# ISLAND AND ANABRANCHING GENERATION PROCESSES – A COMPARATIVE REVIEW IN THE UPPER PARANÁ RIVER

# PROCESSOS DE MULTICANALIZAÇÃO E GERAÇÃO DE ILHAS – UMA REVISÃO BASEADA NO CASO DO ALTO RIO PARANÁ

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**Abstract:**

Although the anabranching channel pattern is frequent in rivers of different sizes and climates, understanding the processes involved in its genesis requires further research, especially focusing on island formation. This article discusses the processes involved in anabranching patterns and island formation, focusing on the environmental characteristics and sedimentary records in a stretch of the Upper Paraná River - PR. We compare the results with concepts and definitions in the literature. Islands in the Upper Paraná River form in two ways: from 1) the stabilization of central bars (in-channel processes) and 2) the floodplain cutoff (off-channel processes). The islands of the first case are generally smaller and younger than those formed by off-channel processes. Both islands can expand their surface by attaching lateral bars. Multi-channeling, island formation, and permanence can be explained through the concept of maximum flow efficiency.

**Resumo:**

Embora o padrão de canal *anabranching* seja muito comum em rios de clima e magnitude variada, a compreensão dos processos envolvidos na sua gênese ainda requer mais estudos, principalmente os que envolvem a formação de ilhas. Este artigo discute mecanismos que levam a multicanalização por meio da geração de ilhas e os registros sedimentares correlatos em um trecho do Alto Rio Paraná - PR. A formação de ilhas no caso estudo se dá por dois processos: 1) Intra canal, pela estabilização de barras centrais e 2) Extra canal, pelo recorte de planície de inundação. Embora as ilhas derivadas do primeiro caso sejam menores e mais recentes (ilhas datadas < 60 anos), podem atingir idade de até 8.200 anos AP. Por outro lado, as ilhas formadas por processo extra canal são maiores (até 10² km de comprimento), mas de idades indefinidas. Tanto ilhas evoluídas de barras centrais como as de recorte de planície de inundação podem aumentar as suas áreas por anexação de barras marginais. A ocorrência de canais múltiplos justificada pela atuação do conceito da Máxima Eficiência de Fluxo.

## 1. Introduction

Interest in research on multiple channel rivers has increased since Brice (1982, 1983) included the anastomosed pattern as a new end-member in the original tripartite classification proposed by Leopold and Wolman (1957) for alluvial channels. Contrary to the braided channel, in which an unstable sandy bar divides the river flow at the barfull level, the anastomosed pattern is essentially multichannel. In this case, the river consists of secondary channels defined by stable islands at the bankfull level. First, the multichannel river was considered a geomorphological rarity, exclusive to arid areas in Australia (STEVAUX and LATRUBESSE, 2017), being studied only from the architectural point of view of its sedimentary record (MIALL, 1977, 1980). Currently, multichannel patterns are recognized in the most varied landscapes and climates on the planet (STEVAUX and LATRUBESSE, 2017).

Although multichannel rivers are extremely common, most of their classifications or descriptions have developed from studies in medium and small rivers as well as in flumes. Latrubesse (2008) presented an initial classification for large multichannel river systems based on the degree of anabranching (number and channels per section), flow magnitude, width/depth ratio, sinuosity, and slope. The author also mentioned that the anabranching pattern is predominant in mega-rivers (medium discharge > 17 000 m³ s⁻¹). In this study, we use the term multichannel in the same manner as anastomosing or anabranching, as mentioned by Stevaux and Latrubesse (2017).

Huang and Nanson (2007) show that anabranching is the product of the slope adjusting with a consequent increase of flow efficiency. On the other hand, the authors also demonstrate that flow efficiency can be significantly increased by channel width reduction through the formation of vegetated islands: the presence of islands decreases channel width. Other studies on multichannel formation processes also present the hydraulic slope, flow, and bed sediment input as essential characteristics of the

system for the development of the anabranching pattern (NANSON and KNIGHTON, 1996; STEVAUX and LATRUBESSE, 2017). Besides, the influence of human activities is added, such as the construction of dams, which alter the balance between the supply of sediments and their transport capacity, which generally impacts the pattern of the river channel (SLOWIK *et al.*, 2018).

In this context, islands are considered an essential component in multichannel pattern physiography. However, these forms have not received much attention regarding the study of their formation until the mid-1990s. Nanson and Knighton (1996) and Nanson (2013) demonstrated that islands can evolve from the interaction between the stabilization of sandy bars and vegetation settlement. Once formed, the island increases by attachment of the lateral bar and frontal bars (NANSON and KNIGHTON, 1996; LELI *et al.*, 2018). Islands are formed by in- and off-channel processes (LELI *et al.*, 2020a). According to these authors, during the in-channel process, islands are formed by fixing central bars to an existing island or bar. Those from the off-channel process result from channel avulsion and floodplain cutoff.

In studies of large rivers in the Amazon, Latrubesse and Franzineli (2005), Latrubesse *et al.* (2005), and Latrubesse and Stevaux (2013) characterized the large lake islands of the Negro River originating from the formation of sandy bars during the Late Holocene, when the river carried a large amount of bed sediment. Lake-island is a rare type of in-channel island practically unknown in the literature (LELI *et al.*, 2016). In the Upper Paraná River, Leli (2015) and Leli *et al.* (2018) observed the occurrence of islands formed from central bars (in-channel processes) and derived from the avulsion process (off-channel process).

Although the recognition of the multichannel pattern is a consensus in the literature, the understanding of its formative processes, morphological resilience, and sedimentology remains the subject of ongoing research (CARLING *et al.*, 2014). The objective of this study is

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to present a review of the processes involved in island formation and multi-channeling development based on the results from the Upper Paraná River. The Paraná River is one of the ten largest rivers in the world (LATRU-BESSE, 2008). In the last 40 years, it has been studied in different fields, mainly ecology (e.g., THOMAZ *et al.,* 2004; IRIONDO *et al.,* 2007) and geomorphology (e.g., ORFEO *et al.,* 2020). Concerning fluvial geomorphology, these studies provided significant knowledge on channel morphology, pattern, hydrology, hydraulics, and sedimentology (STEVAUX, 1994; DRAGO and AMSLER, 1998; ORFEO and STEVAUX, 2002; ALARCÓN *et al.,* 2003; STEVAUX and SOUZA, 2004; MARTINS and STEVAUX, 2005; SANTOS *et al.,* 2017). These facts contributed to the use of the Paraná River as a comparative model for other river systems.

## 2. Method and study area

In this study, we used local and general references. We tried to compare the concepts and definitions with the results obtained in the study area. The greatest difficulties emerged in terms of the different magnitudes of the systems: in general, the basic references in the literature concern river systems smaller than that of the study area.

The Upper Paraná River extends for approximately 600 km, entirely in Brazilian territory, from the confluence of the Grande and Paranaíba rivers (20° 04' 49″ S 51° 00' 08″ W) up to the Sete Quedas Falls (currently, Itaipu Dam's lake), the largest knickpoint in the basin (Fig. 1). The Upper Paraná River Basin is one of the most dammed large river basins in the world (STEVAUX *et al.,* 2009), with more than 150 large dams in operation. Only 235 km of the upper reach, from Porto Primavera and Itaipu dams, are in natural non-dammed conditions. The river in this reach is multichannel and formed by 265 islands, with nodal sections of 1100 m in width up to 12 500 m in the six-channel section of Porto 18 (LELI, 2015; LELI *et al.,* 2018). The Upper Paraná presents the lower slopes typical of large rivers between 3.0 and 6.0 cm km$^{-1}$.
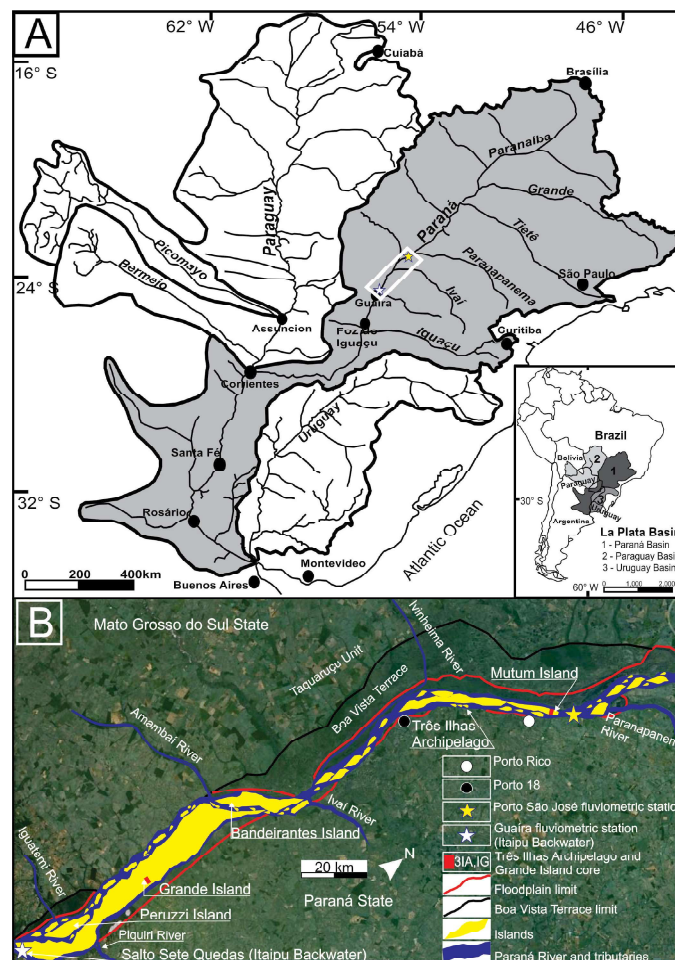


*Figure 1 - A) Paraná River watershed. The white rectangle highlights the study area in the Upper Paraná River. B) Details of the study area. Islands are denoted in yellow.*

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Two Late Pleistocene terraces occurs at the right bank of the river at 20 m (Taquaruçu Terrace) and 10 m (Fazenda Boa Terrace) above the river average water level (STEVAUX, 1993, 1994, 2000). The floodplain develops on the right bank. It presents a very complex morphology generated by a long history of avulsions, island incorporations, and secondary channel developments. Stevaux and Souza (2004) classified this floodplain as a meandering-anastomosed alluvial plain, according to the conception by Nanson and Croke (1992). The left bank is formed mainly by a 20 m tall sandstone wall of the Caiuá Formation (K).

