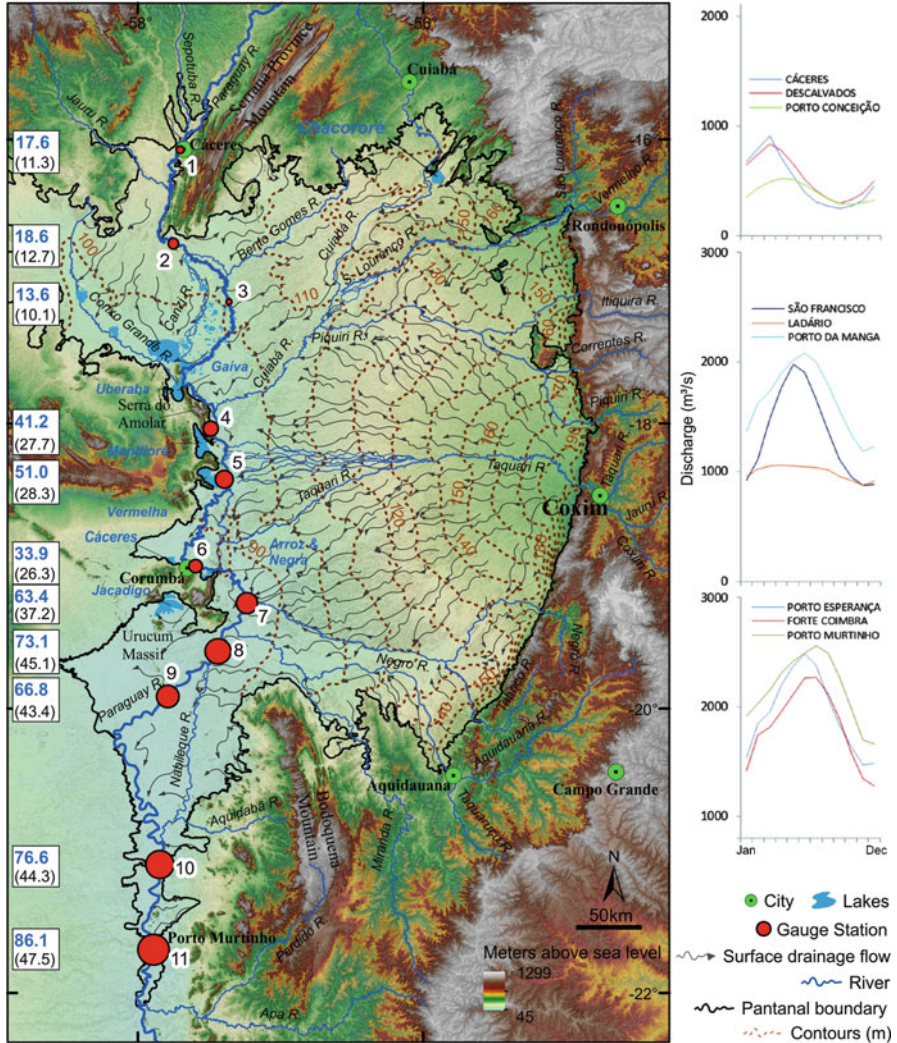
Fig. 11 The Pantanal hydrology of the land surface system. The main rivers are represented as well as runoff pathways (*sinuous arrows*) of surface waters extracted from the SRTM data. Numbers in white boxes are the mean total annual discharge (km³ year⁻¹) at each gauge station during the dry 1970–1974 period (*black*) and during the 1974–1978 humid period (*blue*). Gauge stations in the Paraguay River: (*1*) Cáceres, (*2*) Descalvados, (*3*) Porto Conceição, (*4*) Amolar, (*5*) São Francisco, (*6*) Ladário, (*7*) Porto da Manga, (*8*) Porto Esperança, (*9*) Forte Coimbra, (*10*) Barranco Branco, and (*11*) Porto Murtinho. The flood wave from north to south is evident in hydrographs of nine of these gauge stations, grouped in sets of three according to its geographical position: upstream (Cáceres, Descalvados, and Porto Conceição), middle (São Francisco, Ladário, and Porto da Manga), and downstream (Porto Esperança, Forte Coimbra, and Porto Murtinho)
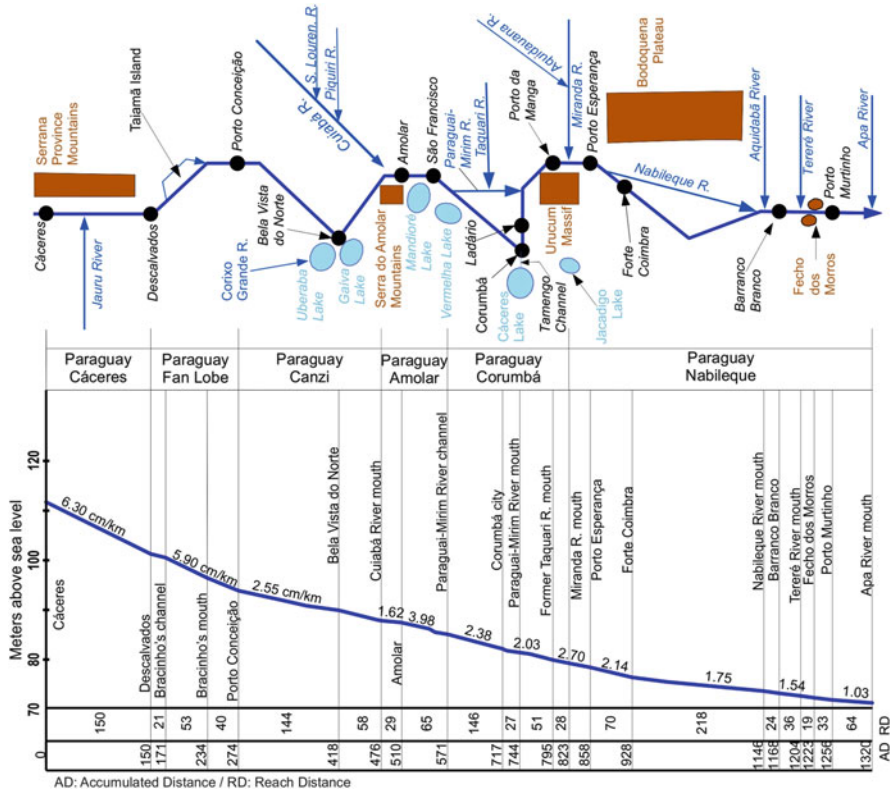
Fig. 12 Hydrographic scheme of the Upper Paraguay River in relation to its gradient profile (not to scale). Longitudinal profile was based on data of Franco and Pinheiro [47]

