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HYDRO-GEOMORPHOLOGICAL AND SEDIMENTOLOGICAL PROCESSES ALONG THE MAJOR FLUVIAL-LACUSTRINE DELTA OF THE PARANÁ RIVER (ARGENTINA). THEIR ROLE IN FLOODPLAIN CONSTRUCTION

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ACKNOWLEDGEMENTS
The authors would like to thank Sr Cristian Vera and Sr Santiago Cañete from Universidad Nacional del Litoral for their assistance during the fieldwork. The authors thank the field data provided by Dra. Zuleica Marchetti. This work was cofunded by Agencia Santafesina de Ciencia Tecnología e Innovación (Project: IO 00088-2018 "Estudio del comportamiento hidráulico y sedimentológico del sistema deltaico Arroyo Leyes – Laguna Setúbal, Santa Fe") and Universidad Nacional dekl Litoral (CAI+D 2020 PI TYPE II. Project: "Estudio geomorfológico, hidráulico y sedimentológico en sistemas secundarios vinculados del Río Paraná: Arroyo Leyes-Laguna Setúbal y Río Colastiné, Santa Fe").

AUTHOR CONTRIBUTIONS

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.5570

Dominguez Ruben: conceptualization, funding acquisition, methodology, investigation, resources, software, writing –initial draft, writing –reviewing and editing; Szupiany: funding acquisition, investigation, supervision, writing –reviewing and editing; Ramonell: resources, writing –reviewing and editing; Ru: investigation, software; Garcia, funding acquisition, writing –reviewing and editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

ABSTRACT

River-dominated sea deltas have been thoroughly studied by different authors. In these environments the interrelationship of the hydro-sedimentological variables between river, tides, and waves, among others, are the main factors controlling the delta formation. However, few studies have focused on the deltaic processes in river-lagoon environments and even fewer in large river floodplains (defined here as a Fluvial-Lacustrine Delta, FLD) and their role in floodplain construction. This study provides a comprehensive and novel approach analysis combining satellite imagery treatment and aerial photographs with a detailed field measurements of sediment samplers, cores, and acoustic techniques applied to quantify flow and discharge distribution along main, secondary, floodplain channels and lagoons systems under different hydro-sedimentological conditions. All data allow a full description of deltaic processes and the main variables that control the evolution of the major FLD located along Paraná River floodplain (Argentina). These results show: i) pre-existing local geology elements affect the deltaic processes; ii) hydro-sedimentological behavior of the main channel and its connection with the floodplain channels and independent basin systems affect the delta evolution; iii) the dynamics (temporally and spatially) of sediment transport input and the interaction with lagoons produce different delta front bars planform and composition, iv) periods of mean and high water levels play a key role in the delta evolution, and v) the rapid vegetation growth above the formed bars favors the sedimentation of fine material, producing permanent changes and leading to floodplain construction. Particularly, our findings suggest a complex interrelationship between the different factors in this particular environment, such as hydrology, local geology, main/secondary and floodplain channels, sediment supply, sediment transport modes, vegetation, and free surface slopes. All these factors act together in a complex manner, providing unique features to the system that could help us better understand the floodplains construction in large river systems worldwide.

Keywords
Fluvial-Lacustrine Delta, Large River System, Floodplain, Sediment Transport, Hydrology, Geology, Delta Processes.

1. INTRODUCTION

Deltas are formed by the abrupt change in hydraulic conditions when rivers outflow into a low-energy system, generating the deposition and redistribution of sediment transport. An increasing number of studies have been conducted exploring deltas in river-marine environments. They analyze the dynamics of river mouth deposits and focus on the action of a series of dominant factors in the environment (Galloway, 1975; Wright, 1977; Orton and Reading, 1993), the hydro-sedimentological and morphological characteristics of distributary channels (Caldwell and Edmonds, 2014; Fagherazzi *et al.*, 2015), water salinity (Fan *et al.*, 2011), and winds (Nardin and Fagherazzi, 2012), among other topics. Most of these studies apply numerical models (Edmonds and Slingerland, 2007, 2008; 2010; Geleysen *et al.*, 2010; 2011; Nardin and Edmonds, 2014), laboratory experiments (Hoyal and Sheet, 2009; Martin *et al.*, 2009), and, to a lesser extent, field measurements (Holtschlag and Koschik, 2002; Esposito *et al.*, 2013). Recent works have highlighted the pressing need for further field measurements in order to quantify the variables involved in the calibration and validation of numerical models (Fagherazzi *et al.*, 2015). The influence of the type and volume of sediment in delta building has been postulated by Orton and Reading (1993). In this sense, Caldwell and Edmonds (2014), through numerical hydro-morphological modeling, indicated that delta morphology is strongly influenced by the grain-size distribution of sediment transport. These authors related deltas with fine material (<63 μm) and elongated planform shapes with fewer, narrower, and deeper distributary channels. They related deltas built with fine material (<63 μm) with elongated planform where fewer, narrower, and deeper distributaries channels were found. Additionally, they showed that if the suspended sediment was mainly wash load, the pulses of high volumes of sediment could generate asymmetric bar patterns. On the other hand, they indicated that deltas provided with coarse material (>63 μm) had a radial (semicircle) planform and a high number of bifurcations with different channel sizes and networks. Other authors explained the planform delta asymmetry and elongated delta front bars as resulting from the presence of subsurface beds of fine material (silt and clays) that dominate the pattern from the upper deposits (Geleynse *et al.*, 2011).

Esposito *et al.* (2013), through field measurements, claimed a relationship between the hydrological regime of the channel and its sedimentology. They defined three stages in the formation of bars/deposits: the first occurs during high-water levels, where the bars are predominantly formed by coarse material (with processes of aggradation and progradation); the second, in a mean water level, where deposition of fine material occurs (mainly aggradation); and, the third one, when the banks remain exposed and recently deposited fine material is consolidated, sometimes causing vegetation growth.

Even though data on marine delta environments abounds, the characterization of lacustrine deltas environments is scarce (Ramonell, 2021). These systems, composed of the main channel, secondary channels, and lagoons located in the floodplain develop a complex network with a hydro-geomorphology and sedimentology connectivity. Even though some studies have dealt with delta formation and evolution in river-lagoon environments, such as Saskatchewa (Smith *et al.* 1989; Morozova and Smith, 2000; Slingerland and Smith, 2004), they provide limited hydro-sedimentological field information. These systems are exposed to different conditions if compared to deltas in river-marine environments, preventing the direct extrapolation of the processes involved in their formation.

Particularly in the Paraná System, there is a large number of secondary systems that interact in the active floodplain with the main channel. Therefore, the authors of this manuscript sought to measure and analyze the dominant hydro-sedimentological processes and the control variables in a major Fluvial-Lacustrine Delta (FLD) of the Parana River.

The analysis was carried out through detailed field measurements (morphological, hydraulic, and sedimentological), the analysis of satellite and drone images, as well as of core samples from the delta front bars.

For this reason, this study centers on the detailed description of the delta processes by measuring the variables involved in FLD morphodynamics, in order to discuss the characteristics of the bed sediment, its extension and evolution, local geology, the sediment transport modes, and its hydrological regime.

2. STUDY SITE AND GENERAL CHARACTERISTICS

The study site encompasses a complex and intricate hydrographic network located in the active floodplain of the Paraná River at its middle reach, near Santa Fe city (31°34’S, 60°36’W), Argentina (Figure 1). The Leyes Channel starts in the confluence of two Paraná secondary channels, Colastinecito and San Javier (see Figure 1b), respectively. Their connection with the Paraná River differs. The Colastinecito Channel has a direct connection with the Paraná main channel, while the San Javier Channel flows along the floodplain upstream through a complex system characterized by multiple channels and lagoons (Figure 1b). Downstream from the confluence, the Leyes Channel receives minor discharge contributions on its right bank (Chipá and Siete Millones channels, Figure 1b); while 12 km downstream, it splits through multiple channels such as Potrero, Falso Toro, and finally, Zanja Brava (ZB) channels, the latter continues in a south-western direction. Downstream, the Zanja Brava bifurcates into Zanja Brava North and Zanja Brava South channels (Figure 1b). The Zanja Brava North Channel outflows into the center of Setúbal Lagoon, while the Zanja Brava South Channel on the left side, after receiving Potrero Channel flow through multi-small branches (Figure 1b). The Leyes Lagoon receives water from the homonymous channel (Lower Leyes Channel), and the Capón Lagoon, which is supplied by the Falso Toro Channel and the Bajos de los Saladillos basin (an independent fluvial source tributary of the Paraná River floodplain) through the Saladillo Dulce and Amargo channels. Both converge before outflow into Capón Lagoon (Figure 1c). Note that the Correntoso Channel connects the Leyes Lagoon to the Setúbal Lagoon. It is worth noticing that the delta is longitudinally limited on both margins by relatively elevated lands where Santa Fe city is located (on the right bank). On the left bank, an old aeolian dune field is placed inside the floodplain (Ramonell, 2021), where small towns, such as South Colastiné and Rincón, thrive (Figure 1b). The total area of FLD Leyes-Setúbal is 170 km^2 and the radial distance is about 16 km^2.

The hydrological behavior of the FLD Leyes-Setúbal presents a strong correlation with the Paraná River main channel, with typically high-water levels from February to July. Figure 1d shows the hydrograph of the secondary channels (San Javier, Leyes, Potrero, Setúbal, Saladillo Dulce and Amargo channels) for the last ten years. It should be noted that the Saladillo channels feature a small basin with hydrological conditions independent of the Paraná River regime, and a discharge one order of magnitude lower than that of Setúbal Lagoon (Figure 1d). A remarkable characteristic of the Saladillo Amargo Channel is its high salinity level throughout the year which, in normal conditions, triples that of the Paraná River (Maglianesi, 1968).

The Paraná middle reach has a mean annual flow of about 17000 m^3/s, an average water level hpp=3.6 m (measured at Paraná Port gage station, Paraná main channel), and a freer surface slope ranging from 2 to 5 10^{-5}. The channel bed is largely composed of medium to fine sand (Drago and Amsler, 1998) with an average total sediment transport of $95x10^6$ tn/year (1990-2018 period) (Lopez Weibel *et al.*, 2022). Approximately 77% corresponds to wash load, 21% to suspended-bed sediment transport, and 2% to bedload (Lopez Weibel *et al.*, 2022). Fine fraction sediments come mainly from the contributions of the Bermejo River, a tributary with headwater on silty soft rocks of the Andean Range, which outflows into the Paraguay River and downstream into the Paraná River. The maximum sediment transport rates are produced between December and May (Amsler and Prendes, 2020; Lopez Weibel *et al.*, 2022).