The average temperature in the region is 22 °C and the annual rainfall is 1200 mm. At the Porto São José gauge station (upstream), with a historical series of 60 years, the average discharge varies from 8400 $m^3 s^{-1}$ during the dry season (June–August) to 13 000 $m^3 s^{-1}$ during the flood period (November–March). The extreme discharges recorded at this station were 33 740 $m^3 s^{-1}$ in 1983 and 2 550 $m^3 s^{-1}$ in 1969. At the Guaíra - PR gauge station (downstream), in operation since 1910, the average discharge is 10 800 $m^3 s^{-1}$, with an extreme of 2 490 $m^3 s^{-1}$ in 1944 and 39 870 $m^3 s^{-1}$ in 1983 (SOUZA FILHO, 1993).

## 3. Sedimentary processes in-channel environment

### 3.1 Sediment transport

The construction of the Porto Primavera hydroelectric dam determined a new configuration of hydrology and load transport in the studied stretch of the Upper Paraná River (CRISPIN, 2001; MARTINS and STEVAUX, 2005; STEVAUX *et al.,* 2009; SOUZA FILHO, 2016). Although effectively completed in 1998, since 1991, the construction of the dam began to interfere in the canal due to the installation of cofferdams for the construction of concrete structures (SOUZA FILHO, 2016). Souza Filho *et al.* (2010) observed changes in the dissolved load in measurements made in Porto São José after dam closure. The authors identified a reduction in P, Ca, Fe, Sr, Si, Mg, Zn, Pb, Al, Cd, Cu, Co, and Ba, and an increase in Na, K, Cl, and Ni as well as an increase in water temperature and a decrease in pH during the flood season.

Analyses from different sources have shown that, during the construction of the Porto Primavera Dam, significant changes in suspended sediment discharge occurred in the region of Porto Rico (Fig. 1). The values of 214.7 kg $s^{-1}$ in the pre-dam period increased to 222.2 kg $s^{-1}$ during construction and drastically reduced to 56.4 kg $s^{-1}$ after dam closure (SOUZA FILHO, 2016). Other studies have confirmed the gradual retention of suspended sediment by the dam. The suspended sediment concentration reduced from 35.0 mg $L^{-1}$ to the current 0.5 mg $L^{-1}$ (CRISPIN, 2001; STEVAUX and TAKEDA, 2002; MARTINS and STEVAUX, 2004). This concentration partially recovered downstream of the confluence of the Ivaí and Piquiri rivers (Fig. 1). The Ivaí River supplies 2 097 292.6 t $y^{-1}$ of suspended sediments (LELI *et al.,* 2017), increasing the concentration to 5.0 mg $L^{-1}$ (FRANCO *et al.,* 2008). The Piquiri River introduces 1 593 506 t $y^{-1}$, increasing the concentration of the trunk river to 16.2 mg $L^{-1}$ (BENNERT, 2018).

Analyzing the bed load is more difficult, owing to the lack of data obtained directly in the field before dam construction, but it is assumed that the bedload transport has also changed (SOUZA FILHO, 2016). Martins and Stevaux (2005) and Stevaux *et al.* (2009) analyzed the bed transport in the Porto São José section over three periods (from 2001 to 2007) (Fig. 1), finding values from 31.36 to 37.31 kg $s^{-1}$ for flows between 6762 and 9769 $m^3 s^{-1}$ and 115.23 kg $s^{-1}$ for a flow of 18 136 $m^3 s^{-1}$.

In general, Souza Filho (2016) suggested that the closure of the Porto Primavera Dam reduced, in the reach near Porto Rico, 74.6% of suspended load and 58.7% of bedload discharges, with a total reduction of 71.7% in sedimentary transport. Such information is essential for understanding some current forms and processes that occur in the Paraná River.

### 3.2 Bedforms

The bedforms of the Upper Paraná River (region of Porto Rico - PR) are lower and upper flow regime flat beds, ripples, dunes, and sand waves (STEVAUX, 1994; STEVAUX *et al.,* 2009). Sand waves are bed forms constructed by the accumulation and overlapping of smaller forms formed during large floods (Fig. 2). In general, sand waves emerge at medium-low water levels, constituting sand bars. Stevaux and Takeda (2002) and Martins and Stevaux (2005) measured dunes up to 100 m in length, up to 2.20 m in height, with a linear movement of 45 meters per month for periods of lower discharge and 67 meters per month during the flood periods (Fig. 3). Antidunes are rare in the Upper Paraná River that normally present low flow regime (Froud number = 0.9, according Martins, 2004). However, Leli (2015) reported the occurrence of antidunes during floods near the Piquiri River mouth.
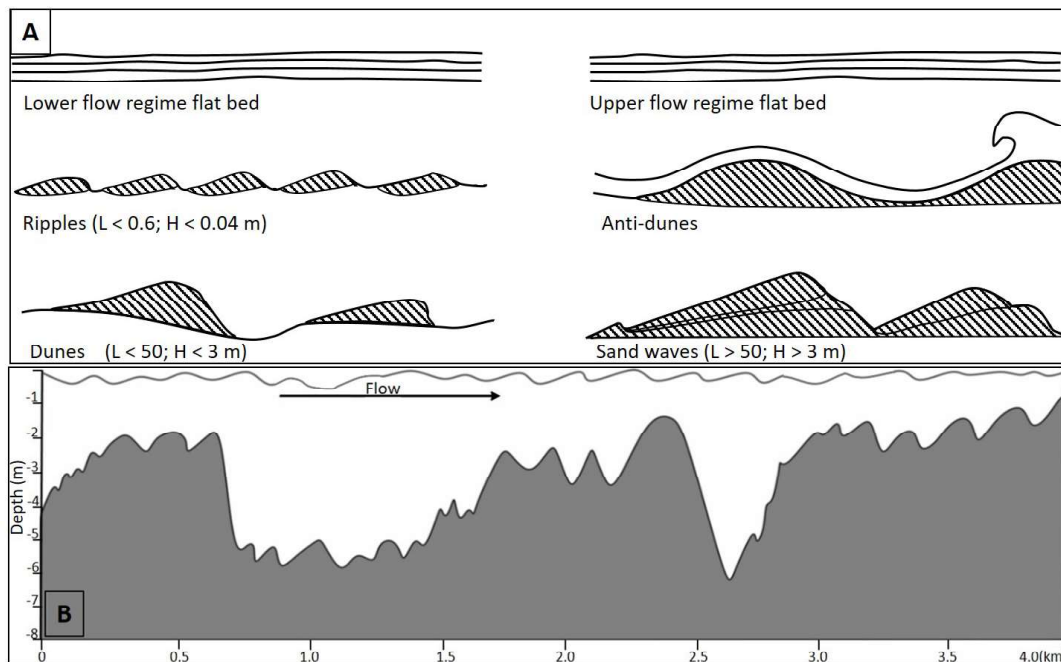
*Figure 2 - Upper Paraná River bedforms. A) Types of bedform in relation to flow regime (Source: SIMONS and RICHARDSON, 1966). B) Typical longitudinal echo sound bathymetrical profile in the Upper Paraná River; it is possible to observe ripples, dunes, and sand waves of different sizes.*
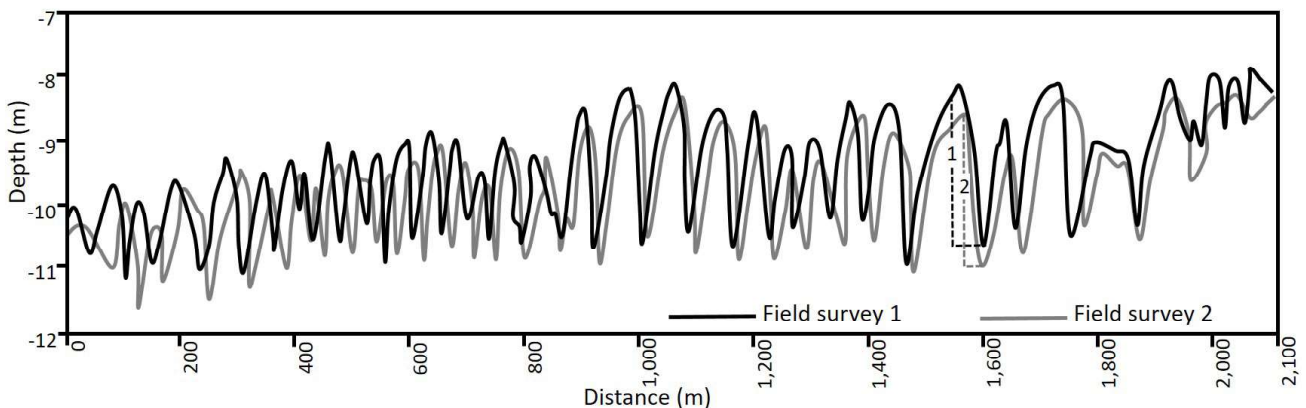


*Figure 3 - Dune displacement in the Upper Paraná River. Bedform displacement was observed over 20 days (Mod. MARTINS and STEVAUX, 2005).*

There were no significant changes in bedload displacement speed after the closure of the Porto Primavera Dam. However, Stevaux *et al.* (2009) found that the average height of dunes reduced from 2.2 to 1.5 m after dam operation. The authors associate this morphological alteration as a result of the alteration in the bedload texture that changed from fine/medium to medium/coarse sand at several points in the channel.