cloud formation in highlands [32] that could distribute rainfall in lowlands areas without floodplains as the Nhecolândia [46].

The Paraguay River plain has geomorphologic heterogeneity in consequence of its geologic position on the western faulted border of the sedimentary basin [15]. The river-mainstem plain comprises five distinct fluvial floodplain compartments, each one presenting different morphologic characteristics, channel pattern, and hydrologic functioning (Fig. 9). The Paraguay River floodplain is variable in style and width, reflecting tectonic control on the western margin of the Pantanal basin and interaction with the distal portion of fluvial megafans. The longitudinal profile of the Paraguay River shows subtle knickpoints in the limit of these compartments (Fig. 12).

The northmost Paraguay-Cáceres river plain compartment, located at the entrance of the Pantanal (Fig. 9) and ending in the farm of Descalvados (gauge station number 2 on Fig. 11), is a 4–5-km-wide confined floodplain, limited by the Jaurú fluvial fan at the right side and the NE lineaments of Serrana Province Mountains at the left margin. The river channel has irregular meanders with some

small anabranching channels, oxbow lakes, and island along this reach. The flood pulse is coincident with austral summer precipitation, and both Cáceres and Descalvados hydrographs show approximately the same behavior with a small increase in the annual discharge in Descalvados station, which results from the confluence of the Jaurú River in the middle of reach (Fig. 11).