Sediment (both fine and coarse) is delivered to FLD Leyes-Setúbal from the Paraná River mainly from Colastinecito Channel (and, to a lesser extent, from San Javier River) where it is redistributed through the different channels downstream (Figure 1b).

Marchetti *et al.* (2020) highlighted the role exerted by vegetation in the delta-building process and described the following eight vegetation types in the system: two types of forests (Salix open and Salix semiopen forests), two shrublands (Sesbania and Ludwigia shrublands), and four marsh-aquatic prairies (Marsh, Lenitic, Semilenitic, and Lotic prairies). Vegetation mainly grows in low-water levels, and enhances sediment capture in high-water levels and/or sediment transport conditions, increasing and accelerating the longitudinal and vertical growth of the delta bars. Despite the important advances achieved, the authors emphasize that the influence of vegetation on sediment retention and delta bar growth requires further research (Marchetti *et al.*, 2020).

The prevailing wind direction in the study site is eastern with relatively low magnitudes (mean value of 10-20 km/h) producing mean wave magnitudes of 0.2 m. Additionally, though less frequently, southern winds blow with a magnitude above 20-30 km/h. Occasionally, during short storms, waves of up to 1 m occur.

3. METHODS AND DATA ANALYSIS

In order to evaluate the long- and short-term morphodynamics, Joint Research Centre data (Global Surface Water) was used, based on the water surface permanence classification methodology described by Pekel *et al.* (2016). The implementation is through the identification of water pixels by treating Landsat images 5, 7, and 8 with normalized indexes (Pekel *et al.*, 2016). According to the data available, a period of 35 years, between 1984 and 2019, was considered. The results allowed us to classify water surface and their area extension and seasonal or permanent deposition-erosion processes. Additionally, different satellite Landsat 5-7-8, Sentinel-2, and PlanetScope imagery (Planet Team, 2017) was analyzed in order to evaluate recent morphodynamic changes.

The hydro-sedimentological processes were assessed using a set of five field campaigns (Table 1), involving bathymetric surveys (transverse and longitudinal profiles), flow discharge and suspended sediment measurements, bed sediment samples, cores on two selected delta front bars, and drone mapping. To assess the influence of the highest sediment transport period on the Paraná River system, two campaigns were conducted during the Bermejo River flood stage (FC2018 and FC2019a, Table 1).

Table 1. Summary of field campaigns: dates, survey sites, water level, and type of measurements.

			Type of measurements			
Field Campaign	Study sites	h_{PP} [m]	H-M[a]	S[b]	St[c]	G[d]
FC2018 May 03 to 09, 2018	Setúbal Lagoon and Leyes, Potrero, Falso Toro, Ubajay and Zanja Brava channels	4.15	X	X		X
FC2019a March 21, 2019	Setúbal Lagoon	3.5	X	X		
FC2019b October 22, 2019	Delta front bar	1.26			X	
FC2020a May 26, 2020	Delta front bar	0.70				X

FC2020b August 11, 2020	Leyes, Potrero, Falso Toro, Ubajay and Zanja Brava channels	0.3 4	X	X	

[a] Hydrodynamics and morphology: ADCP measurements and bathymetric surveys.

[b] Sedimentology: suspended sediment (point and depth-integrated samples) and bed sediment sampling.

[c] Stratigraphy: Core sampling.

[d] Geomorphology: Drone survey.

Morphology measurements were performed along a series of cross-sections, each one 200-500 meters apart (248 cross-sections) using a 200 kHz Raytheon single beam echo sounder (SBES), deployed on a small survey vessel. Data from points x, y, and z were interpolated on a regular grid using standard kriging methods to create a bathymetric map. Discharges and flow structure data were collected at 29 cross-sections with an acoustic Doppler current profiler 1200 kHz Rio Grande (ADCP) ('XS' cross-sections in Figure 1b). Both the echo sounder and the ADCP were linked to a DGPS differential positioning system, with a horizontal ± 2 cm resolution. The water surface slope and bed profilers were surveyed using longitudinal profiles (blue line, Figure 1b).

Two depth-integrated suspended sediments were sampled with a US P-61 sediment sampler. Due to the large number of channels covered and the area extension, two sampling verticals were measured per cross-section, at 1/3 and 2/3 of each channel width (*w*). Moreover, 15 near-water surface samples were taken along different cross section of Setúbal Lagoon.

The suspended sediment samples were processed in the laboratory to compute sediment concentrations (for both fine <63 μm and coarse >63 μm fractions) and grain size distribution. Wet sieving, water evaporation, sediment drying, and weighing were performed for each sample to segregate wash load and sand fractions of sediment concentrations in the volumes sampled. Particle size was measured with a laser diffraction analyzer (LH 910 Horiba).

Twenty six bed sediment samples were collected using a drag cone in the center of each cross-section (XS, Figure 1b). At Setúbal Lagoon, 3-bed samples were also collected across each section (right, center, and left bank). Dry sieving or laser diffraction techniques, depending on the fine material content of each sample, were deployed.

Based on the Bottom Tracking methodology (Latosinski *et al.*, 2017), the apparent bed sediment movement was measured through static ADCP measurements, anchoring the boat during 5-minute intervals. Four points along Zanja Brava Channel until Setúbal Lagoon (BT points in Figure 1b) were surveyed.

To complete and update the geotechnical and sedimentological information already available for the study area (Ramonell, 2005; 2021; Marchetti *et al.*, 2020), representative core samples in the emerged delta front bars were collected during FC2019b (low water level period). The cores were analyzed in the laboratory to determine the stratigraphic patterns and grain size distribution of each bed identified.

In order to identify the deposition patterns (plan view) of delta front bars, a photographic survey with a DJI Mavic 2 Pro drone was deployed during a period of extraordinary low-water level in the Paraná fluvial system (February-May 2020) (FC2020a), covering an area of approximately 10 km^2.

4. RESULTS

4.1 Temporal and spatial morphodynamic changes

In order to analyze the main and most relevant morphodynamic changes of the study system, Figure 2a shows satellite image sequences from 1981 to 2018 (last 37 years) (see Figure 1b dashed line for study area location). Note that a similar water level condition was used to compare the different sub-periods (hpp ≅ 2m).

Two important conditions should be considered along the FLD Leyes-Setúbal during the floodplain construction. The first condition to be highlighted is that the FLD Leyes-Setúbal building process was initially influenced by exposed consolidated Pleistocene cohesive sediments, with which the deltaic system began to evolve (red delimited areas in Figure 2a; for more information see Ramonell, 2021).

The second condition that influenced FLD Leyes-Setúbal development was the hydrologic variation along the system and its associated sediment transport. As illustrated in Figure 2b (Leyes Channel discharge), the last period (1977-2022) could be divided into 6 sub-periods according to the water discharge variation. Firstly, the extraordinary flood (due to its magnitude and duration) that took place during 1982-1983 with a significant impact on the entire Paraná River system and, particularly, on the Leyes Channel. Changes in the hierarchy of the deltaic channels occurred after this event that modified the hydro-sedimentology configuration permanently. In this framework, permanent morphologic changes took place (widening and deepening processes) at Leyes Channel, which increased its capacity to capture water and sediments from the Paraná River main channel. Moreover, as it can be seen in Figure 2a, the Zanja Brava Channel enlargement began with a hierarchization process that is still underway, capturing higher flow discharge and sediment transport from Leyes Channel, and decreasing the hierarchy of the Lower Leyes. This behavior led the delta to develop mainly in a north-south direction (downstream) and, to a lesser extent, on Leyes and Capón lagoons.

After this flood, during 1984-1992, a mean water level with the typical annual variations of the system is observed, though with no considerably high water levels. No significant planform changes were reported during this period, and no emergence of new delta bars (see pictures from 1981 and 1991 in Figure 2a), although advances of the delta could have occurred at the subsurface water level.

During 1991-1999, a humid period was recorded. During this period, Zanja Brava Channel continued its opening and hierarchization process and, simultaneously, Falso Toro Channel did, transferring water and sediments towards Capón Lagoon, and generating minor deltas (Figure 2a, image since 1999). This period was characterized by an important vertical bar accretion, delta growth and floodplain construction (see Figure 2a).

The period of 1999-2009 was characterized by mean/low water discharges and, therefore, by no significant appearance of delta mouth bars. Given the emergence of the bars formed in previous periods, vegetation growth and sediment consolidation was accentuated, transforming the deposits into permanently emerged delta formations.

Subsequently, during the 2009-2019 period, flows were higher than in the previous ones, leading to a sustained deltaic growth both vertically and longitudinally, mainly at the mouth of the Zanja Brava Channel and, to a lesser extent, at the Correntoso, Lower Leyes, and Falso Toro channels.

Finally, the extraordinarily low-water level (minimum recorded hpp≅-0.5 m) during 2019-2022 led to the emergence of the submerged banks and a rapid growth of vegetation on them.

Figure 3a presents the results of the method proposed by Pekel *et al.* (2016), who classified the exposed water surface into 10 classes. These classes include: permanent, new permanent, permanent lost, seasonal, new seasonal, seasonal lost, seasonal to permanent, permanent to seasonal, ephemeral permanent, and ephemeral seasonal. The permanent class refers to the condition when water occupies the surface all year round, while the seasonal class is when the surface is occupied for less than 12 months. Regarding the transition class, new permanent occurs in the conversion from soil to permanent water, and the loss of permanent occurs in the conversion from permanent water to soil. On the other hand, new seasonal occurs when the transformation from soil to seasonal takes place, while seasonal loss occurs when the transition from seasonal to soil takes place. Since the previous classification only depends on the initial and final conditions, a classification of permanent ephemeral was developed to describe the interannual patterns, when the land is replaced by permanent water that then disappears, or seasonal ephemeral, when the land is replaced by water and then disappears.

Pekel's methodology shows a trend of permanent loss (red colors) in the delta front influenced mainly by Zanja Brava (and minor deltaic channels), Lower Leyes, Correntoso, and Falso Toro channels (Figure 3a).

The area near Zanja Brava Channel displays the most important morphological transformations, which indicate the area with the highest sedimentological activity and delta aggradation/progradation. Note also the permanent loss and depositional processes when Falso Toro outflows into Capón Lagoon before 1991 as described above. However, due to its lower hierarchy, these delta deposits occupy a reduced area in comparison to Zanja Brava (North and South). The decrease in channel capacity of the Lower Leyes Channel (width reduction) is worth noticing, with reduced permanent loss regions in its mouth (see Zanja Brava deposits).

Special attention deserves the lower permanent loss of water surface downstream from Lower Leyes mouth that losses hierarchy after the 1982-1983 flood.

As far as the Correntoso channel mouth is concerned, another transformation area (from permanent to seasonal) with sedimentation processes is observed. Note that Correntoso moves the sediments supplied by Capón (provided by Saladillo Channel) and Leyes lagoons, both with lower sediment transport capacity.