Such changes in the bedload are due to changes in the river regime introduced by the operation of the dam. Santos (2010) and Santos *et al.* (2017) estimated that the movement of the coarser bedload occurs during discharges greater than 10 853 m³ s⁻¹. However, as the water

is normally stored in the dam during the rainy season, it significantly reduces the flood peak downstream. In this way, the flows of greater competence for the mobilization of the coarser sediment are rare or disappear, and only the transport of the finer load is maintained. In such a condition, the finer material is removed from the bedload and not replaced because the dam prevents its replacement from upstream. The coarser material does not move and forms lag deposits that pave the channel (armoring effect) with a consequent reduction in the bedform height and steepness (STEVAUX *et al.,* 2009; STEVAUX and LATRUBESSE, 2017).

### 3.3 Bars

Bar morphologies are formed from the accumulation of bedforms that emerge at the mid-water level of the river. Generally, sandy bars are ephemeral and can be eroded during river floods, but they can also stabilize and evolve into islands (STEVAUX, 1994; ORFEO and STEVAUX, 2002; LELI, 2015; LELI *et al.,* 2018). The factors that contribute to the stabilization and fixation of the sandy bars are, mainly, the absence of extreme floods (floods with above average flow) for a relatively long period and vegetation cover development (STEVAUX, 1994). Although its surface consists mainly of sand, when the barfull level is reached during ordinary floods, the bar can receive a deposition of fine material (clay and silt), which forms thin layers of mud on the surface. This situation protects the surface of the bar from wind erosion and serves as a substrate for the implantation of pioneer grass and herbaceous vegetation. The more this type of flood occurs, the greater the chances of a bar being preserved in eventual larger floods. In this way, the bar starts functioning as an in-channel floodplain, with aggradation of fine sediments (FERNANDEZ *et al.,* 1993; STEVAUX, 1994).

Bars can be classified according to their morphology (SUNDBORG, 1956; COLLINSON, 1970), size (SMITH, 1974), stability (JACKSON, 1975), occurrence mode (isolated or in the group) (SMITH, 1974, 1982), and based on the channel pattern (READING, 1978; KELLERHALS *et al.,* 1976). The highly accepted classification of Smith (1976) uses the morphology and position in the channel to classify a bar as longitudinal, transverse, point or diagonal. Suguio and Bigarella (1990) contributed to the classification of the bars considering the position in the channel (lateral and longitudinal bars) and the formation process. Santos *et al.* (1992), Souza Filho (1993), Stevaux (1994) and Turra *et al.* (1999) presented the first classification of the bars of the Upper Paraná River (Fig. 4, Tab. 1) that included the central, lateral, attachment, frontal (or island head bar), and confluence bar. Leli (2015) and Pereira (2016) identified, in the Paraná River, the Moa bar, a special type of lateral bar formed during flood events, described early in the Amazon Basin rivers (LATRUBESSE, 1992; STEVAUX and LATRUBESSE, 2017).



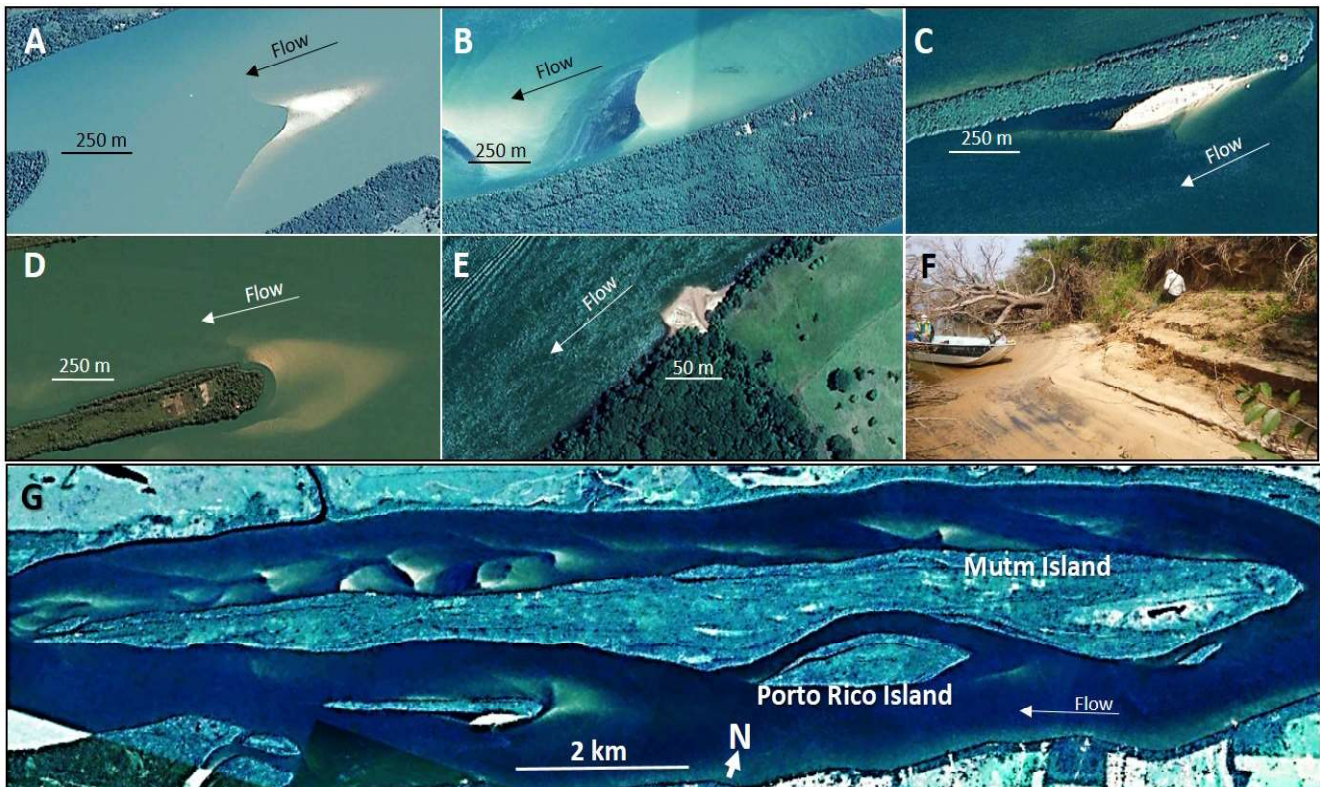*Figure 4 - Sand bars of the Upper Paraná River: A) central bar; B) lateral bar; C) annexation bar; D) head island bar; E) confluence bar; F) Moa bar; and G) Mutum and Porto Rico islands with lateral bars in its right bank. Note the longitudinal scars generated by lateral bar annexations on the surface of the island.*

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**Table 1: Emergent depositional forms in the channel**

| Form | Description | Reference |
|---|---|---|
| Central bar | Amoeboid triangular-shaped sand body, 200 to 1000 m in length. Formed in an isolated manner in the central sectors of the channel by the emersion of sand waves at the average level of the water. | Santos *et al.* (1992) |
| Lateral bar (Attachment bar) | Elongated morphology, with a high length/width ratio. Deposited 10 to 20 m from the island (or channel) banks due to the low-velocity zone occurrence. When they join the island (or channel), banks are called attachment bars. | Santos *et al.* (1992) and Santos *et al.* (2017) |
| Island head bar | Defined as modified forms of the central bars, with an emergent extension of up to 45 ha and a length greater than 1500 m. They are formed when a central bar is attached to the upstream part of an island and gains greater stability. | Souza Filho (1993) |
| Confluence bar | Formed by the combination of two different flows (rivers confluence). The hierarchical dynamics between the flows allows for the formation of low-speed zones with reduced transport capacity, forming the deposition of the sedimentary load at the confluence. | Turra *et al.* (1999) |
| Flood bar (Moa bar) | Relatively narrow forms anchored on the high banks of the river channels. They are formed during a flood when the concentration of suspended sand load is higher than in average flow. Moa bar occurs due to increased roughness and decreased flow velocity near the channel banks. | Latrubesse (1992) |
| Island | Different from bars, islands are channel deposits that stay emergent at the bankfull level. In general, islands are formed by fine overbank deposits. They are depositional, vegetated forms of varying sizes and can be in any part of a channel. They can be formed by the evolution of a central bar (in-channel processes) or by floodplain cutoff (off-channel processes). Both types of islands can have the area expanded by the process of bar attachment (in-channel processes) (Fig. 5, 6, and 8). | Stevaux (1994), Leli (2015), and Leli *et al.* (2017) |

## 4. Islands

According to the definition provided by Brice (1964), islands differ from the bars in that they keep the river flow separate at the bankfull level and persist in the system from $10^1$ to $10^3$ years in the Upper Paraná River (LELI, 2020a). These characteristics give the islands a fundamental role in the flow hydrodynamics of multichannel rivers (Fig. 5, Tab. 1). Islands are formed by processes developed inside (in-channel) or outside (off-channel) the channel. The island formation process is an important and determining factor in age, size, surface morphology, and characteristics of the vegetation cover (LELI *et al.,* 2018; LELI *et al.,* 2020a).

### 4.1 Central bar island (in-channel processes)

A stable and partially vegetated sandy bar is the precursor stage for central bar island formation (Fig. 5A, B, C and D). Leli *et al.* (2018, 2020a,b) found that the presence of vegetation in the bar favors the deposition of fine sediment on its surface. Thin sediments, in turn, increase fertility and help plant development in a positive feedback system. With the vertical accretion of fine sediments, the surface of the island bar progresses gradually, rising in relation to the water level, which allows for the fixation of larger plants until, finally, it is covered by tree vegetation (STEVAUX, 1994). The process continues until the surface of the island reaches the approximate level of the natural levee system. Stevaux (1994) established, based on the sedimentary composition, that the separation between the bar and island occurs in the contact of the basal sand with the top mud.