Leaving the confined Paraguay-Cáceres river plain, the river forms the modern lobe of the Paraguay megafan ([35]; Fig. 9), an active depositional lobe characterized by two main anabranching systems. An important bifurcation of the Paraguay River channel (Bracinho River) and the downstream channel rejoining form the 30-km-long Taiamã Island. Recently, crevasses upstream of the Taiamã Island are diverting important water flow into the floodplain on the right margin of the river, turning the Canzi River a multichannel system with many anabranching channels (Fig. 7). A comparison among hydrographs of gauge stations situated upstream (Cáceres and Descalvados) and downstream (Porto Conceição) of these crevasses confirms important loss of water to the Canzi River during the river peak discharge (Fig. 11). When water level is sufficiently high, the Paraguay also loses water southward as sheet flow over the surface of the abandoned lobes. Myriad small lakes in the floodplain accumulates large amount of water diverted from the main channel and contributes to retarding the flood wave.

The Paraguay-Canzi plain is a compartment with reduced river gradient in relation to the upstream reaches (Figs. 9 and 12). The floodplain is a large area of active sedimentation, receiving water and sediment from the Paraguay and Canzi rivers. The plain also receives water and sediments from the Cuiabá River. A large number of lakes form in the floodplain, including the largest Uberaba and the Gaíva lakes. The water accumulation in this lake-floodplain is so forceful that the peak in the Amolar gauge station, at the end of this floodplain, occurs in May–June, about 60 days after it passes by Descalvado gauge on March. The Paraguay-Amolar floodplain produces a bottleneck effect on the water coming from the Paraguay and Cuiabá, incurring the delay of the flood-pulse wave. Such a huge mass of dammed water accumulates in the Paraguay-Canzi floodplain, feeding lakes and swamps and producing a huge continuous water body of more than 10,000 km^2 during June and July (Fig. 13). The importance of this area in the hydraulic regulation of the Upper Paraguay River was highlighted in the report [48].

The Paraguay-Amolar is a narrow floodplain limited by the Serra do Amolar mountains and the Cuiabá and Taquari megafans that conjointly acts as a bottleneck for the flow of the Paraguay River (Figs. 9 and 13). It has about 53 km long, ending with the floodplain extension near the Vermelha Lake. Despite only 6 km wide, the Paraguay-Amolar floodplain has empty spaces constituted by the large Vermelha and Mandioré lakes and a series of irregular water bodies covered by floating macrophytes and cut by channel-levees. The Cuiaba River that flanks the eastern side of the floodplain also supplies the area with large amount of sediment through crevasse splays (Fig. 13). The reach is also influenced by the Cuiabá and the north portion of the Taquari active fans (Fig. 9), which supplies with water the Paraguay through many anabranching distributive channels. Thereby, the hydrograph of the São Francisco gauge station in the middle portion of the reach also shows it flood-
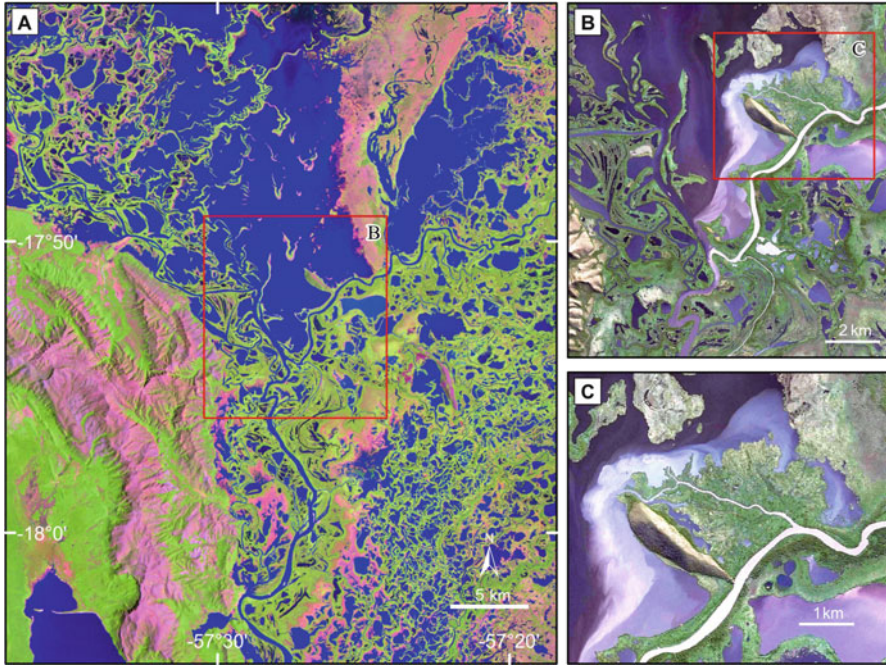
Fig. 13 Narrow river plain in the Serra do Amolar bottleneck causes flow constriction and backwater flooding upstream. (**a**) In consequence, the water level rises in the floodplain of the Paraguay and Cuiabá rivers, as well as in the Uberaba and Gaíva lakes, creating a large area often inundated (Satellite image Landsat 5 TM, R5G4B3, from December 1985). (**b**, **c**) The reduction in sediment load transport makes this area a site of active sedimentation, exemplified by crevasse splays in the lower course of the Cuiabá River