Considering the period from 1985 to 2019 (the last extraordinary low-water level period of 2020-2022 was not considered), Figure 3b shows the Setúbal Lagoon mean annual area and mean annual water level ($\bar{h}pp$) variation over time. As described above, the area variations of the Setúbal Lagoon (and delta growth) were strongly influenced by the changes in the water level. However, Figure 3b confirms that the lagoon area decreased during humid (1991-1998) and mean water level (2006-2015) periods. This behavior suggests that the combination of high-mean water levels and their occurrence in the months of maximum sediment supply from the Paraná main channel (December-March) can lead to delta growth. During this lapse of time, an average reduction of 106 ha per year took place, corresponding to 2% per year of the current lagoon extension (approximately 5500 ha).

4.2 Bed morphology and bed sediment characteristics

Bed sediment grain size distribution (clay, silt, and sand content) and bed morphology along the FLD Leyes-Setúbal area (survey FC2018) is presented in Figure 4a. This figure shows that important grain size differences were observed between channels of different hierarchies. Main channels located upstream from Zanja Brava mouth are composed 100% of sand, e.g., Leyes, Falso Toro, Potrero, Zanja Brava, and Lower Leyes channels, where d_{50} is equal to 363 μm, 194 μm, 189 μm, 303 μm, and 313 μm, respectively (d_{50} is the corresponding particle size when the cumulative percentage reaches 50%). This behavior indicates the sediment segregation of the channel bed grain size according to their hydraulic characteristics. The absence of fine material interaction with the bed along all Leyes-Zanja Brava North/South channels (Figure 4a) suggests that the fine suspended sediments may reach Setúbal and Capón lagoons by delta distributary channels. However, for even smaller channels (such as Ubajay Channel with d_{50} =34 μm), deposition of fine fraction sediments occurs.

Downstream the channel mouth (sections XS22 and XS23), the percentage of silt and clay dominates the channel bed material as a result of the fine fraction deposition coming from the Paraná River main channel. Moreover, Setúbal Lagoon presents high spatial variability, according to flow and sediment transport supply (e.g., Correntoso and Zanja Brava North/South channels). The mean bed grain size sampled at the West, Center, and East regions of Setúbal Lagoon along the three cross-sections (XS25, XS26, and XS28; see Figure 1b) denotes the increased size of bed material towards the right bank. This spatial variation is ascribed to the Correntoso Channel which contributes mainly with coarse material from its channel (especially during higher water levels), and low wash load. Despite the fact that Lower Leyes and Falso Toro carry flow and sediments (wash load) to the Capón Lagoon subsystem, these are deposited in the lagoons and, therefore, the Correntoso Channel has a limited amount of fine fraction sediments for most of its hydrological conditions (note that the fine material transported by the Correntoso Channel was observed only during high water-sediment stage periods).

Along Zanja Brava Channel, bed morphology shows two reaches that differ in depth and stratigraphic features. The most relevant singularity of bed morphology is the abrupt bed discordance (see the red dashed box in

Figure 4a) at Zanja Brava Channel (initially identified by Ramonell, 2005). Upstream from the bed discordance point, the channel is deeper and reaches the characteristic sandy bed of the Ituzaingó Formation. Downstream, the channel flows over Pleistocene cohesive substrate about 10 m average above sea level (Ramonell, 2021) (see Figure 4a). Even though some sediment samples could be taken from this reach (see grain size in Figure 4a), compacted cohesive material was identified in the field. This channel bed material is confirmed through satellite imagery during the extraordinary low water level recorded between 2020-2022. In this sense, Figure 4b,c shows the characteristics of the bed material, where sand bars (including bed forms) and the exposed Pleistocene cohesive substrate are observed.

Figure 5a displays the particular abrupt bed discordance and its temporal evolution measured through the longitudinal profiles of the channel bed elevation (above sea level) during 2012-2020. A 55 m downstream displacement shift during the first period (2012-2016) can be observed along with another of about 22 m in the second period (2016-2020). Considering that both periods comprise 4 years, the higher displacement of the first period could be explained by the 2016 flood (Figure 1d), which occurred before the bed profile presented in Figure 5a (2012-2016). Additionally, Figure 5a shows the dune field developed upstream from the bed discordance point, where bed channel material is dominated by sand, which only appears in bars close to the banks downstream from the bed discordance (Figure 4b,c). Just upstream from the bed discordance, a progressive filling of about 2.5 m can be observed between 2012 and 2016 and approximately 1.5 m from 2016 to 2020. This fact suggests that only a fraction of bedload transport passes through the discordance and, therefore, accumulates upstream. However, at bed discordance, the angles are 16°, 11°, and 13° for 2012, 2016, and 2020, respectively. These factors indicate that both processes, i.e., deposition upstream and bedload sediment transport downstream the discordance are generated to provide sedimentological continuity. Downstream, as a result of both processes described above, and added to the widening of the channel, the sand fraction covers only part of the channel cross-section (this sand fraction was captured as bed samples during the field campaign) (Figure 4b,c). Further field data and analysis are required in order to better determine the behavior of the hydrometric/hydraulic conditions (sediment transport) and the depositional processes upstream and sediment transport downstream the discordance.

The bed longitudinal (about 9 km long), free surface elevation (surveyed with DGPS-RTK), and depth-averaged velocity profiles (see the blue line in Figure 1b for location) during 03-2012 (mean-low water level, hpp=2.35 m) is presented in Figure 5b. Upstream from the bed discordance, the mean value of the free surface slope is 5.7 10^{-5}, increasing to 1.1 10^{-4} downstream. From the bed discordance, water depth decreases, width and flow velocity increase followed by changes from single to multiple channel patterns. These changes guarantee the coarse fraction sediment transport through Zanja Brava Channel until

Setúbal Lagoon according to the bed sediment characteristics presented in Figure 4a. Notice that the free surface slope is one order of magnitude higher compared to that of the main channel of the Paraná River (Ramonell *et al.*, 2020).

Downstream from the delta channels mouth, the bed morphology of Setúbal Lagoon is quasi-flat, with smooth variations in a 2 m to 3 m range, and an apparently marked channel slightly displaced rightwards (Figure 4a). A series of artificially generated holes resulting from dredging activities should be noted in the lagoon contraction (between XS28 and XS29).

4.3 Suspended and bedload transport

Table 2 lists the flow discharge (Q), suspended coarse (Qss) and fine (Qw) fractions sediment transport for each cross-section, measured during FC2018 survey. Notice the higher Qw content, with a mean Qw/Qss ratio equal to 9 (ranging from 3 to 26). This behavior is mainly explained by the direct connection with the Paraná River during the high wash load period through the Colastinecito Channel, where a high concentration of wash load is introduced to Leyes Channel. The wash load in the FLD Leyes-Setúbal system supplied by Colastinecito nearly doubles that supplied by the San Javier River, even when the flow discharge from the latter is almost six-fold greater. Notwithstanding the fact that

Colastinecito and San Javier are both secondary channels of the Paraná River, San Javier flows hundreds of kilometers from its mouth downstream through a floodplain, characterized by minor secondary channels and a series of lagoons that capture most of the wash load before its confluence with the Colastinacito Channel (Figure 1b).

At the bifurcations located downstream Leyes Channel, the wash load correlates with flow bifurcation and remains in suspension with no bed exchange along the Zanja Brava North Channel until the Setúbal Lagoon. As already explained, this is reflected by the absence of fine material (silts and clays) along Leyes and Zanja Brava North channel beds (see Figure 4a).

Suspended coarse material presents high variability along FLD Leyes-Setúbal due to local hydraulic changes. This fact is in line with the high variability in bed grain size between channels of different hierarchies, suggesting a continuous grain size selection (from suspended and bed transport) by each channel according to the hydraulic characteristics. Nonetheless, the absence of Qss at the cross-sections located on Setúbal Lagoon stands out. It indicates a high deposition rate of this material immediately downstream from the delta front bars in agreement with the channel bed composition (Figure 4a).

Table 2. Flow discharge (Q) and transport of fine and coarse suspended sediments (Qw and Qss) surveyed (FC2018).

Channel/Lagoon	**Cross-sections**	**Q [m³/s]**	**Q_{w*} [kg/s]**	**Q_{ss*}[kg/s]**
Colastinecito	XS1	294	79	3
San Javier	XS2	1681	49	16
Leyes	XS7	2089	111	11
	XS9	188	15	2
Falso Toro	XS8	657	35	5
Potrero	XS6	791	42	5
	XS14	722	39	6
Zanja Brava	XS11	904	46	11
	XS18	1205	65	7
Zanja Brava South	XS20	502	28	13
	XS22	170	11	1
Zanja Brava North	XS21	519	28	4
	XS23	906	48	3
Setúbal	XS25	2805	98	8
	XS26	2809	111	0
	XS28	2810	112	0

* Average value of suspended sediment samples taken at cross-sections.

To confirm the above-mentioned, Figure 6a illustrates the apparent bed displacements (measured with the ADCP Bottom Tracking function; see Latosinski *et al.*, 2017) through static measurements in the transition zone of Zanja Brava South channel and Setúbal Lagoon (see points in Figure 1b for location). In agreement with the transition from sand to fine grain size bed (Figure 4a), a reduction in bed particle movement from 0.021 m/s in BT1 to a near-zero in BT4 occurred. Consistent with this reduction in bed displacement, Figure 6b shows the time-average velocity deceleration towards the Setúbal Lagoon (BT4). Note that even with velocity reduction, coarse material is observed in the bed up to BT3 and a strong reduction above BT4. Thus the material captured in BT1-BT2-BT3 corresponds to the sand that manages to overcome the bed discordance and occupies part of the bed material; and, given the velocity reduction towards the ZB South Channel mouth, no displacement of particles is observed near the bottom (Figure 6a). In addition, the velocity decrease at Zanja Brava South Channel results from the flow discharge bifurcation upstream towards the Zanja Brava North Channel.

During the high contributions of suspended sediments from the Bermejo River (January-May), towards FLD Leyes-Setúbal, particular patterns of sediment input are produced. This phenomenon is explained by the sediments entering from the Correntoso (from Leyes-Capón lagoons) and Zanja Brava channels (North and South) and, therefore, generating different turbidity patterns along the Setúbal Lagoon. To illustrate this phenomenon, Figure 7 shows a sequence of satellite images from March to April 2019, with B4-B8-B2 of Sentinel-2 band combinations.