The sedimentary sequence of this type of island demonstrates the channel phase composed of sand from the initial bar, followed by the phase of island formation with the vertical accretion of fine deposits during the floods (Fig. 6A). In cores from Mutum Island, the contact between sand and the island environment is dated 8200 y BP (LELI *et al.*, 2020b).
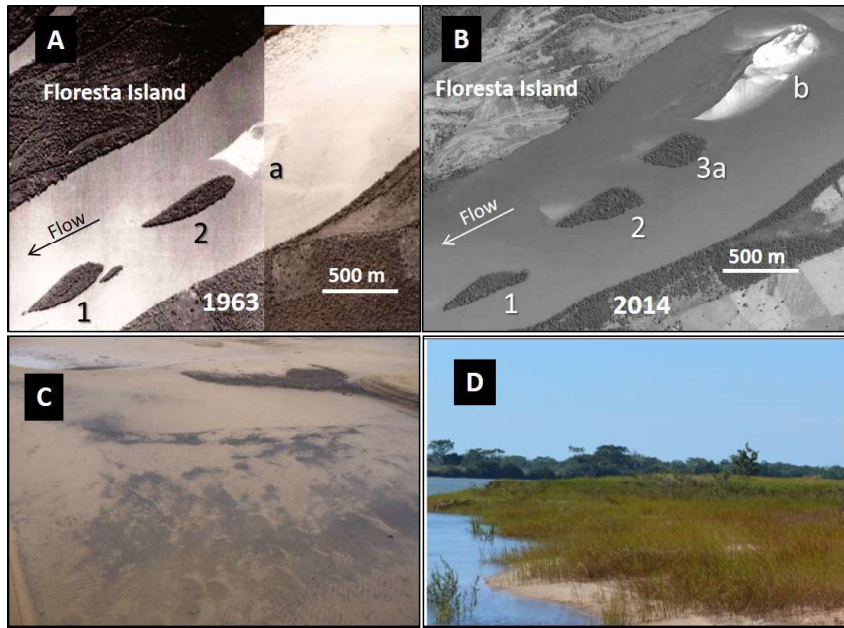
*Figure 5 - Evolution process from central bar to island in the Upper Paraná River. A) Aerial photograph in 1963 showing two islands (1, 2) and an upstream central bar (a). B) The former bar evolved to an island (3a) forming the Três Ilhas Archipelago in the 2014 satellite image. A new sand bar formed upstream the archipelago (b). C) and D) The surface of the sand bar (b) covered by fine sediments (C) and grassy vegetation and some shrubs (D). Source B: Google Earth™, SPOT sensor, 2014.*
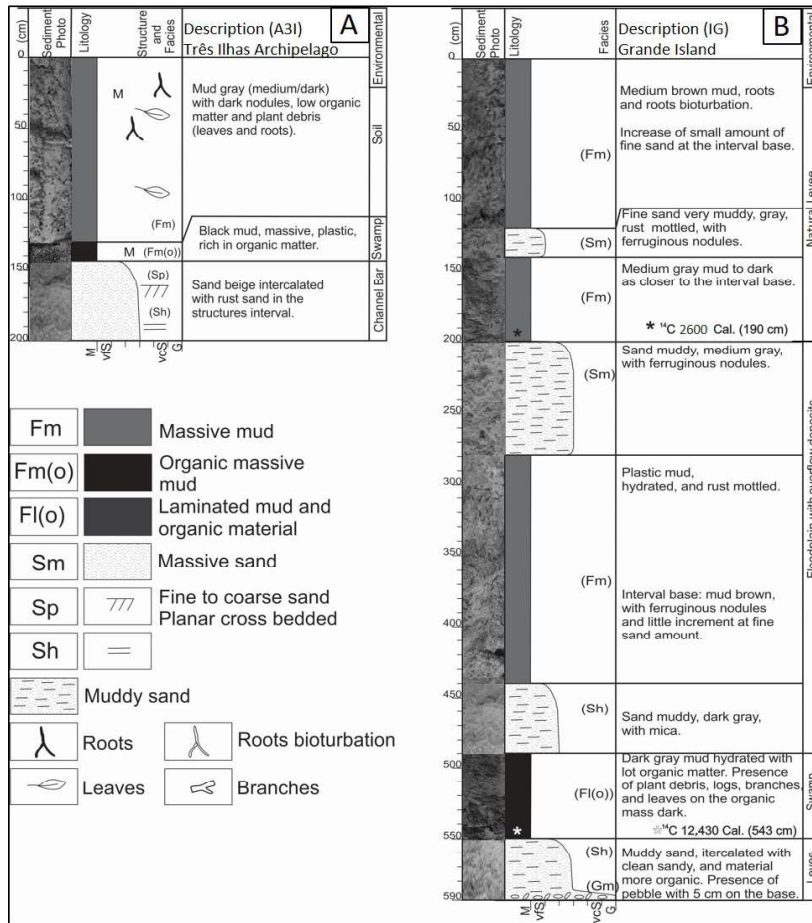


*Figure 6 - Depositional sequence and sedimentary facies of islands in the Upper Paraná River. A) Central bar island (in-channel processes). Location information is presented in Figures 1 and 4. B) Floodplain cutoff island (off-channel processes). Floodplain deposits are very old (12 430 y BP) when compared with the current natural levee deposits (2600 y BP) in the island border. Location information is presented in Figures 1 and 8. Source: Leli (2015).*

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**4.2 Floodplain cutoff island (off-channel processes)**

A floodplain cutoff island is formed by the avulsion and incision of a channel on the floodplain and its junction with the main channel downstream (Figs. 7 and 8). Thus, the deposits of this type refer to the processes in which the floodplain environment was formed. It is a very common process in avulsion river systems in several rivers in the Pantanal, as mentioned by Assine (2003). Avulsion is favored in rivers with water levels higher than the surface of the floodplain, generating a hydraulic difference that favors the flow into the plain. This flow is usually fast and highly erosive. Ramonell *et al.* (2011) reported speeds of up to 2 m s$^{-1}$ in an avulsion on the Paraná River near Santa Fé, Argentina. The nature of the floodplain bank is also a factor in the installation of a crevasse. Sandy banks, for example, are more susceptible to erosion than muddy banks and are potentially subject to crevassing, enabling the formation of floodplain channels.
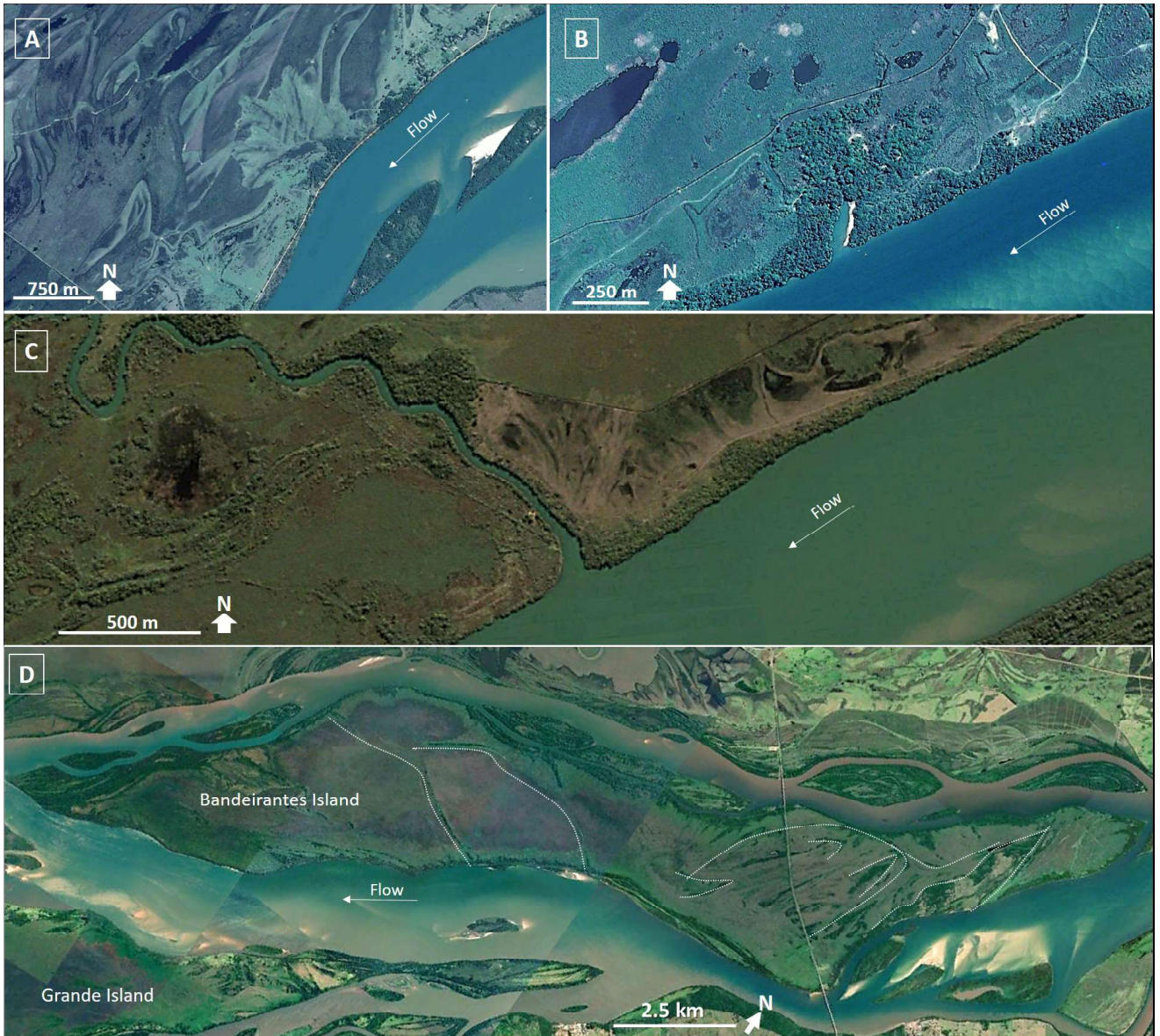


*Figure 7 - Floodplain cutoff islands formation processes (off-channel). A) Levee crevasse and splay with indefinite drainage; B) Levee crevasse with the beginning of a floodplain channel formation; C) Floodplain channel formed from a crevasse. This channel connects to the Paraná River 25 km downstream; D) Bandeirantes Island formed by floodplain cutoff. The right channel is the former crevasse channel that cut the floodplain. Note that some features on island surface were inherited from the ancient floodplain.*

*Figure 8 - Grande Island, the largest on the Paraná River. Formed by floodplain cutoff, this island divided the river into two wide channels. Due to its impressive size (8 km wide and 90 km long), this island functions as a floodplain with natural levees, floodplain channels, and bay flood areas. Features inherited from ancient floodplain are shown in general and with details: paleo-natural levees (1), paleochannels (2), paleo-islands (3).*

The longitudinal and transverse floodplain slopes and the magnitude of the avulsion channel determine the size and shape of the cutout sector. As part of the floodplain, the islands formed by the floodplain cutoff preserve its inherited features as flood channels, paleo levees, and paleochannels (Fig. 8). In the case of the Paraná River, islands of this type are generally much larger than those of the central bar at approximately 100 km in length, as in the case of the Bandeirantes and Grande islands (Figs. 1, 7, and 8). However, it is very difficult to establish the age of these islands because deposit dating refers to their deposition in the floodplain and not their incision due to the avulsion of the channel (Fig. 6B). Stevaux and Souza (2004) reported a very important phase of generalized avulsion in the Upper

Paraná River about 2800 yr BP. It is possible to see in the core IG – Grande Island (Fig. 6B): the formation of the current island natural levee began 2600 yr BP, after the floodplain cutoff.