pulse peak on May, about three months later than in those verified for Cáceres and Descalvados stations.

Placed downstream of the Vermelha Lake, the Paraguay-Corumbá compartment is a 27-km-wide plain drained by an anabranching reach formed by the Paraguay and the Paraguai-Mirim rivers. This flat floodplain (slope around 2.3 cm/km) is not homogeneous but covered by paleochannels of anabranching channels of the ancient Paraguay River ([49]; Fig. 14). Inactive during the low-medium water level, these paleochannels receive water during the flood, so that flood-pulse peak takes a month to run from São Francisco to Porto da Manga gauge stations, the last one located near the mouth of the Miranda River at the end of the Paraguay-Corumbá river plain. The hydrographs of São Francisco and Ladário gauge stations show that 10% of the Paraguay discharge is diverted to the Paraguai-Mirim. However, this difference increases twofold during the flood (Fig. 14). The narrowing of the Paraguay floodplain near the mouth of the Miranda River, constrained by the highlands of the Urucum Massif and the fringe of the Miranda fluvial fan, constricts the river flow and functions as a second bottleneck along the Paraguay River course (Urucum Bottleneck).
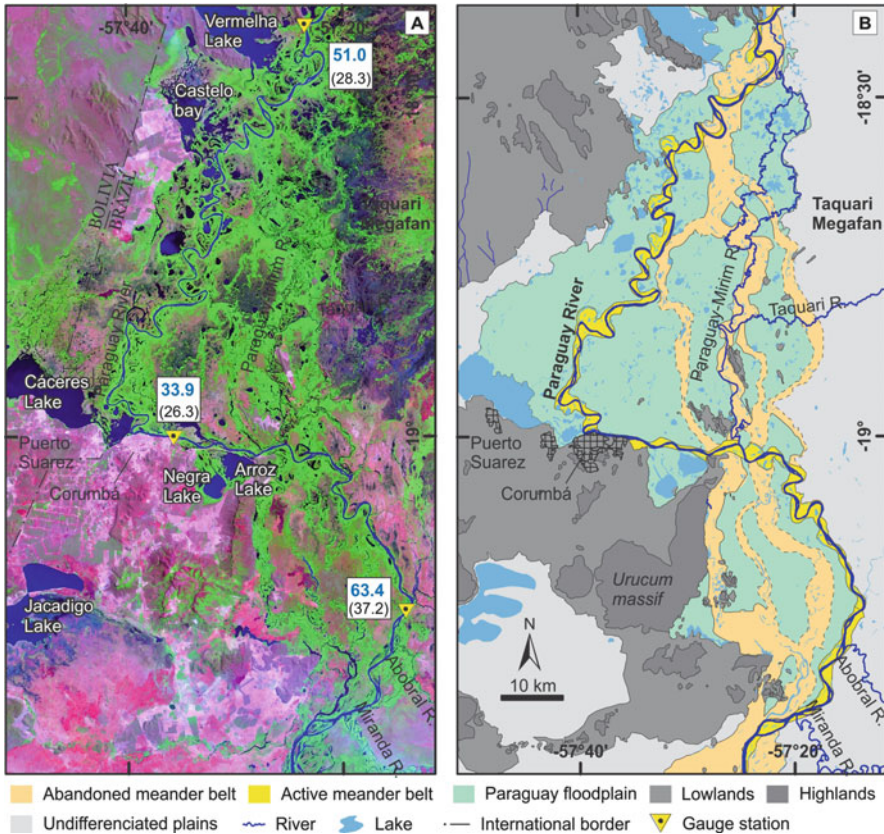
Fig. 14 Hydrology in the large Paraguay-Corumbá plain is strongly controlled by active land-forms. This reach of the Paraguay River is marked by abandoned meander belts, where the Paraguay River channels were formerly placed before its avulsion to its actual meander belt. Many lakes are closely influenced by the Paraguay flooding dynamics. (**a**) Landsat 7 ETM+ (R7G4B3) image from September 1999; (**b**) geomorphological map showing distinct zones and paleo landforms (after [49]). Numbers in white boxes are the mean total annual discharge (km^3 year^{-1}) at São Francisco (5), Ladário (6) and Porto da Manga (7) gauge stations during the dry 1970–1974 period (*black*) and during the 1974–1978 humid period (*blue*)