Initially, the wash load is transferred from the Paraná main channel to the Leyes Channel (supplied mainly through Colastinecito Channel, 26-02-2019) and reaches the Setúbal Lagoon throughout the Zanja Brava North and South. The Zanja Brava North and South channels contribute fine suspended sediments in the Center and East regions of Setúbal Lagoon, while in the West side, lower fine suspended sediment is supplied by Correntoso Channel producing a clear shear layer along Setúbal Lagoon (18-03-2019). Occasionally, and according to the hydrological behavior of the Leyes and Saladillo systems, contributions (suspended sediment) from Correntoso Channel (from Capón and Leyes lagoons by the Falso Toro and Lower Leyes channels can be observed (12-04-2019).

Along the Setúbal lagoon, the shear layer generated by the Correntoso and Zanja Brava channels mouth remains downstream. This behavior can be explained by the uniform transversal hydrodynamic pattern over Setúbal Lagoon, with low velocities pattern (approximately 0.2-0.5 m/s) and a flat bed (no bedforms were observed, see Figure 4a). Therefore, low turbulence intensity does not generate significant diffusion/convection processes along the lagoon section. Note also the absence of Kelvin-Helmholtz instabilities, very common in this type of shear layer junction flow (Nezu and Nakagawa, 1993).

The hydro-sedimentological dynamic during mean and extraordinarily low-water levels (FC2018 and FC2020b, respectively) is illustrated in Figure 8. Note that the percentages refer to the control section XS5 (see the position in Figure 1b). Regarding the discharge distribution, the following general behavior stands out: (i) continuity between the control section (XS5) and Setúbal Lagoon (XS25), which indicates the small influence that the Saladillo Channel had during the hydrological conditions under analysis; (ii) prevailing contribution from San Javier River, accounting for 60% and 100% of discharge for FC2018 and FC2020b, respectively. Minor contributions from Colastinecito, Chipa, and Siete Millones channels; (iii) during FC2020b, Colastinecito reverses its flow towards the Paraná River. This suggests a complex level behavior between the Paraná main Channel and the San Javier River subsystem, producing an inflow/outflow from Colastinecito Channel depending on the Paraná main channel water level variation; (iv) different flow partitions of Leyes Channel are produced. While the Potrero Channel captures nearly the same percentage (30%), Falso Toro decreases from 23% to 0.2% and Lower Leyes Channel increases from 10% to 48% during FC2018 and FC2020b, respectively; (v) this behavior causes an outflow into the

Setúbal Lagoon of a similar percentage (about 50%) between the Correntoso and Zanja Brava channels due the different hydrometric conditions. However, the high water levels from Saladillo Channel could increase the discharge into the Correntoso, which could subsequently modify the free surface levels of the Capón and Leyes lagoons and, simultaneously, decrease the inflow from the Falso Toro and Lower Leyes.

4.4 Stratigraphy and morphology patterns of delta front bars

An extraordinarily low-water level (approximately 80 years recurrence time) in the Paraná River was recorded between 2019 and 2022, leading to the emergence of the delta front bars. This particular hydrological event allowed, through aerial surveys and cores, to characterize the planform patterns and grain size composition of these bars. The cores were taken from two delta front bar sites, one at the emerged bar just downstream from the Zanja Brava North Channel mouth, and the other downstream from the Correntoso Channel mouth (see location in Figure 10a). Both cores were carried out during the FC2019a survey.

As it can be observed in Figure 9, different sedimentology patterns and grain size distributions are present in both sites. The total thickness of the extracted material in Profile 1 (P1-Zanja Brava North core) is 1.96 m below the exposed surface with a sampling compaction process of 0.14 m. Figure 9a depicts four sedimentary structures with different grain size distributions (see the sediment grain size distribution in Figure 9c). P1.1, P1.2, and P1.3 beds present a clear planar interstratification. In the first one, 0.86 m thick (P1.1), sand and silt (49% and 47%, respectively) prevail with a low presence of clay material (less than 5%) and a brownish-brown color (d_{50}=57 μm). There are two underlying beds of 0.25 m and 0.50 m, respectively (P1.2 and P1.3) made up of silty (71% and 66%, respectively) and sandy (22% and 24%, respectively) material, with a smaller amount of clay (7% and 10%) and slight differences in mean diameter (d_{50}=29 μm and d_{50}=18 μm, respectively). The bed color varies from light to dark brown (possibly explained by the presence of organic matter). This color remains even in the last bed, being about 0.30 m thick (P1.4), where sandy material prevails (60%), but also silts and, to a lesser extent, clay can be observed (36% and 4%, respectively) (d_{50}=102 μm).

The Correntoso core (P2) is 1.2 m, and no compaction was registered. Here, three sedimentary structures with a grain size distribution decreasing in depth are distinguished with a higher sand content if compared to P1 core. The upper bed, about 0.44 m thick, is mostly made up of fine sands with a low presence of silt and null clay (d_{50}=217 μm, Figure 9c). No cross-stratification is observed. Beneath, a silty-sandy bed (28% and 70%, respectively) of about 0.35 m can be distinguished. It shows a dark and light brown bicoloration (the dark one is dominated by organic material), with a mean diameter d_{50}=109 μm (Figure 9c). Finally, a bed of about 0.40 m is observed, composed of 70% silts, 19% sands, and 11% clays.

Figure 10 presents the aerial photographs of the representative areas of the delta front bars during the Paraná extraordinary low-water level (FC2020a, hpp=0.7 m). It should be noted that these deposits, according to Figure 2a, were submerged most of the time in the last years/decades (mean and high-water levels), thereby suggesting that their formation and growth took place under this condition.

Three regions with a particular bar morphology can be identified: West, Center, and East, depending on the size of the deltaic channels and the type of sediment supplied. Note that the cores described above (P1 and P2) match the Center and West zone, i.e., sediments transported by Zanja Brava North and Correntoso, respectively (Figure 9a).

The West delta area features a wing shape (Figure 10), typical of a sand-dominant material and in line with its grain size distribution (Figure 9b, core P2). The growth of these bars is explained by the progradation or lateral attachment to the existing bars, through the coarse fraction re-suspended from the bed upstream during high-water levels (P2-1 formation) but with fine material deposition during medium- to low-water leves (P2-2 and P2.3 beds).

The emerged bars above the Center and East zones differ significantly in terms of morphology and dominant grain size composition (Figure 9a, core P1) of the deposits produced by the Correntoso Channel. Notice that the material supplied to the delta front by the Zanja Brava North/South and smaller channels, especially during the January-April period, is predominantly silt and clay (see Table 2). This results in elongated bars that characterize many deltas with prevailing wash load transport (Orton and Reading, 1993; Caldwell *et al.*, 2014). The Center zone mainly controlled by Zanja Brava North Channel, presents the largest progradation of the delta front bars, characterized by successive lateral spills, forming smaller wing-shaped or triangular bars at their distal edge points (Figure 10) (Orton and Reading, 1993). On the other hand, in the East zone (Zanja Brava South), radial deposits dominate, formed by low hierarchy deltaic channels flowing into the stagnation zone (Caldwell *et al.*, 2014).

Finally, no marked influence was observed over the delta front bars since the wind effect (Orton and Reading, 1993) is low given its low intensity and permanence as described in Section 2.

5. DISCUSSION

This paper analyzes the complex building processes that occur on the major FLD at the floodplain of the Paraná River, one of the main and largest river systems in the world (Latrubesse, 2008). In particular, it deals with a deltaic process along a floodplain system in direct connection with the Paraná River main channel (Colastinecito Channel), channels of floodplain (San Javier River), secondary channels, and an independent water basin (Saladillo System).

In the FLD Leyes-Setúbal system, the main source of flow discharge is supplied by the San Javier River, which comes from the floodplain upstream crossing complex multi-channels and lagoons. The complex floodplain configuration (channel network, Figure 1b) generates discharge lag and filters the suspended sediment. On the other hand, the Colastinecito Channel connects Leyes and Paraná main channels. This connection may present different scenarios depending on the water level of the Paraná River main channel and sediment transport (mainly wash load) coming from the Bermejo River system during the first months of every year (January to May) (Lopez Weibel *et al.*, 2022). Moreover, depending on the water levels of San Javier and Paraná rivers, different conditions may arise at Colastinecito Channel, such as being in phase with the Paraná main channel (capture flow and sediment from the main channel to the delta system) or reversing its flow towards the Paraná (higher water level of the San Javier River) (Figure 8b).

Downstream the delta system, water level variation, i.e., periods of mean and high-water levels, played a fundamental role in the delta depositions. Despite the sub-surface growth of the delta lobes downstream, as it can be seen in the aerial images during the extraordinary low-water levels between 2020 and 2022, during mean and high water levels, the deposition is also vertical, leaving the banks exposed in mean/low conditions. A peculiarity of this environment is its rapid vegetation growth. The interaction between vegetation and water flow produces low energy zones that favor sedimentation both on the bank edges and on the vertical axis during high water levels. This process is explained by the rapid proliferation of the vegetation that usually surrounds them. Also, by the fact that, during higher water levels, a low energy flow is generated over the islands as a result of the flow resistance from vegetation, favoring sedimentation, vertical growth and consolidation of the deltaic islands. More details about vegetation characteristics and their role in the sedimentation processes are available in Marchetti and Ramonell (2014) and Marchetti *et al.* (2020).

Another distinctive characteristic of the system is the high variability of its flow distribution under different hydrometric stages. Downstream from San Javier-Colastinecito confluence, the flow discharge distribution remains constant in the first bifurcation between Leyes and Potrero channels, for the two different measured water levels (Figure 8). Nevertheless, the downstream behavior has a strong influence on the water level conditions (Leyes-Falso Toro or Zanja Brava-Lower Leyes channels). For instance, Capón and Leyes lagoons receive flow and sediments not only from Lower Leyes and Falso Toro but also from Saladillo Channel, with independent hydrological conditions. Therefore, the inflow channels to Capón and Leyes lagoons develop a complex hydrodynamic behavior, resulting in free surface elevation that controls the Falso Toro and Lower Leyes discharges and sediment input (lag effect shown in Figures 7 and 8). Therefore, aside from the local behavior, the flow discharge from Correntoso Channel to the Setúbal Lagoon also varies depending on the Paraná River and Saladillo system hydrological conditions.

Downstream from the Zanja Brava Channel, the appearance of the consolidated Pleistocene substrate gives the system another particular characteristic. From the bed discordance, significant changes in hydraulic conditions, channel pattern, and sediment transport occur. Such is the case that, upstream from the bed discordance, the Zanja Brava Channel flows through a sandy bed, characterized by the presence of a dune (Figure 5a). Downstream, the channel significantly widens and increases its free surface slope and flow velocity thereby ensuring that the sediments that overcome the bed discordance continue downstream until the delta front. However, due to the channels width increment, the sediment transport coming from upstream does not cover the whole channel bed (Figure 4b,c), forming isolated banks, which could be identified during the extraordinary low-water level. The progressive discharge bifurcations produce continuous segregation of grain size bed material, depending on the channel hierarchy.