Sedimentary studies of the floodplain cutoff islands in the Upper Paraná River are similar to the depositional model of the floodplain in the area studied in the upper section. Leli (2015) compared the deposits of Grande Island with those from the floodplain and found similar processes and ages (Fig. 6B). It consists of basal sandy channel deposits overlaid by a typical floodplain sequence of mottled sandy mud intercalated with layers of fine muddy sand. At the top, fine deposits from crevasse splay can occur. Floodplain deposits of Grande Island were dated at 12 430 yr BP.

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An impressive other example of floodplain cutoff island is the Bananal Island formed by the avulsion of the Araguaia River (Fig. 9). Gradually, the original channel (the current Javaes River) was abandoned becoming a secondary channel and transferring the major of its flow to the avulsion channel: the current Araguaia River. The Bananal is probably the largest fluvial island in the world with 330 km in length and 70 km in width.
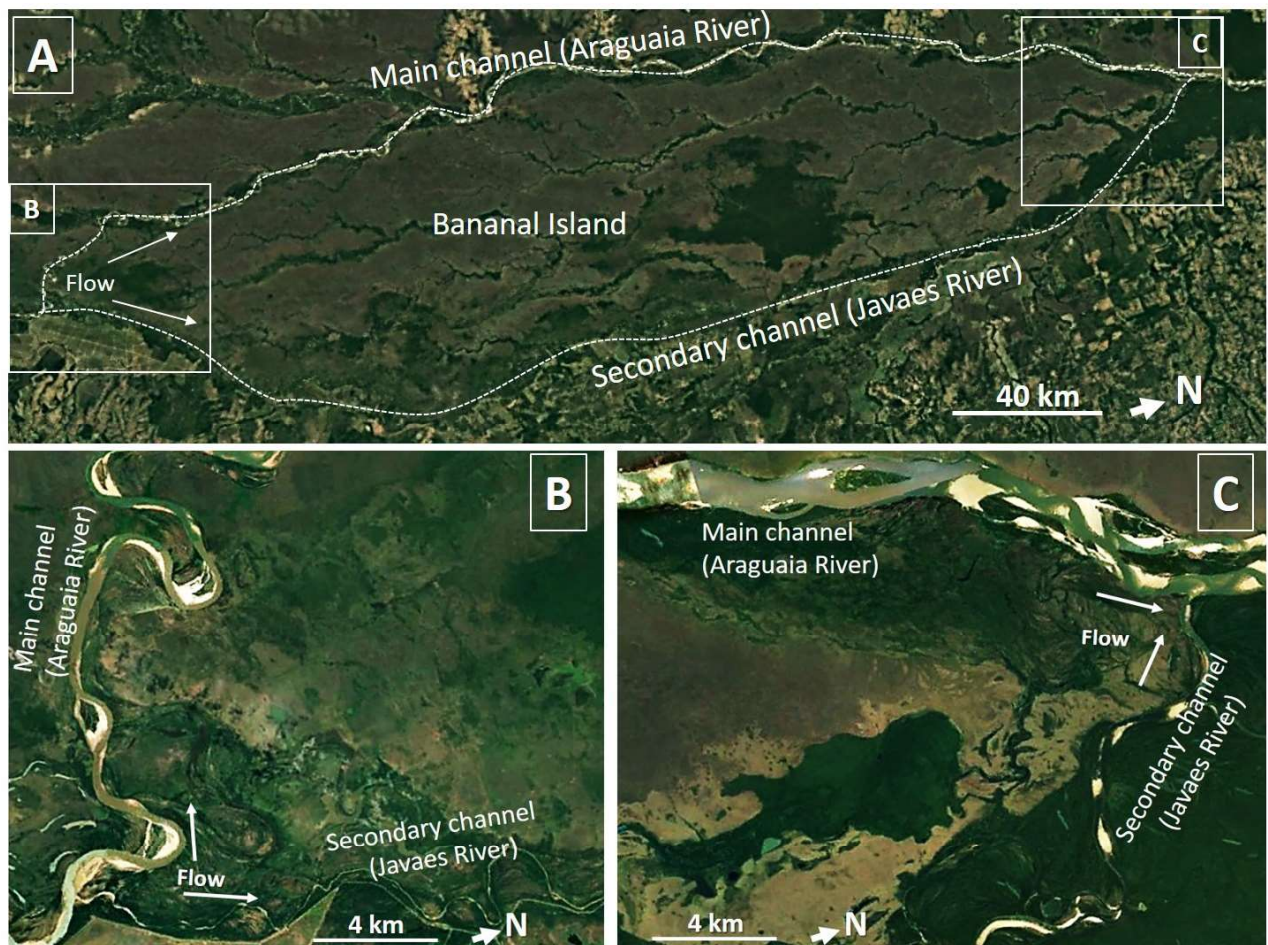


*Figure 9 - (A) The Bananal Island formed by the Araguaia River and its original channel, Javaes River, in detail at diversion (B) and junction (C) points.*

### 4.3 Superficial expansion of the islands

After its formation, both the central bar island and the floodplain cutoff island can reduce or expand in area, depending on the hydrological and hydraulic conditions, and transported load availability (STEVAUX and LATRUBESSE, 2017). Leli *et al.* (2020b) defined composite islands as islands that increased in size. The island surface expands due to the attachment of lateral and frontal bars (STEVAUX, 1994; LELI *et al.,* 2018). The presence of the island in the channel separates the flow, generating a hydraulic disturbance called a low-speed flow zone (Fig. 10) (SANTOS *et al.,* 2017; LELI, 2015; LELI *et al.,* 2020b). When the bedform downstream entrainment approaches the low-speed flow zone, the deposits form a lateral and/or an island head bar. In general, the lateral bar forms 10 to 20 m away from the island, generating a bar island (LELI, 2015; LELI *et al.,* 2018). Mutum Island, a central bar island, was formed by this process. On the surface of the island, it is possible to observe the long longitudinal scars of the ancient bar-island channels that were formed during the island evolution (Fig. 4G).
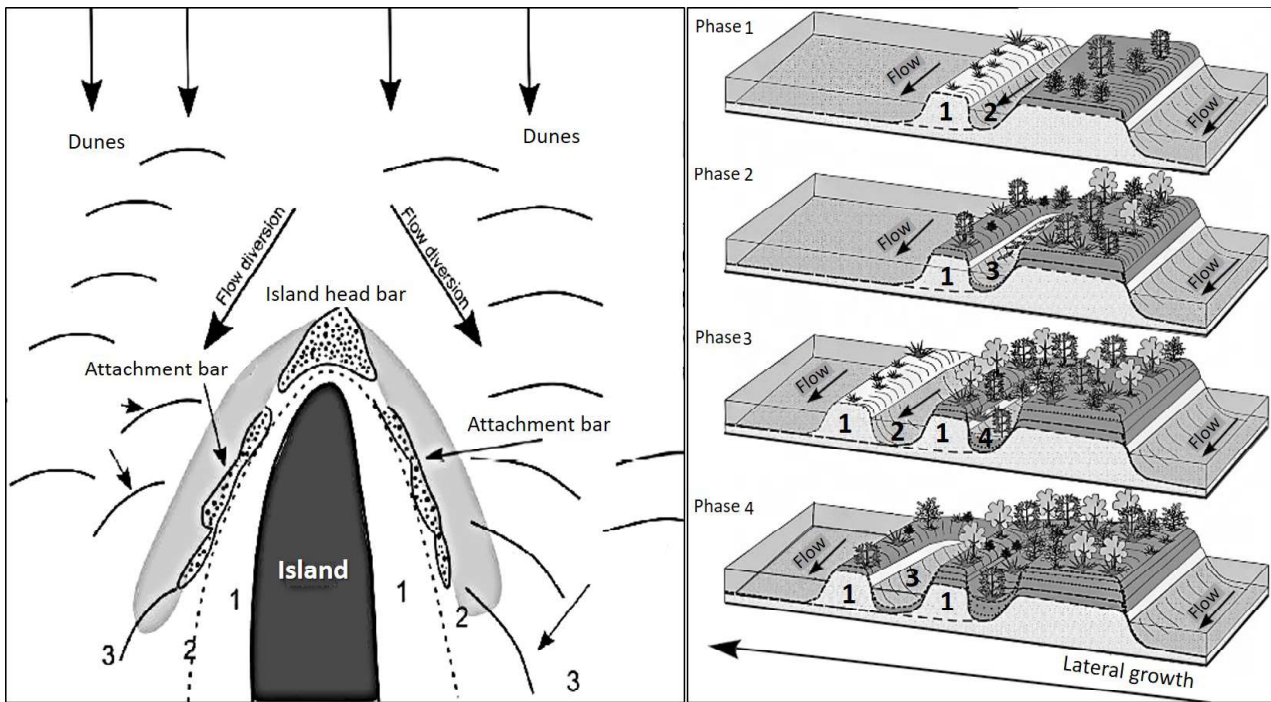
Figure 10 - Left: Lateral and frontal bar formation by flow separation. The obstruction caused by an inland generates a U-shaped low-velocity zone (2). The bed form entertainment deposit at the low-velocity zone forming attachment bars (lateral and island head bars) (3) (Mod. SANTOS et al., 2017). Right: Scheme for island surface expansion by lateral bar attachment. Phase 1: the deposition of a lateral bar (1) defines a bar-island channel (2). Phase 2: Vertical aggradation of fine sediment on the bar and island; the bar-island channel changes to a blind channel (3) and begins to be silted. Phase 3: A new lateral bar and a new bar-island channel is formed (1) and the blind channel changes to a swamp (4) inside the island, where the process of vertical aggradation of fine sediments continues. Phase 4: The process continues, and the former island has its area expanded (Mod. LELI, 2015).