Downstream the confluence of the Miranda River, the Paraguay River enters in a less subsiding area at the south portion of the wetland. In this area, the actual meander river belt cut the Pleistocene deposits of the Nabileque megafan [50]. Remarkable is the presence of a large paleomeander belt of the Paraguay River in which today the Nabileque River flows as an underfit stream resulted from an important avulsion occurred around 4,000 years ago ([51]; Fig. 9). Comparing the hydrographs of Porto Esperança, upstream of the avulsion point, with Forte Coimbra, located downstream of the avulsion point, it is possible to verify that the Paraguay River loses about 10% of its water to the Nabileque River during the flood seasons (Fig. 11).

4 Hydraulic Bottlenecks and the Flooding Wave

Inundation dynamics in the Pantanal wetland are greatly dependent of its geomorphology and many attempts to define patterns and forecast river water levels were made [52–56]. The inundation paths result from the intricate pattern of interconnected fluvial fan and interfan systems that link many catchment areas. The complex flooding wave is also constrained by the heterogeneous Paraguay River plains, formed by alternation of extensive floodplains separated by natural bottlenecks.

The structure and function of the flow dynamics of these floodplains are very important for navigation as well as for the sustainable exploitation of the ecosystem services provided by the Pantanal wetland (including tourism; see [57]). The more impressive and important hydrological phenomenon in the Pantanal is the backwater effect produced by the narrow reaches of Paraguay-Amolar and Paraguay-Nabileque over their respective upstream reaches. The flood permanence is always larger than 50% with extremes of 85% (ANA/GEF/PNUMA/OEA 2005).

Backwater is controlled by geological features reflected by knickpoints in the river longitudinal profile (Fig. 12). Furthermore, gauging backwater reaches is very difficult because the relation between water level and discharge during the flood is unclear (Ponce, op. cit.). Through satellite image, however, it is possible to identify the influence of the bottlenecks of Serra do Amolar and Urucum that favors water accumulation in the upstream reaches of Paraguay-Canzi and Paraguay-Corumbá, respectively (Fig. 15).

ANA/GEF/PNUMA/OEA (2005) report presents a simulation for the Paraguay-Canzi river compartment considering a water level elevation of 1.0 m in the Amolar gauge station. The backwater extends by 270 km from Amolar up to the Descalvados gauge station. Under this condition, the average hydraulic slope is reduced from 3.5 to 1.8 cm/km, whereas the discharge remains constant (943 m³/s). A continuum backwater includes waters from both the Paraguay River and the lower Cuiabá River (Figs. 13 and 15).