The delta front bars are strongly influenced by the sediment transport characteristics upstream (Orton and Reading, 1993). The sand fraction dominates the banks and the right side of the Setúbal Lagoon, which is supplied by the Correntoso Channel, while the sand and silt fractions dominate the Center to East zones. In this sense, the core samples of the delta front bar are composed of silts, fine and very-fine sands, with low clay content (<10% depending on the measured deposit, Figure 9b,c). Note that the wash load of the Paraná main channel and Leyes are composed of 27% clay and 73% silt (Amsler and Prendes, 2020). Therefore, it is suggested that the clay (and low silt material) trend continues downstream, with a small influence on the delta front deposits and Setúbal Lagoon bed (Figures 7, 9, and 10). The velocity over Setúbal Lagoon ranges from 0.2 to 0.5 m/s (in mean water level), which is higher than the critical velocity suggested by Mangini *et al.* (2003) to generate the flocculation and deposition conditions for this material. Thus, it could be concluded that most clay material would be transported downstream the Setúbal Lagoon until the contraction zone (Figure 1b), where flow velocity increases again.

On the contrary, the low contribution of wash load throughout the Correntoso suggests a source of bed material itself during high-water levels. These water conditions produce coarse sediment pulse and deposition over the Setúbal Lagoon right side (Figure 4). However, as described in Figure 7, sometimes the wash load is transported by Capón and Leyes lagoons, resulting in the deposition of this material (see silt presence in the grain size distribution of P2-2 and P2-3 beds).

Aggradation deposits were mainly produced by fine suspended material (silts and very fine sands) that play a key part in delta-building processes. This was emerged during the last Paraná extraordinary low-water level in 2020-2022. In addition to the symmetrical fractal-type bars, well-defined channels are observed with elongated and lateral overflows, developing a large number of spills (Figure 10). The Center delta front bars present an elongate planform shape and generally maintain a single dominant direction. As these are growing due to aggradation and progradation, during the low-water periods, the submerged bars are exposed, favoring vegetation growth and consolidation, and producing a significant decrease in the lagoon area (Figure 3). Therefore, according to the river mouth stages proposed by Esposito *et al.* (2013), the second (mainly aggradation) and third (bars consolidation and vegetation growth) states predominate here.

A particular delta morphology formation of quasi-radial type sub-deltas resulting from smaller distributary channels that outflow into stagnation flow zones (see East zone of delta front bars, Figure 10) is produced. Therefore, according to the characteristics of sediment transport, the hierarchy of the delta channels, and the flow conditions at the delta outlet, different sedimentation patterns are observed (Caldwell and Edmonds, 2014).

6. CONCLUSIONS

This study provides a detailed morphodynamic and hydro-sedimentological analysis of a Fluvial-Lacustrine Delta (FLD), developed by different channels and lagoons present in a large river active floodplain (Paraná River, Argentina).

It has been demonstrated that FLD differs significantly from previous studies on deltas in river-marine environments, due to its network complexity, geology, hydrology and sediment transport, floodplain limits, and vegetation. Even though there are studies that have been undertaken formation and evolution in river-lagoons environments (Smith et al. 1989; Morozova and Smith, 2000; Slingerland and Smith, 2004), the novel approach of this article is found in the detailed description of the hydro-geomorphology and sedimentology processes (with field data) combining traditional and surrogate through different technologies.

This study shows that FLD systems present a fragile equilibrium in their hydraulic and sedimentological behavior, leading to discontinuous and heterogeneous morphological dynamics. The flow and sediment transport that reaches the delta front may come from different sources, one with a direct connection with the main channel, from channels that flow along the floodplain and/or from independent channels. Each one has different hydrological regimes (Figure 1d) and sediment input characteristics.

The main channel water level variations result in a complex free surface slope variation between secondary channels and floodplain lagoons, which results in different hydraulic, sedimentological, and morphological responses throughout the system. This complex channel network and hydraulic and sediment supply generate different rates of delta advance, sedimentological composition, and depositional processes along the delta front, which, in turn, could interact with cohesive deposits.

Due to the unique characteristics of these systems, it is not possible to make direct extrapolations of the processes that occur in deltas of marine environments well described in previous studies. Therefore, the present research provides a thorough explanation of the different governing processes and their role in building floodplains, which can be directly applied to other similar environments of large river systems around the worldwide.

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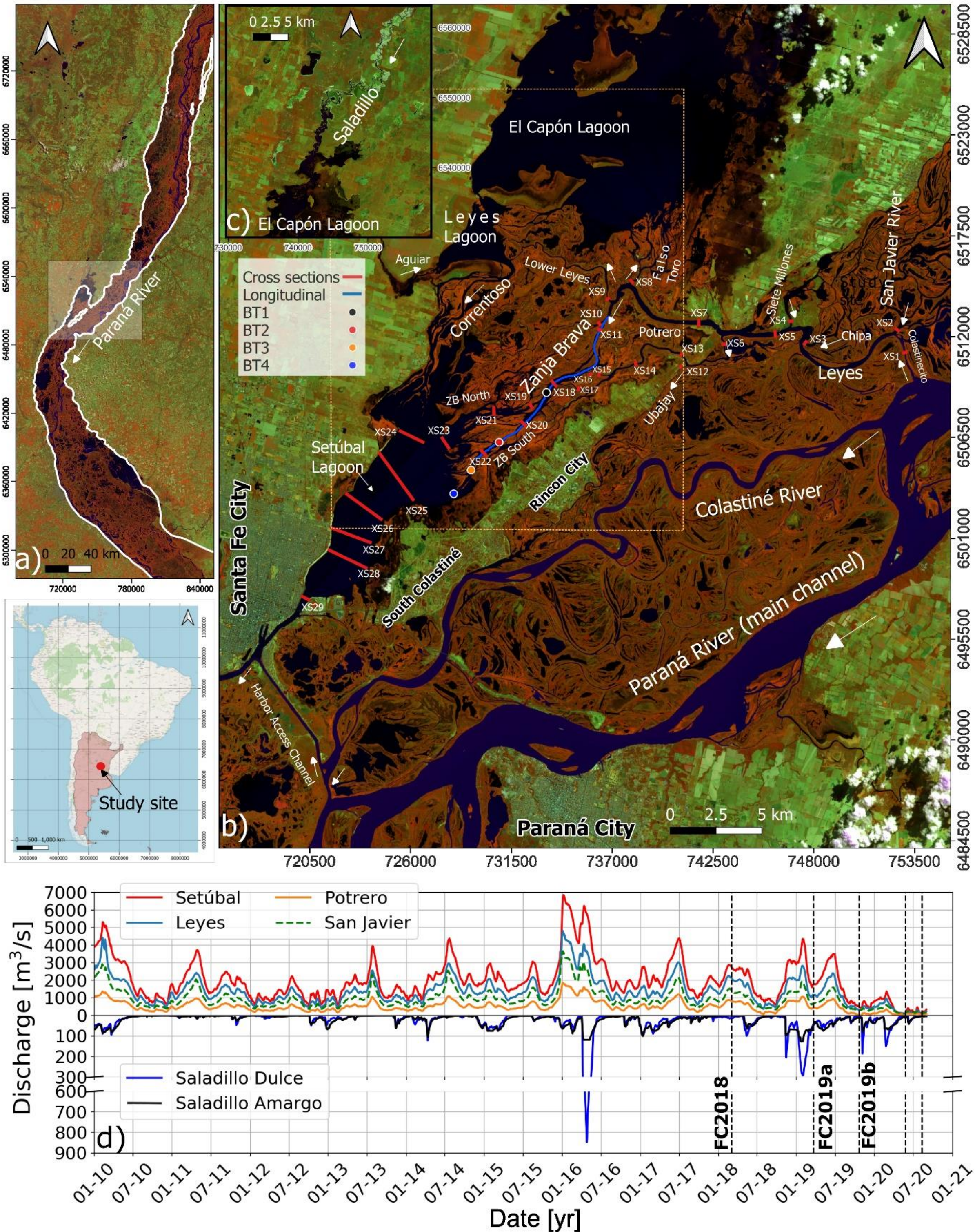

Figure 1. a) Active floodplain of the Paraná River middle reach; b) Fluvial-Lacustrine Delta Leyes-Setúbal. Location of cross-section, longitudinally measured, and static ADCP bedload measurements (BT); c) Saladillo Channel mouth into the Capón Lagoon. Background images:

Sentinel-2 bands B8A-B11-B4 (Coordinate Reference System UTM 20S). Date: 28-03-2018; and d) Hydrographs of FLD Leyes-Setúbal for the last 10 years. The date of each field campaign (FC) is listed. Source of hydrological data: National Water Information System-Secretariat of Infrastructure and Water Policy, Argentina.