## 5. Discussion

### 5.1 Geomorphological approach

The anabranching pattern of the Upper Paraná River in this study has more than 200 islands of different dimensions, morphologies, and geneses. Off-channel process islands form via channel avulsion and floodplain cutoff. It is a complex mechanism involving natural levee crevassing, crevasse channel formation on the floodplain, and crevasse channel re-junction to the river channel. In turn, the central bar island forms from the stabilization of a central bar followed by vertical aggradation of fine sediments deposited during the floods. Different islands formed by the in- and off-channel processes indicate that the channel has gone through periods of different hydrological conditions in the anabranching system formation. Island age varies when comparing the two forming processes. Absolute dating processed in different island types (STEVAUX, 1994; LELI, 2015; LELI et al., 2020b) suggest that the island construction by in-channel

processes is more active and has been present in the system since the beginning of the Holocene. Such stability and permanence are observed in the Mutum Island formed 8200 y BP, Porto Rico Island formed 920 y BP (ZVIEJKOVSKI et al., 2017), and the Três Ilhas Archipelago (Fig. 4G and 5) with islands that are 60 years old. Although the study section is affected by the Porto Primavera Dam, it is relevant to consider that the system still has a minimal condition for the in-channel process functioning. This was confirmed by the occurrence of a large central bar upstream of the Três Ilhas Archipelago, which has been stable for 17 years and colonized by grassy and shrubby vegetation (Fig. 5).

The ages of the floodplain cutoff islands (formed by off-channel processes) varied between the Late Pleistocene and the Late Holocene. However, these ages are related to floodplain deposition and not that of the floodplain incision, which indicates island forma-tion. Studies carried out by Stevaux and Souza (2004) reported a major avulsion event in Upper Paraná River in the Upper Holocene, around 2800 y BP. This event

may be responsible for the generation of many flood-plain cutoff islands in the river system. This was the last event that formed this type of island. Currently, the rare avulsions occurring in the system do not have sufficient strength or magnitude to excavate secondary channels in the plain (Fig. 7). Fortes *et al.* (2004) suggested that the occurrence of neotectonic events in the Holocene may have triggered major avulsion in the river system.

In both cases of island formation, the bedload supply and lateral bar formation are important for island expansion. Although the construction of dams in the upper basin, especially the Porto Primavera Dam, has reduced the transport of suspended sediment and bedload, the system continues to form lateral and central bars. The annexation of lateral and frontal bars to both types of islands is currently observed. However, it is impossible to determine the velocity of these processes and compare them with the pristine condition.

### 5.2 Hydraulic approach

Since the 1990s, multi-channeling has been studied more closely by river geomorphologists. The pioneering work of Nanson and Knighton (1996), Tooth and Nanson (2000), Huang and Nanson (2000), and Huang and Nanson (2007) not only proposed a new classification for multichannel rivers, but also asked about the need for a river to promote multi-channeling. At that time, Huang and Nanson (2000) stated that the channeling could improve specific stream power ($\omega$). According to the stream power equation ($\omega = \gamma Qs/w$), $\omega$ is increased by increasing s and/or reducing w at the discharge (Q) and water density ($\gamma$) constants.

Based on this premise, the authors proposed the principle of maximum flow efficiency. This theme was later mentioned by Latrubesse (2008), who applied this concept to justify the multiple patterns of the largest river systems in the world. According to the author, mega-rivers ($Q > 17\ 000\ m^3\ s^{-1}$) must transport large amounts of water and sediment for hundreds to thousands of kilometers under very low hydraulic slopes (< 0.00005), thus justifying multi-channeling. However, this process occurs in rivers of any magnitude, including the small Australian courses in which Nanson and Knighton (1996) established the classification of multichannel rivers. The iconic inquiry posed by the title of Huang

and Nanson's article (2007) "*Why some alluvial rivers develop an anabranching pattern*" was answered in a detailed theoretical study. Using hydraulic equations, the authors concluded that, in the impediment to adjust the slopes, rivers reduce the width of the channel and increase its efficiency. Practical evidence was presented by Gon (2012) and Stevaux *et al.* (2013), who calculated the efficiency of the multiple channels of Upper Paraná River using the transported load. The authors compared the transport rates in nodal sections with those in multi-channel ones (up to six channels) and concluded that as the channel widened, the number or width of the islands directly increased. In truth, as the width increased (from 2 to 6 km), the channel compensated by islands formation, maintaining the effective width (sum of the channel widths in one section) of approximately 2.5 km and the specific channel power at approximately 3.2 W m$^{-2}$ throughout the multichannel reach.

### 5.3 Sedimentary approach

The sedimentary records of the Paraná River deposits are relatively simple, although applying facies analysis is difficult because of the few preservations of sedimentary structures (STEVAUX, 1994). A comparison of the depositional architecture model of Upper Paraná River with the classic model for anastomosed rivers proposed by Smith (1986) (Fig. 11) shows that the fundamental difference lies in the type of deposit stacking. The classic model, based on rivers under a strong tectonic influence, shows vertical stacking, generating vertical tabular bodies of sand wrapped in the mud. Such architectural evidence supports the generation of depositional space by tectonic subsidence. This model was quite popular among sedimentologists linked to oil prospecting to the point of stating that the formation of anastomosed pattern would only be possible in the case of areas subject to subsidence (SMITH, 1986; SHUSTER and STEIDTMANN, 1987). In the case study, it was evident that the generation of space by channel widening generates lateral (horizontal) accretion of deposits, without the need for subsidence. Unlike the classic tectonic-influenced model, it is quite likely that the Paraná River model could be the most common in the anabranching rivers of the world. Its architecture consists of a sandy basal lithosome covered by a muddy lithosome.
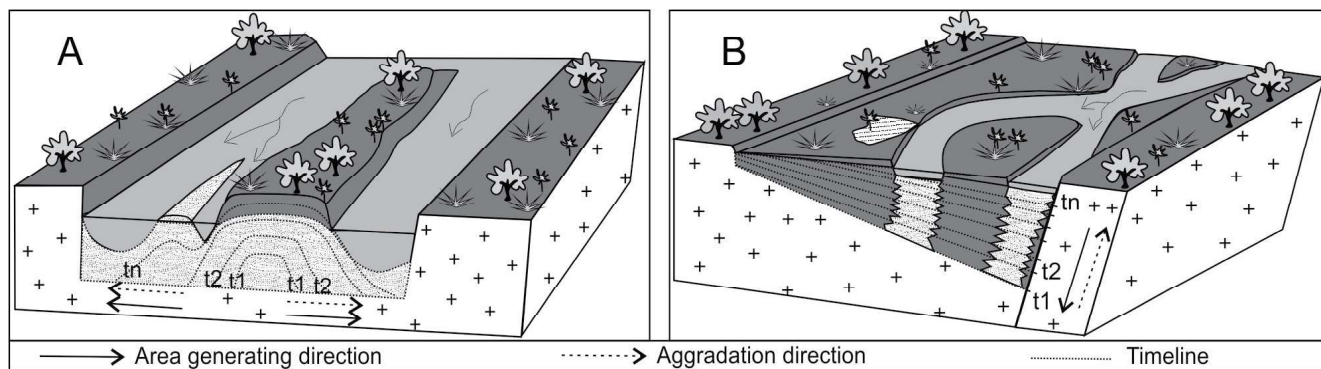
*Figure 11 - 3-D model of the depositional architecture of multichannel rivers. A: Upper Paraná River. Observe horizontal accretion over time (t1, t2, ... tn) (See Fig. 10 for further clarification). B: 3-D model of the tectonic-influenced anastomosed rivers (SMITH, 1986). Vertical accretion (t1, t2, ... tn) is generated by the subsidence of the alluvial plain. Source: Leli et al. (2020b).*

## 6. Conclusion

The Upper Paraná River has developed apparently active anabranching with the same hydrosedimentary characteristics as those estimated since the beginning of the Holocene. Although the basin underwent minor climatic changes during this period, such changes were not sufficiently intense to significantly affect the multi-channeling processes of the system. The changes imposed by the construction of dams throughout the upper basin likely affects the current hydrosedimentary processes. However, considering the immense size of the system, the reaction and relaxation times can span decades or even centuries.

Islands derived from the central bar, formed by in-channel processes, are directly related to the hydraulic balance of the system. Island formation is the way the river compensates for the increase in channel width. If the original dimension of the formed island is not sufficient to maintain flow efficiency, the island grows by the annexation of lateral and frontal bars. In contrast, islands from floodplain cutoffs are not related to hydraulic balance, but for such allochthonous reasons as a) occurrence and the dimension of the natural levees, b) floodplain transversal and longitudinal slopes, c) floodplain surface morphology (occurrence of flood channels, paleo-natural levees, paleochannels, etc.), and d) space available for sediment accommodation (more "empty" plains tend to accumulate water and sediment favoring the formation of avulsion channels). Once a floodplain cutoff island is formed, it can annex laterally and frontally in the same manner as a central bar island.