A comprehensive view of Pantanal flood dynamics is depicted in Fig. 16. Nine satellite images (MODIS data) in the hydrological year of 2006 compose a temporal window of the wave, flood-pulse advancement, the bottleneck damming effects, water transference, and the strong control of tributary fans over the hydrology in the mainstem river. The Pantanal is fully dry in the beginning of January. The areas of permanent water accumulation are restricted to floodplain lakes and to some portions of the active lobe in the Taquari River megafan. During the dry period, water flows only through river channels. The flood initiates on January, and the Paraguay-Canzi river plain starts to flood due to the bottleneck effect imposed by the Sera do Amolar and the Cuiabá River plains. Up to April, all floodplains upstream of the Paraguay-Amolar bottleneck are completely flooded. Some areas of the active and ancient lobes of the Taquari River megafan are also flooded. On May, the Paraguay-Corumbá river plain is also flooded, and the huge water body includes the active portions of Taquari megafan. On June, the flood spreads over all
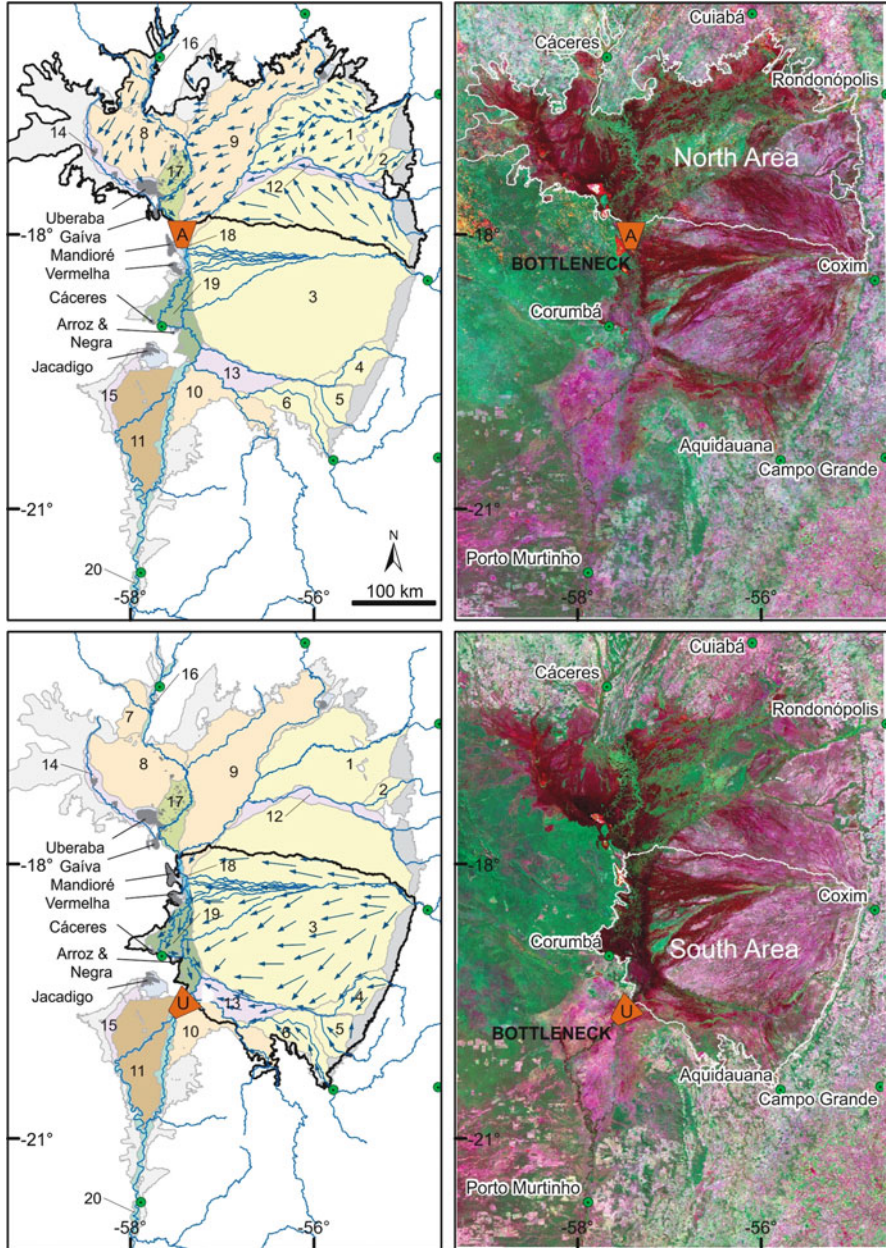
Fig. 15 The two bottlenecks that exert strong control (damming effect) on the flooding extent, magnitude, and duration in the Pantanal wetland. The Serra do Amolar bottleneck (A) delays the northerly flood-pulse wave. The Urucum bottleneck (U) slows down the flood-pulse wave southward and enhances the inundation in the Paraguay-Corumbá plain, in the fringe of the Taquari megafan and in areas draining to the Negro River interfan floodplain (numbers refer to depositional systems as identified in the Fig. 9)
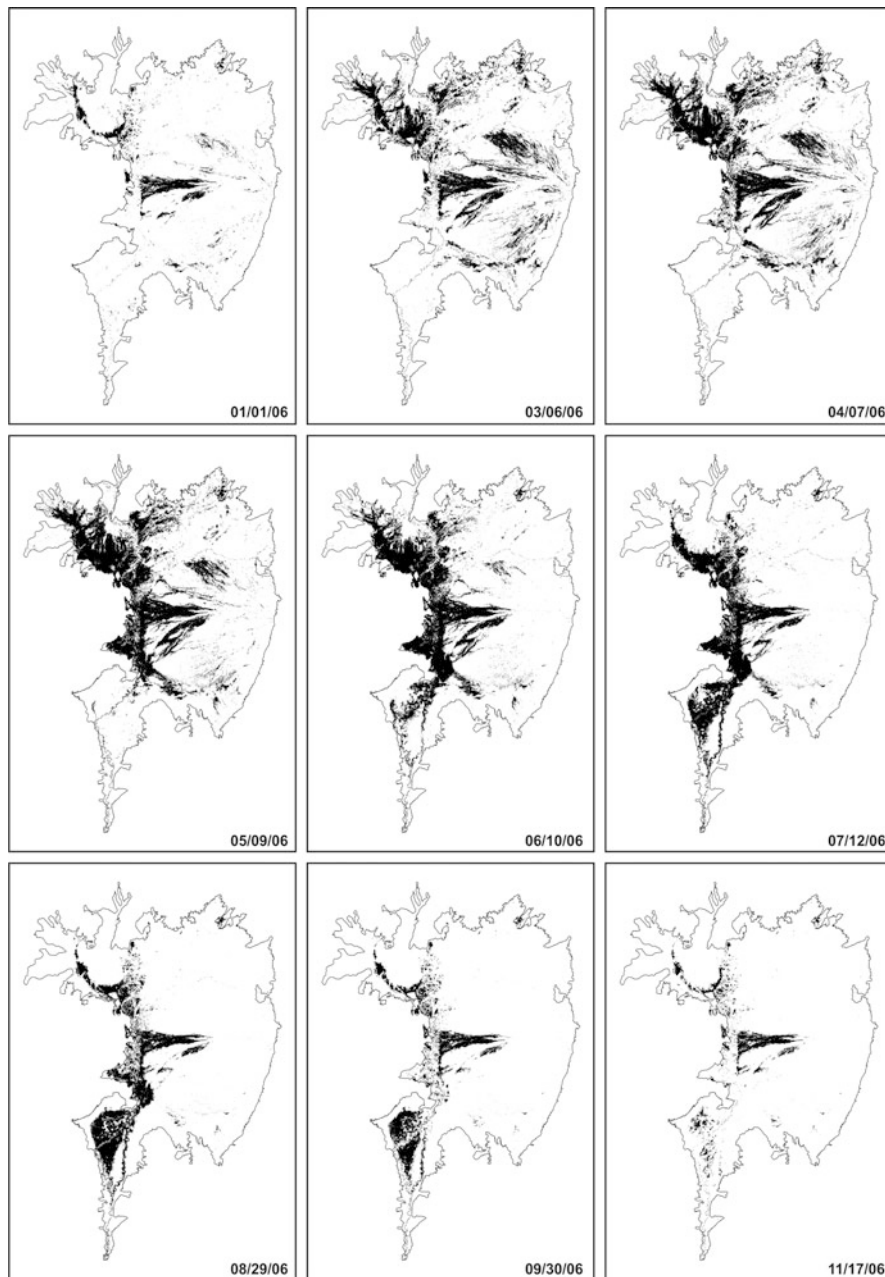
Fig. 16 Synoptic view of the annual spatial and temporal flood-pulse dynamics in 2006 (January to November) based on multitemporal MODIS images [54]. The successive images record the water transfer from borders to center and from north to south and how bottlenecks are effective in damming the water flow and enhancing the upstream floods. The effect of the Urucum bottleneck is clear after comparing images from May 9 to August 29