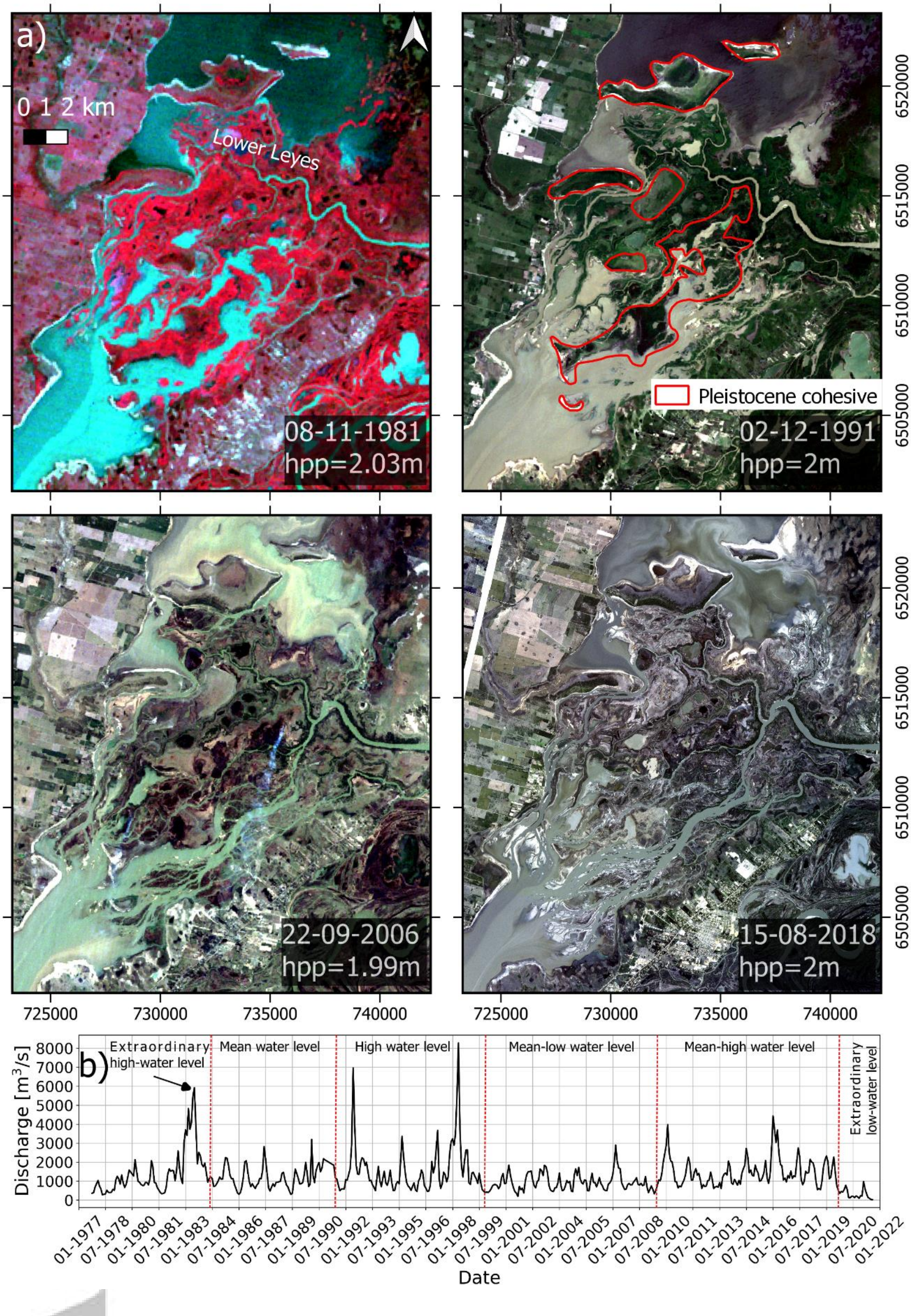

Figure 2. a) Satellite Landsat-2 and 5 and PlanetScope (Planet Team, 2017) imagery showing elevated consolidated Pleistocene cohesive sediments, where the deltaic system began to evolve and; the

morphodynamic changes of the study site along the different hydrological sub-periods during the last 37 years. Note that the water level of hpp≅2 m at the Paraná Port gage station (discharge at Leyes Channel of 550 m^3/s) was used for comparison purposes. Source: National Water Information System-Secretariat of Infrastructure and Water Policy, Argentina. Note the dashed line for reference location in Figure 1b.

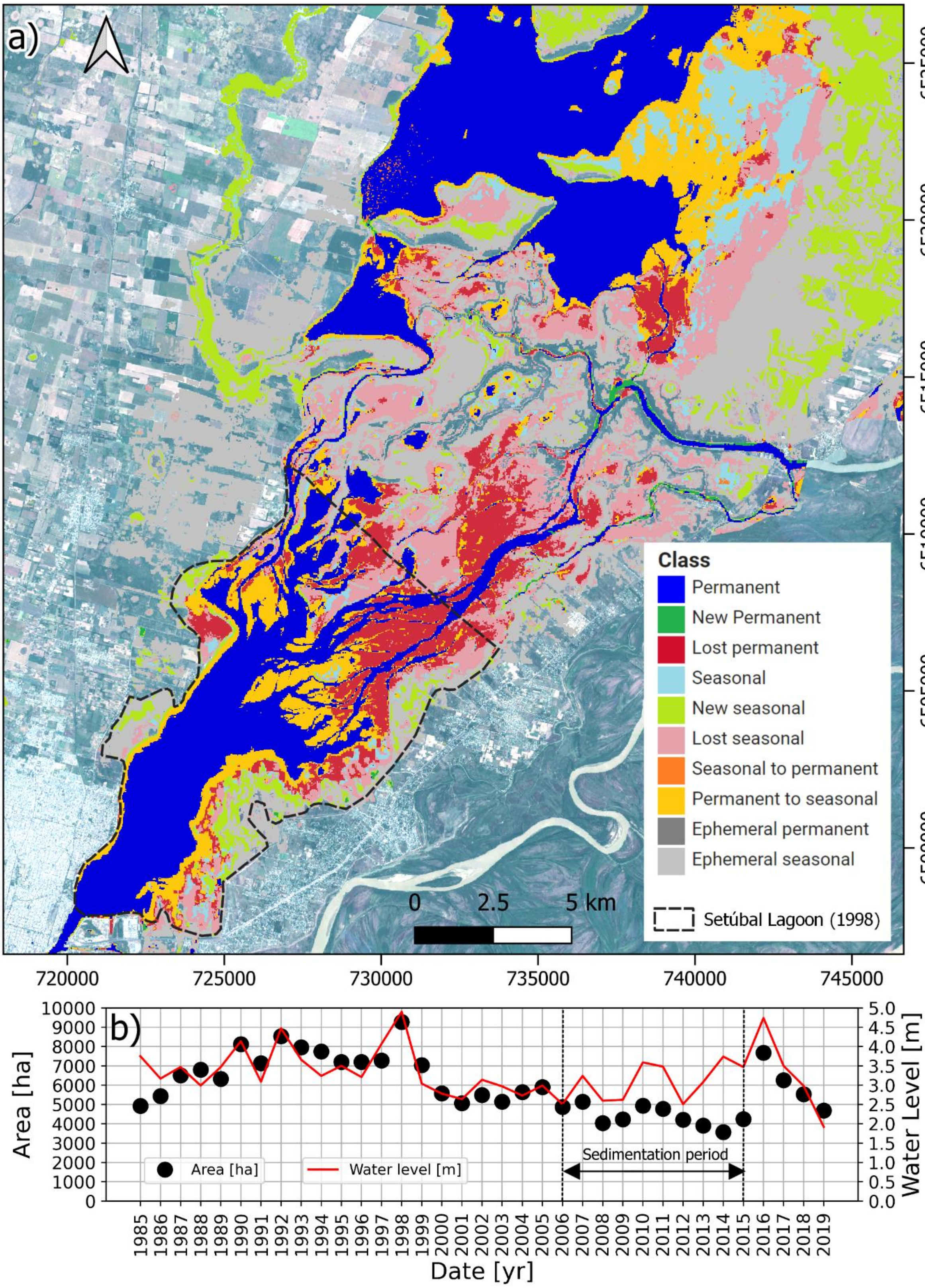

Figure 3. (a) Water permanence from 1984 to 2019 according to Pekel *et al.* (2016) methodology and (b) mean annual area variation of Setúbal

Lagoon (scattered black points) and mean annual water level (red line, recorded at Paraná Port station) between 1985-2019. Source: National Water Information System-Secretariat of Infrastructure and Water Policy, Argentina.

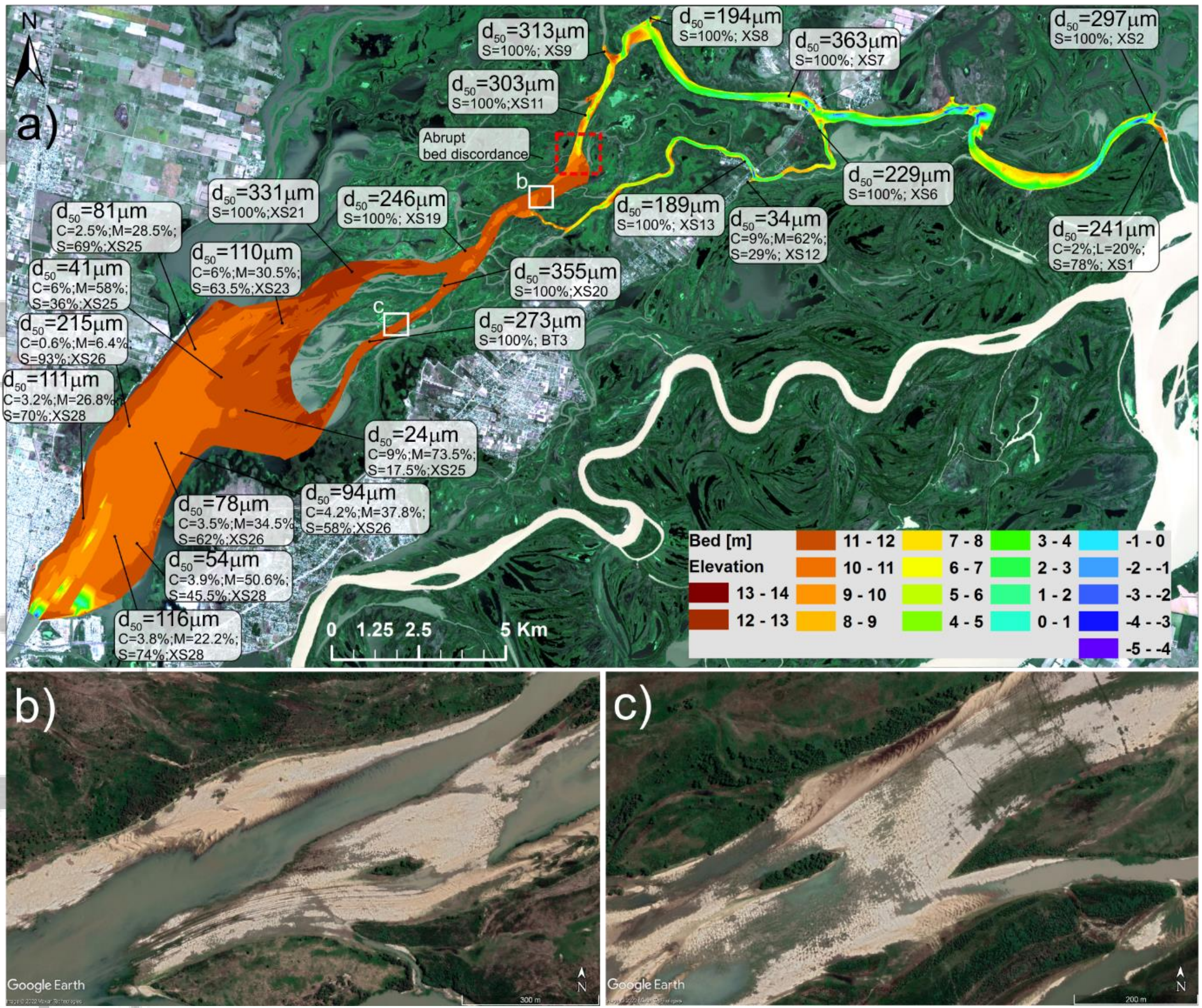

Figure 4. a) Bed morphology and grain size characteristics along the FLD Leyes-Setúbal. S: sand, M: silt, and C: clay. Bed elevation is referred to as sea level; b) and c) sand bars and Pleistocene cohesive substrate regions downstream the abrupt bed discordance. See the white box in Figure 4a for location. Source of satellite images: Google Earth, January 2022.