Thus, future fluvial geomorphology research, specifically in Brazil, should focus on a) reformulating the classification of multichannel rivers given the new results obtained in large river systems, mainly in the tropical belt; b) achieving a more detailed understanding of the hydraulics involved in the formation of multiple channels; and c) establishing sedimentary models, not only for island deposits, but for the floodplain itself. These topics suggest the need for new paradigms in fluvial geomorphology to replace those defined in the 1950s and 1960s based on medium and small fluvial systems in a temperate climate. These suggestions should be included in the objectives of the Oriented Working Group on the Fluvial Sub-system within the scope of the Brazilian Relief Classification System (SBCR).

## References

ALARCÓN, J.; SZUPIANY. N. ; MONTAGNINI, D. ; GAUDIN, H. ; PRENDES, H. ; AMSLER, M. Evaluación del transporte de sedimentos em el tramo médio del Río Paraná. In: Primer Simposio Regional sobre Hidráulica de Ríos, 1., 2003, Buenos Aires. **Anais...** Buenos Aires, Argentina. p. 1-15. (http://irh-fce.unse.edu.ar/Rios2003/RE/RE_1_1.pdf).

ASSINE, M. L. **Sedimentação da bacia do Pantanal Mato-grossense, centro-oeste do Brasil**. Tese (Livre-Docência). Instituto de Geociências e Ciências Exatas, Universidade

*Rev. Bras. Geomorfol. (Online), São Paulo, v.22, n.1, (Jan-Mar) p.103-120, 2021*

116

Estadual Paulista, Rio Claro. 2003. 106p.

BENNERT, A. **Morfologia e estrutura de fluxo na formação de ambientes de confluência: estudo de caso dos Rios Paraná e Piquiri.** Dissertação (Mestrado em Geografia). Universidade Estadual do Oeste do Paraná, Marechal Cândido Rondon. 2018. 111p.

BRICE, J. C. Channel patterns and terraces of the Loup Rivers in Nebraska. **Geological Survey Professional Paper,** 422-D, p. 1-47, 1964.

BRICE, J. C. **Stream Channel Stability Assessment**. Washington, D.C., Federal Highway Administration, Report No, FHWA/RD-82/021, 1982.

BRICE, J. C. Planoform properties of meandering rivers. In: ELLIOT, C.M. (org.) **River Meandering**. New York, American Society of Civil Engineers, p. 1-15, 1983.

CARLING, P.; JANSEN, J.; MESHKOVA, L. Multichannel rivers: their definition and classification. **Earth Surface Processes and Landforms**, v. 39, p. 26-37, 2014. DOI: 10.1002/esp.3419.

COLLINSON, J. D. Bedforms of the Tana River, Norway. **Geographical Annals**, v. 52, n. 1, p. 31-56, 1970. https://www.jstor.org/stable/4621528.

CRISPIM, J. Q. **Alterações na hidrologia do canal após a construção do reservatório a montante: O caso da Usina Hidrelétrica Engenheiro Sérgio Motta (Represa de Porto Primavera) Rio Paraná**. Dissertação (Mestrado em Ecologia de Ambientes Aquáticos Continentais). Universidade Estadual de Maringá, Maringá. 2001. 25p.

DRAGO, E. C.; AMSLER, M. L. Bed sediment characteristics in the Paraná and Paraguay Rivers. **Water International,** v. 23, n. 3, p. 174–183, 1998. Doi.org/10.1080/02508069808686764.

FERNANDEZ, O. V. Q.; SANTOS, M. L.; STEVAUX, J. C. Evolução e características faciológicas de ilhas no Rio Paraná, região de Porto Rico, (PR). **Boletim de Geografia**, v. 11, n. 1, p. 5-15, 1993. DOI: https://doi.org/10.4025/bolgeogr.v11i1.12173.

FORTES, E., STEVAUX, J.C., WOLKMMER, S. Neotectonics and channel evolution of the lower Ivinhema River, A right-bank tributary of the upper Paraná River, Brazil. **Geomorphology**, n. 70, p. 325-338, 2005.

FRANCO, A. A.; ETCHEBEHERE, M. L. C.; STEVAUX, J. C. Hipótese sobre os condicionantes neotectônicos do barramento natural da foz do rio Ivaí (PR/MS) com base em levantamento ecobatimétrico. **Revista Geociências UnG**, v.7, n. 1, p. 78-86, 2008.

GON, P. P. **Morfologia e hidrodinâmica em rios multicanais ("*anabranching*"): exemplo do Alto Rio Paraná**. Dissertação (Mestrado em Geociências e Meio Ambiente). Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro. 2012. 69p.

HUANG, H. Q.; NANSON, G. C. Hydraulic geometry and maximum flow efficiency as products of the principle of least action. **Earth Surface Processes and Landforms**, v. 25, p. 1-16, 2000.

HUANG, H. Q.; NANSON, G. C. Why some alluvial rivers develop an anabranching pattern. **Water Resources Research**, v. 43, n. 7, p. 1–12, 2007. DOI: https://doi.org/10.1029/2006WR005223.

IRIONDO, M. H.; PAGGI, J. C.; PARMA, M. J. (org.) **The Middle Paraná River: Limnology of a Subtropical Wetland**. Publisher: Springer, p. 382, 2007.

JACKSON, R. G. Hierarchical attributes and a unifying model of bed forms composed of cohesionless sediment and produced by shearing flow. **Geological Society of American Bulletin**, v. 96, n. 11, p. 1523-1533, 1975. DOI:https://doi.org/10.1130/0016-7606(1975)86<1523:HAAAUM>2.0.CO;2.

KELLERHALS, R.; CHURCH, M.; BRAY, D.I. Classification and analysis of river processes. **Journal of the Hydraulic Division**, v. 102, n. 7, p. 813-829, 1976.

LATRUBESSE, E. M. **El Cuaternário fluvial de la cuenca del Purus en el Estado de Acre, Brasil.** Tese (Doutorado em Ciências Geológicas). Universidad Nacional de San Luis, San Luis. 1992.

LATRUBESSE, E. M. Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers. **Geomorphology,** v. 101, p. 130–145, 2008. DOI: https://doi.org/10.1016/j.geomorph.2008.05.035.

LATRUBESSE, E. M.; FRANZINELLI, E. The Late Quaternary evolution of the Negro River, Amazon, Brazil: implications for island and floodplain formation in large anabranching tropical system. **Geomorphology,** v. 70, p. 372-397, 2005. DOI: https://doi.org/10.1016/j.geomorph.2005.02.014.

LATRUBESSE, E. M.; STEVAUX, J. C.; SINHA, R. Grandes sistemas fluviais tropicais: uma visão geral. **Revista Brasileira de Geomorfologia**, v. 6, n. 1, p. 01-08, 2005. DOI: http://dx.doi.org/10.20502/rbg.v6i1.35.

LATRUBESSE, E. M.; STEVAUX, J. C.. Anavilhanas and Mariuá archipelagos: Fluvial Wonders from the Negro River, Amazon Basin. In: VIERIA, B. C., SALGADO, A. A. R.,

117

*Rev. Bras. Geomorfol. (Online), São Paulo, v.22, n.1, (Jan-Mar) p.103-120, 2021*

SANTOS, L. J. C. (org.) **Landscape and Landforms of Brazil.** Springer, 2013, p. 157-170.

LELI, I. T. **Gênese, evolução e geomorfologia das ilhas e planície de inundação do Alto Rio Paraná, Brasil**. Tese (Doutorado em Geociências e Meio Ambiente). Instituto de Geociências e Ciências Extas, Universidade Estadual Paulista, Rio Claro, 2015. 129p.

LELI, I. T.; STEVAUX, J. C.; ASSINE, M. L. Ilha lago: Uma morfologia dos mega sistemas fluviais anabranching. In: XI Simpósio Nacional de Geomorfologia (SINAGEO), 11., 2016, Maringá. **Anais...** Maringá, p. 15-21. http://www.sinageo.org.br/2016/trabalhos/3/3-433-740.html

LELI, I. T.; STEVAUX, J. C.; CREMON, É. H.; NOBREGA, M. T. River functioning analysis from suspended sediment and water discharge study: the case of the Ivaí River, souther Brazil. **Revista Brasileira de Geomorfologia**, v. 18, n. 1, p. 125-141, 2017. DOI: 10.20502/rbg.v18i1.1139.

LELI, I. T.; STEVAUX, J. C.; ASSINE, M. L. Genesis and sedimentary record of blind channel and islands of the anabranching river: An evolution model. **Geomorphology**, v. 302, p. 35–45, 2018. DOI: https://doi.org/10.1016/j.geomorph.2017.05.001.

LELI, I. T.; STEVAUX, J. C. ASSINE, M. L. Origin, evolution, and sedimentary records of islands in large anabranching tropical rivers: The case of the Upper Paraná River, Brazil. **Geomorphology,** v. 358. 2020a. https://doi.org/10.1016/j.geomorph.2020.107118.

LELI, I. T.; STEVAUX, J. C. ASSINE, M. L. Architecture, sedimentary facies and chronology of a composite island: a model from the Upper Paraná River, Brazil, **Geomorphology,** In Press, Journal Pre-proof 2020b. https://doi.org/10.1016/j.geomorph.2020.107457.

LEOPOLD, L. B.; WOLMAN, M. G. River channel patterns: braided, meandering and straight. **United Stated Geological Survey**, n. 282B, p. 1-50, 1957. DOI: https://doi.org/10.3133/pp282B.

MARTINS, D. P. **Dinâmica das formas de leito e transporte de carga def fundo do Alto Rio Paraná**. Dissertação (mestrado), Programa de Pós-graduação em Geografia, Universidade Estadual de Maringá, Maringá, PR, 2004.

MARTINS, D. P.; STEVAUX, J. C. Características Hidráulicas e Morfológicas do Rio Paraná na Seção Porto São José-PR. **Ciência e Natura**, v. Esp, p. 117-130, 2004.

MARTINS, D. P.; STEVAUX, J. C. Formas de leito e transporte de carga de fundo no Alto Rio Paraná. **Revista Brasileira de Geomorfologia**, v. 6, n. 2, p. 43-50, 2005.

MIALL, A. D. A review of the braided-rivers depositional environment. **Earth Science Review**, v. 13, n. 1, p. 1-62, 1977.