the Pantanal including the Paraguay-Nabileque river plain that begins to be flooded. On July, the upper plains start draining, and the flood in the Paraguay-Nabileque reaches its maximum. During August and September, all upper river plains are drained and only the Paraguay-Nabileque remains flooded. At the end of the year, the Pantanal is dry again (Fig. 16) and the annual hydrologic cycle resets following the summer rainfall.

The water and sediment flows running over the irregular and rough surface of the floodplain develop erosive and depositional sites forming complex habitats. However, the original concept of *moving littoral* [58] is not applied in all areas of the Pantanal where the water enters the floodplain through different paths mainly through the anabranching channel systems, water body intercommunications, and the rising of the groundwater. Unlike the Amazon floodplain, in Pantanal the flooded areas may or may not exchange water with rivers [54]. Natural levees within floodplains work like dams because water only overpasses these levees at a certain water level threshold. Otherwise, small channel splits, temporarily or permanently connected to the mainstream, transfer the rising water to distant areas of the floodplain, before the rising river waters overpass the levees [53]. The Pantanal flood pulse is therefore distinct from the flood-pulse concept developed by Junk et al. [58] as a model for large Amazon rivers, in which the exchanges occur between the river and its surrounding floodplain. In the Amazon floodplain, the river is active and the floodplain receives and returns the water passively.

In the Pantanal, the river eventually loses water to the floodplain, and the water does not return to the river channel at the same river stretch but kilometers downstream. The relatively long time span of water damming into different floodplains of different provenance can affect water quality of the mainstem river in different moments of the hydrological year with strong influence on the Pantanal ecology and biogeochemistry. One of the well-known but still poorly studied phenomena related to water quality and ecology is regionally named "dequada" or "decoada" [59]. The phenomenon is associated to the return of floodplain water to the channel, which changes in water tranparency, pH, electron conductivity, dissolved oxygen (DO) and carbon dioxide (CO_2) lead to fish mortality [50, 60]. "Decoada" has also great relevance to greenhouse gas exchanges with the atmosphere, in particular methane (CH_4) and carbon dioxide (CO_2) [60]. The flood magnitude and "decoada" intensity show a direct relation measured by an intensity index for the "decoada" in the Paraguay River and its main tributaries [61].

5 Conclusion

Due to its morphology, drainage structure, and dynamics, the fans present very peculiar ways in transferring water and sediment to the mainstem river, with profound implications to flow regime, ecology, biodiversity, and local socioeconomy [63–65].

The narrow relation between the Pantanal ecology and its hydrological regime is well known [49, 61, 66, 67]. Water and sediment loads (dissolved, suspended, and

bed loads) are very important not only for the floodplain morphogenesis and system maintenance, but on recycling nutrients to the biota. In this case, the action of the flood pulse [58], with variables as frequency, recurrence, intensity, tension, and permanence, over sites of different morphology has a relationship (connectivity in the concept of [68]) with the riparian vegetation and other ecological variables [69].

This chapter also highlights that avulsions and bottlenecks largely dictate the hydrodynamics and the ecohydrology of the Pantanal wetland. On the other hand, land-use changes (deforestation) in the highlands [31, 41, 70] necessarily need to be reverted (reforestation and livestock-agroforestry systems; see [32]) to likely decelerate the actual sediment load rate. By reintroducing tree elements in the Pantanal headwater landscape, besides to recover important ecosystem services as evapotranspiration and carbon storage [40], it is likely to reduce the rate of an eventual "anthropogenic accelerated avulsions" into the plains that ultimately can reduce ecosystems' resilience and make it difficult to promote the sustainable development in the lowlands. This issue is particularly important considering the possible climate change scenarios for the region [12].

The fluvial "avulsive and bottleneck" dynamics seasonally affects both local and regional ecohydrological processes, such as flora (and consequently fauna) distribution [42], tree biomass allocation [42], as well as biogeochemistry dynamics in floodplains and lakes [46, 60]. Moreover, it shows that avulsive processes are commonplace in Pantanal, and changes in land use, particularly in river headwaters in the highlands [44, 45], can accelerate the avulsions, making difficult a sustainable use of the Pantanal lowlands.

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