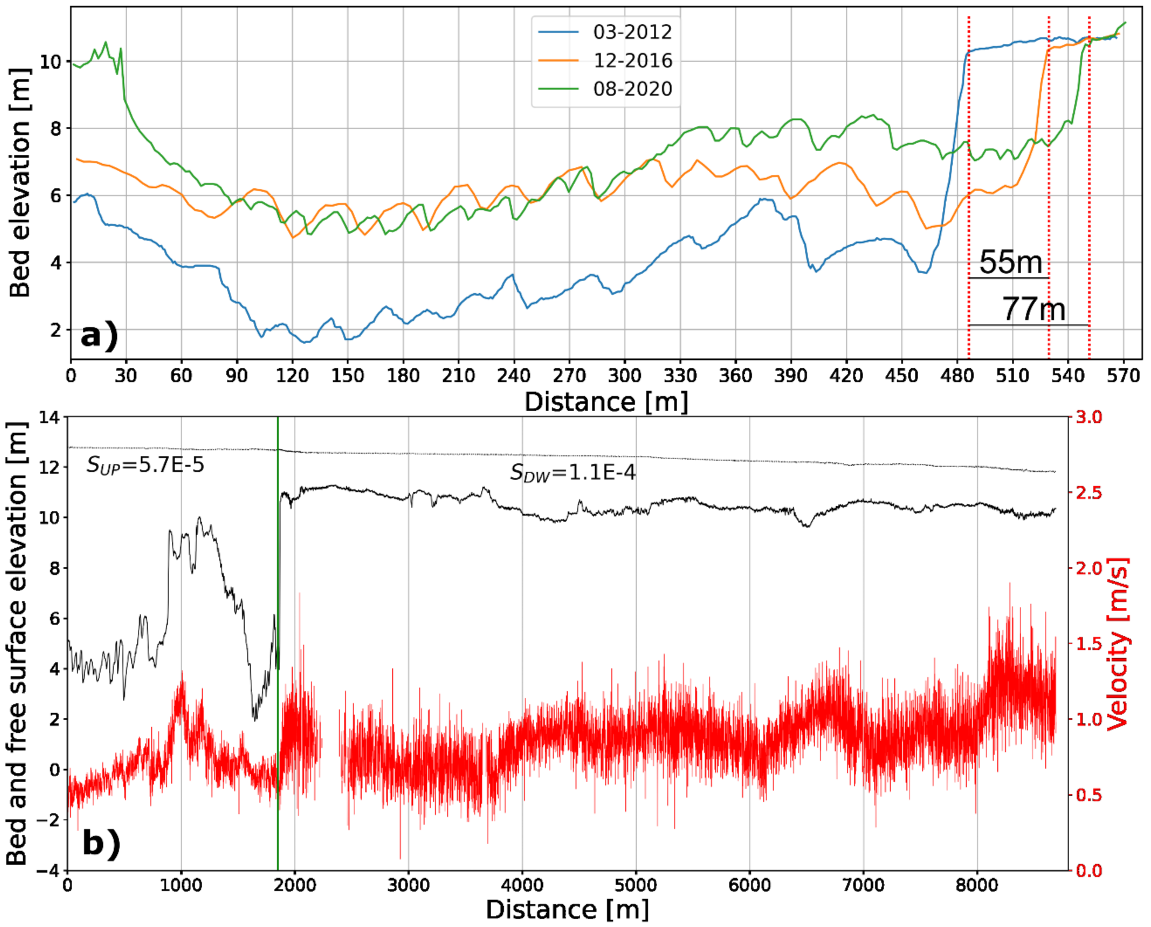

Figure 5. a) Bed discordance evolution and bedform characteristics along Zanja Brava Channel during 2012-2020 (see red dashed box in Figure 4a for location), S_{UP} and S_{DW} are the free surface slope upstream and downstream from discordance, respectively; b) Bed morphology (black line), free surface level (black dashed hairline), and depth-averaged velocity (red line) along the longitudinal profile surveyed in the Zanja Brava Channel/Zanja Brava South Channel (see the blue line in Figure 1b for location). Bed and free surface elevation are referred to as sea level.

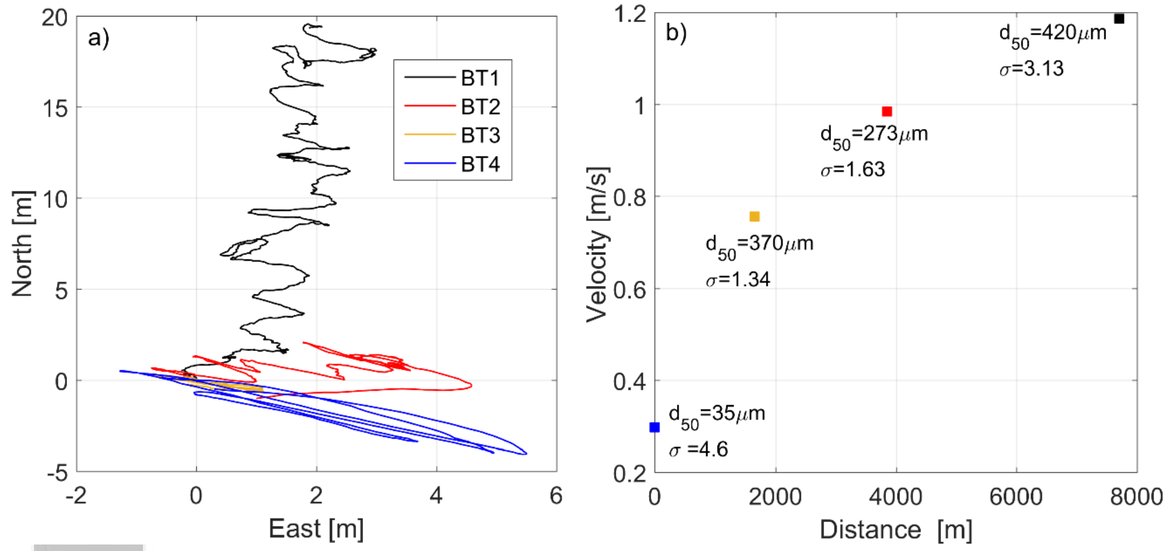

Figure 6.- (a) Bed particle displacement (North and East arbitrary reference) using ADCP through the Bottom Tracking system with the static vessel; (b) time-average velocity (5 min interval) in the different static measurements (BT1-BT4) in the transition zone (see point location in Figure 1b). Note that BTs are represented in both figures with the same colors. Distance in figure b is from the first BT4.

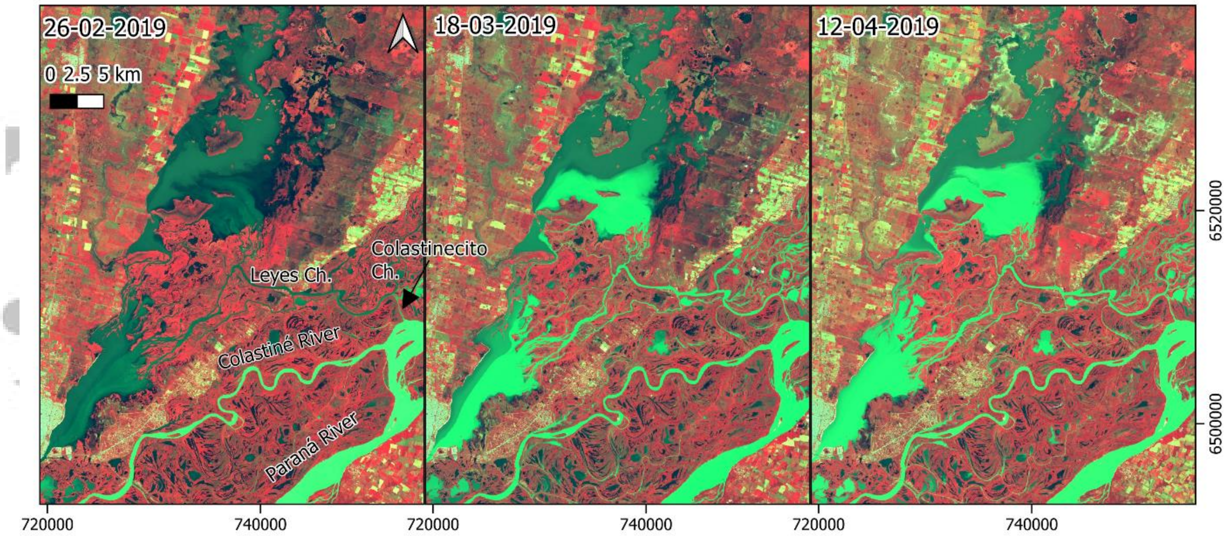

Figure 7. Dynamics of the fine sediment jet plume through Capón, Leyes, and Setúbal lagoons. Sequence of Sentinel-2 satellite images during 2019. The Sentinel-2 band composition is B4-B8-B2. For location see the dashed line reference in Figure 1b.

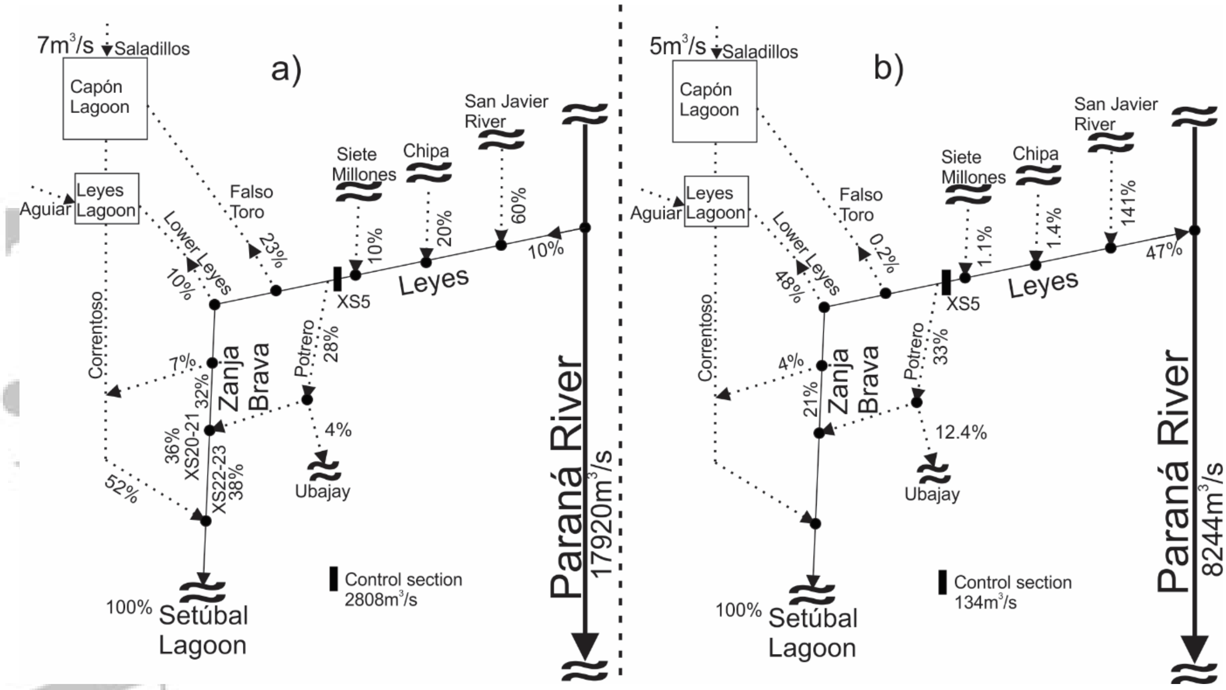

Figure 8. Flow discharge distribution scheme (in percentages correlated with XS5 flow discharge) for both hydrometric conditions surveyed. (a) FC2018 and (b) FC2020b. See the location of control section XS5 in Figure 1b.