MIALL, A. D.. Lithofacies types and vertical profile models in braided river deposits: a summary. In: MIALL, A. D. (org.) **Fluvial Sedimentology**. Calgary: Canadian Society of Petroleum Geologists Memoir, 5, 1980, p. 597-604.

NANSON, G. C. Anabranching and Anastomosing rivers. In: SHRODER, J.; WOHL, E. (org.): **Treatise on Geomorphology.** Academic Press: 2013, p. 330-345.

NANSON G. C.; CROKE J. C. A genetic classification of floodplains. **Geomorphology** n. 4, 1992, p. 459–486.

NANSON, G. C.; KNIGHTON, D. A. Anabranching rivers: Their cause, character and classification. **Earth Surfaces Processes and Landforms**, v. 1, p. 217–239, 1996. DOI: https://doi.org/10.1002/(SICI)1096-9837(199603)21:3%3C217::AID-ESP611%3E3.0.CO;2-U.

ORFEO, O.; STEVAUX, J. C. Hydraulic and morphological characteristics of middle and upper River (Argentina and Brazil) reaches of the Parana. **Geomorphology**, v. 44, p. 309–322, 2002. DOI: https://doi.org/10.1016/S0169-555X(01)00180-5.

ORFEO, O.; STEVAUX, J. C.; PARSONS, D. . Geomorphological and sedimentological characteristics. In: METCALFE, C. D.; COLLINS, P.; MENONE, M. L.; TUNDISI, J. G. **The Paraná River Basin: Managing Water Resources to Sustain Ecosystems Services**. Publisher: Taylor & Francis Group, 2020, p. 41-60.

PEREIRA, M. S. **El Río Paraná: geomorfología y morfodinámica de barras e islãs em um gran río anabranching.** Tese (Doutorado). Facultad de Ciencias Naturales y Museo. Universidad Nacional de La Plata, La Plata, 2016. 381p.

RAMONELL, C. G.; SZUPIANY, R. N.; LATRUBESSE, E. M.;GARCÍA, M., PEREIRA, M. S.; GALLEGO, M. G.; MARCHETTI, Z. Y.; CAFARO, E. D.; PAIRA, A. R.; LATOSINSKI, F. G.; BOSISIO, A. C.;TORRES, G. Procesos de formación del río Paraná medio. Nuevos paradigmas para su estudio. In: Quinto Simposio Regional Sobre Hidráulica de Rios, 5., 2011. **Anais…**Memorias del Quinto Simposio Regional Sobre Hidráulica de Rios, Ríos, Argentina. 2011. p. 7-8.

READING, H. G. **Sedimentary environments and facies.** Oxford: Blackwell Scientific Publications, 1978. 557p. DOI: HTTPS://DOI.ORG/10.1002/ESP.3290060116.

SANTOS, V. C. **Processos fluviais em barras de soldamento: Rio Paraná – PR**. Dissertação (Mestrado em Geociências).

*Rev. Bras. Geomorfol. (Online), São Paulo, v.22, n.1, (Jan-Mar) p.103-120, 2021*

118

Universidade Estadual Paulista Júlio de Mesquita Filho, Rio Claro, SP, 2010. 86p.

SANTOS, M. L.; FERNANDEZ, O. V. Q.; STEVAUX, J. C. Aspectos morfogenéticos das barras de canal do Rio Paraná, região de Porto Rico (PR). **Boletim de Geografia**, v. 10, n. 1, p. 11-24, 1992.

SANTOS, V. C.; STEVAUX, J. C.; ASSINE, M. L. Fluvial processes in attachment bars in the Upper Paraná River, Brazil. **Revista Brasileira de Geomorfologia,** v. 18, n. 3, p. 483-499, 2017. DOI: http://dx.doi.org/10.20502/rbg.v18i3.1135.

SIMONS, D. B.; RICHARDSON, E. V. Resistance to flow in alluvial channels. **United States Geological Survey**, n. 422J, p. 1-70, 1966. (https://pubs.usgs.gov/pp/0422j/report.pdf).

SHUSTER, M.W.; STEIDTMANN, J.R.. Fluvial-sadstone architecture and thrust-induced subsidence, Nortnern Green River, Wyoming. In: ETHRIDEG, F.G; FLORES, R.M.; HARVEY, M.D. (org.). **Recent developments in fluvial sedimentology**. Society of Economic Paleontologists and Mineralogists, n. 39, Tulsa Oklahoma, EUA, 1987, p. 279-281.

SLOWIK, M.; DEZSÓ, J.; MARCINIAK, A.; TÓTH, G.; KOVÁCS, J. Evolution of river planforms downstream of dams: effect of dam construction or earlier human-induced changes? **Earth Surface Processes and Landforms**, v. 43, p. 2045-2063, 2018. DOI: 10.1002/esp.4371.

SMITH, N. D. Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. **Journal of Geology**, v. 82, n. 2, p. 205 - 224, 1974.   DOI: 10.1086/627959.

SMITH, D. G. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. **Geological Society of America Bulletin**, v. 87, n. 6, p. 857–860, 1976. DOI: https://doi.org/10.1130/0016-7606(1976)87%3C857:EO VOLM%3E2.0.CO;2.

SMITH, N. D.. Some comments on terminology for bars in shallow rivers. In: MIALL, A.D. (org.). **Fluvial Sedimentology.** Canadian Society of Petroleum Geologists: Calgary, 1982, p. 85-87.

SMITH, D. G. Anastomosed river deposits: sedimentation rates and basin subsidence, Magdalena River, North West of Colômbia, South America. **Sedimentary Geology**, v. 46, p. 177-196. 1986.

SOUZA FILHO, E. E. **Aspectos da geologia e estratigrafia dos depósitos sedimentares do Rio Paraná em Porto Primavera (MS) e Guaíra (PR)**. Tese (Doutorado). Instituto de Geociências, Universidade de São Paulo, São Paulo. 1993. 214p.

SOUZA FILHO, E. E. Barragem de Porto Primavera e o transporte fluvial na seção de Porto São José, Rio Paraná. **Mercator,** v.15, n. 4, p. 65-81, 2016. DOI:  10.4215/RM2016.1504.  0005.

SOUZA FILHO, E. E.; ZANETTI, K.; PINESE, J. P. P.; FRANÇA, V. A hidroquímica do Rio Paraná após a barragem de Porto Primavera. **Boletim de Geografia**, v. 28, p. 101-112, 2010. DOI: https://doi.org/10.4025/bolgeogr.v28i2.10369.

STEVAUX, J. C. **O Rio Paraná Superior: Geomorfogênese, sedimentação e evolução quaternária.** Tese (Doutorado). Instituto de Geociências, Universidade de São Paulo, São Paulo. 1993. 260p.

STEVAUX, J. C. The upper Paraná river (Brazil): Geomorphology, sedimentology and paleoclimatology. **Quaternary International**, v. 21, p. 143–161, 1994. DOI: https://doi.org/10.1016/1040-6182(94)90028-0.

STEVAUX, J.  C. Climatic events during the Late Pleistocene and Holocenein the upper Parana River:  Correlation with NE Argentina a South - Central Brazil. **Quaternary International**, v. 72, n. 1, p. 73-85, 2000.   DOI: 10.1016/S1040-6182(00)00023-9.

STEVAUX, J. C.; LATRUBESSE, E. M. **Geomorfologia Fluvial**. São Paulo: Oficina de Textos, 2017. 320p.

STEVAUX, J. C.; SOUZA, I. A. Floodplain construction in an anastomosed river. - **Quaternary International**, v. 114, p. 55 - 65, 2004. DOI: https://doi.org/10.1016/S1040-6182(03)00042-9.

STEVAUX, J. C.; TAKEDA, A. M. Geomorphological processes related to density and variety of zoobenthic community of the upper Paraná River (Brazil). **Zeitschrift für Geomorphologie**, v. 129, p. 143–158, 2002.

STEVAUX, J. C.; MARTINS, D. P.; MEURER, M. Changes in a large regulated tropical river: The Paraná River downstream from the Porto Primavera Dam, Brazil. **Geomorphology**, v. 113, p. 230-238, 2009. DOI: https://doi.org/10.1016/j.geomorph.2009.03.015.

STEVAUX, J. C.; CORRADINI, F. A.; AQUINO, S. Connectivity Processes and riparian vegetation of the upper Paraná River, Brazil. **Journal of South American Earth Sciences**, n. 46, p. 113-121, 2013. DOI: https://doi.org/10.1016/j.jsames.2011.12.007.

SUGUIO, K.; BIGARELLA, J. J. **Ambientes Fluviais. Geomorfologia Fluvial**. Segunda Edição. Florianópolis: Editora da UFSC/UFPR, 1990, 183 p.

SUNDBORG, A. The River Klarälven, a study of fluvial processes. **Geographical Annals**, v. 38, n. 3, p. 238-316, 1956. DOI: 10.2307/520285.

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THOMAZ, S. M.; AGOSTINHO, A. A.; HAHN, N. S. (org.). **The Upper Paraná River and its floodplain: physical aspects, ecology and conservation.** Leiden: Backhuys Publishers, 2004.

TOOTH, S.; NANSON, G. C. The role of vegetation in the formation of anabranching channels in an ephemeral river, Northen plains, arid central Australia. **Hydrological Processes**, v. 14, p. 3099-3117, 2000.

TURRA, T.; MARQUES, V.; STEVAUX, J. C. Confluence Bar of the São Pedro Brook in the Paraná River: Genesis and Environmental Importance. **Boletim Goiano de Geografia,** v. 19, n. 1, p. 50-54, 1999. DOI: https://doi.org/10.5216/bgg. v19i1.15302.

ZVIEJKOVSKI, I. P.; STEVAUX, J.C.; LELI, I.T.; PAROLIN, M.;CAMPOS, J. B. Sponges as a complement of sedimentary facies analysis in island deposits of Upper Paraná River. **Journal of South American Earth Sciences,** n. 79, p. 143-151, 2017. DOI: 10.1016/j.jsames.2017.07.013.

*Rev. Bras. Geomorfol. (Online), São Paulo, v.22, n.1, (Jan-Mar) p.103-120, 2021*

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