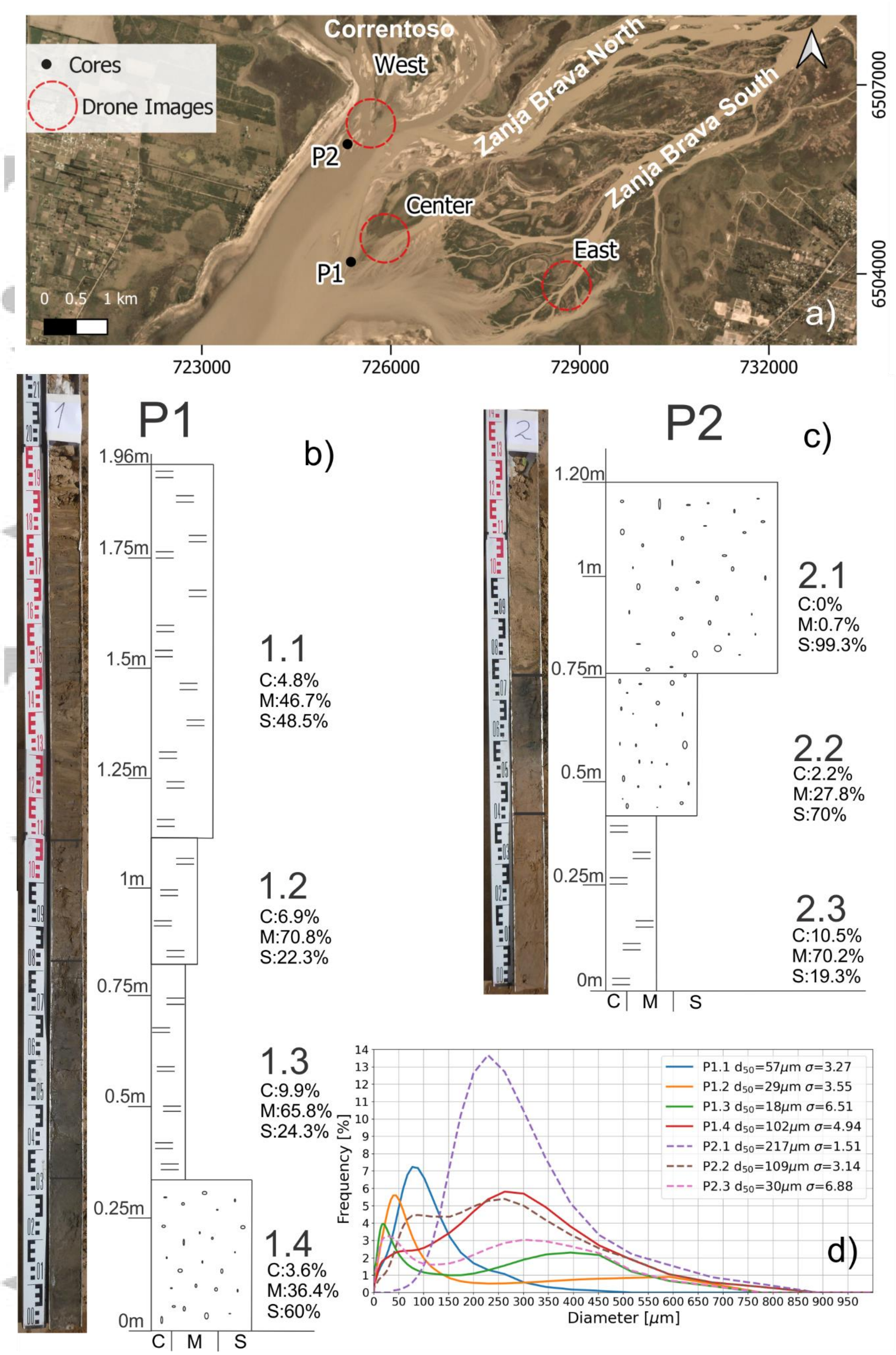
Correntoso
West
Zanja Brava North
Zanja Brava South
Center
East
Cores
Drone Images
P1
P2
0 0.5 1 km
6507000
6504000
723000
726000
729000
732000
a)
P1
b)
1.96m
1.75m
1.5m
1.25m
1m
0.75m
0.5m
0.25m
0m
C M S
1.1
C:4.8%
M:46.7%
S:48.5%
1.2
C:6.9%
M:70.8%
S:22.3%
1.3
C:9.9%
M:65.8%
S:24.3%
1.4
C:3.6%
M:36.4%
S:60%
P2
c)
1.20m
1m
0.75m
0.5m
0.25m
0m
C M S
2.1
C:0%
M:0.7%
S:99.3%
2.2
C:2.2%
M:27.8%
S:70%
2.3
C:10.5%
M:70.2%
S:19.3%
d)
Frequency [%]
Diameter [μm]
P1.1 d50=57μm σ=3.27
P1.2 d50=29μm σ=3.55
P1.3 d50=18μm σ=6.51
P1.4 d50=102μm σ=4.94
P2.1 d50=217μm σ=1.51
P2.2 d50=109μm σ=3.14
P2.3 d50=30μm σ=6.88

Figure 9. a) Satellite image with core position; b) stratigraphic profiles of delta front bars on the river mouth of Zanja Brava North; Correntoso channels; c) grain size distribution per bed; particle size distribution corresponding to each bed detected in both cores.

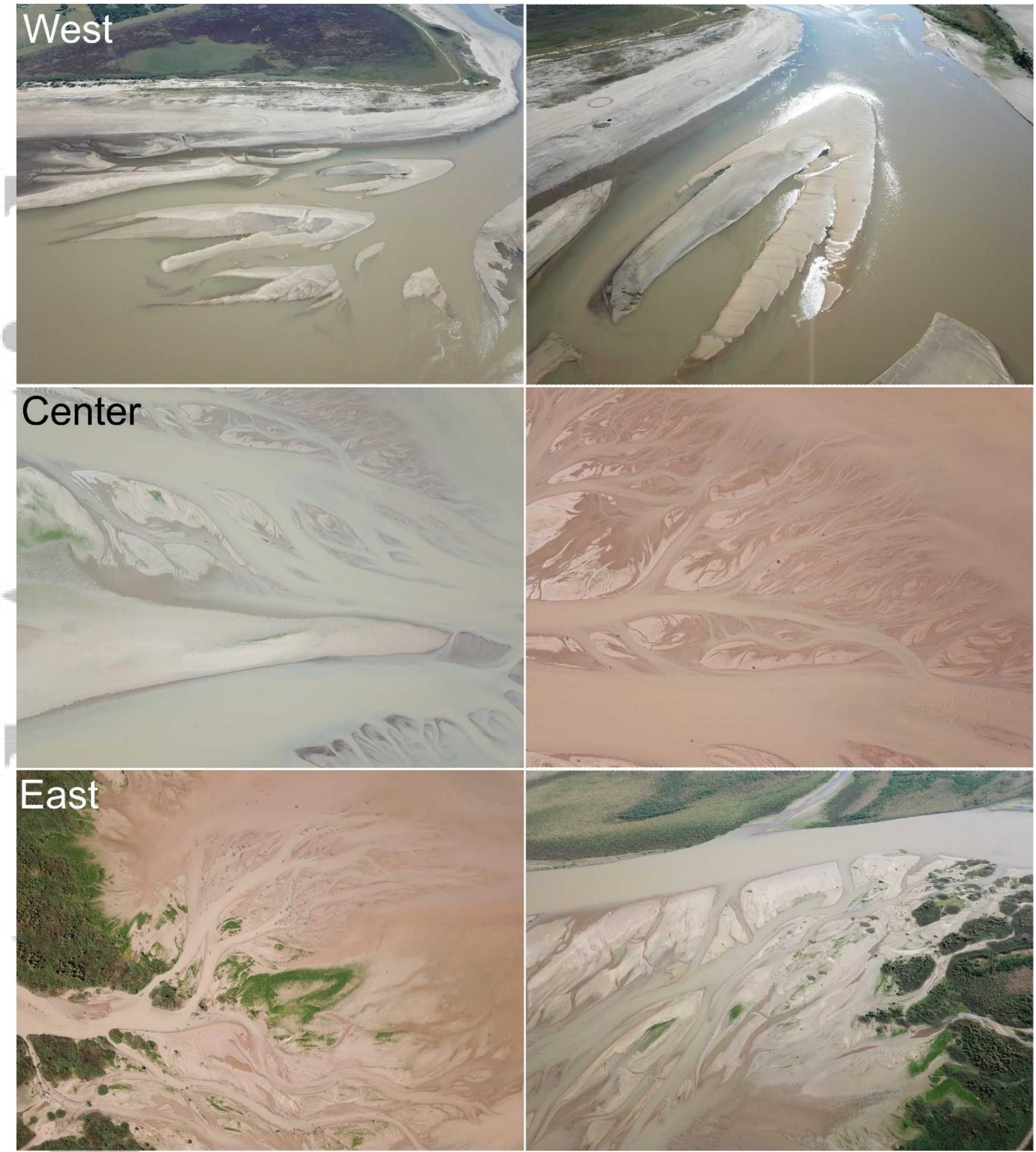

Figure 10. Drone images from the Paraná extremely low-water level (26-05-2020). Particular river mouth deposits formed at different delta front bars in different channels supplied (see Figure 9a).