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GEOMORPHOLOGIC, CIRCULATION AND DYNAMIC ANALYSIS IN A MEANDERING TIDAL CHANNEL, BAHÍA BLANCA ESTUARY (ARGENTINA)

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ABSTRACT

A meander of La Lista tidal channel (Bahía Blanca Estuary, Argentina) was selected in order to study the relationship between the geoforms that control the meandering channel evolution (mainly tidal flats and marshes) and the dynamic and circulation characteristics of these channels. To achieve this goal a general survey was made in August 1999. The topographic characteristics of the channel and cross-section profiles from different sectors of the meander were compared with typical river profiles. Morphologic similarities between meander tidal channel cross-section (characterized by bidirectional flows) and meander river cross-section (characterized by unidirectional flows) were analysed. The largest velocities were measured during the ebb period (87 and 67 cm s^{-1} for U and V, respectively); during the flood period, the highest values registered were 53 and 33 cm s^{-1} for U and V, respectively. Differences among the tidal current profiles along the meander were observed. Comparing the current velocity gradients in the different stations, the higher variations were observed during the flood period.

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INTRODUCTION

The Bahía Blanca Estuary is located in the southwest of the Buenos Aires Province (Argentina). It is characterized by a complex tidal channel network with a meandering drainage pattern (Figure 1). The relationship between a quasi-stationary and semidiurnal tidal wave and the presence of salt marshes and tidal flats constitutes the principal mechanism responsible for both general circulation and tidal channels evolution. The tidal range varies between 2 and 4 m from the mouth to the head (Perillo y Piccolo, 1999).

The internal zone of the estuary is characterized by the presence of numerous tidal channels which have a notably meandering drainage pattern. According to Amos (1995) in these environments controlled by the tide it is practically impossible to find a tidal channel

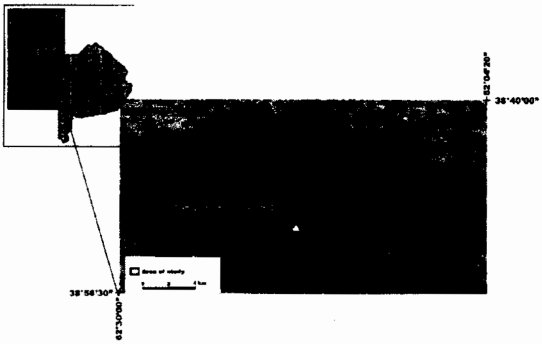

Figure 1. *Area of study*

without this typical drainage pattern. However, no theoretical explanations have been advanced concerning the reasons for this preferential drainage pattern. According to Perillo *et al.* (1993) little is known about current circulation on tidal flats.

River and stream meanders have been studied extensively. The first studies date back to the end of the XVIII Century. The most important advances were observed between 1950 and 1980 (Finch and Trewartha, 1950; Leopold and Wolman, 1957, 1960; Schumm, 1977; Derruau, 1977; Fredsoe, 1978; Reading, 1979). The origin and evolution of meanders and their abandonment through cutting mechanisms in rivers have been abundantly treated in the hydraulics, geological and specially the geographical literature (Polanski, 1974; Strahler and Strahler, 1978, 1992; Patton et al, 1983; Ikeda and Parker, 1989; Dietrich and Whiting, 1989; Capitanelli, 1992). Also, several studies based on circulation models applied in bend channels have been developed, such as Nelson and Smith (1989) and Johanesson and Parker (1989). Furthermore, geomorphological analysis based on the geometrical characteristics of different meanders (e.g., radius of curvature, arc length, etc.) of several European and American rivers were made (Schumm, 1977) but very little was done for South American cases.

Also, analysis of the geomorphology and dynamics of tidal channels is relatively poor, so are the studies about the topics related to the dynamic and circulation that originate meanders in these kind of channels. Some papers based on the relationship between tidal current measurements and tidal flats could be mentioned (Boon, 1975; Perillo and Sequeira, 1989). Besides, several studies about tidal channels in the Bahía Blanca Estuary were developed applying diverse methodologies (Gómez and Perillo, 1985; Perillo and Sequeira 1989; Ginsberg and Perillo, 1990; Ginsberg, 1991; Perillo and Piccolo, 1991, 1993; Gómez *et al.*, 1996; Ginsberg and Perillo, 1999). Others authors (Pethick, 1969; Amos, 1995; Luternauer *et al.*, 1995) assume that the basic circulation model would be the same as in rivers, but there is no evidence to prove it.

Meandering is not associated to specific climatic, hydrological or geological conditions, but it is common to all rivers or channels with an equilibrium between its load capacity and the volumes transported. According to several authors (Leopold and Wolman, 1957; Derruau, 1977; Fredsoe, 1978; Ikeda and Parker, 1989) meandering is a consequence of an equilibrium between the net current potency and the resistance of the channel banks.

In a tidal channel the currents are reversible. This characteristic constitutes the largest difference between tidal channels and rivers. The influence of these currents in both the distribution and transport of sediments affects the evolution of the bottom morphology. Moreover, in a tidal channel the depth changes gradually as the tidal cycle develops. In consequence, the channel shows different conditions from a flood tide period concentrated in the thalweg to a full bank situation. In the ebb tide period an inverse process is generated. But, during the ebb period the action of a strong transversal current proceeding from the tidal flats and salt marshes should be considered. These currents were detected for the first time in Canal Principal of the Bahía Blanca Estuary by Perillo and Sequeira (1989).

We focus our study on a specific meander of La Lista tidal channel in the Bahía Blanca Estuary. The main objectives are a) to define the general meandering characteristics and their relationship with tidal flats, salt marshes and islands, b) to describe the transversal and longitudinal current circulation in the meander, c) to analyse the relationship between the tidal channels and the general circulation of the estuary.

METHODOLOGY

To define the geomorphologic and oceanographic processes occurring at the meander, as series of bathymetric and hydrographic surveys were made.

Bathymetric survey

Bathymetry consisted on a series of transverse survey lines every 50 m made at spring high tide to allow maximum coverage including part of the adjacent tidal flats. A Raytheon DE-719B echosounder with a 208 kHz frequency was employed and positions were fixed with a GPS Garmin Surveyor II. All depth values measured from the echosounder records were corrected to the Datum Plane for the study area using tide records from a tidal gage specially installed at the meander (Figure 2). All positions were estimated in the Gauss Krügger system of coordinates.

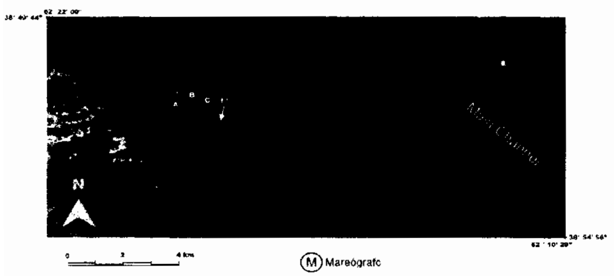

Figure 2. *Location of the measurement sites in La Lista Channel.*

Tidal Currents

Following the general procedure developed by Perillo and Piccolo (1993) to study estuarine cross-sections, three stations (A, B and C) were situated at the meander (Figure 2). Table 1 shows the geographic coordinates corresponding to the position of the sites. A 2D acoustic currentmeter FSY2D with a sampling rate of 2 s was used to measure both components of the tidal currents. At each station vertical profiles were obtained by lowering and hoisting the currentmeter very slowly from the surface to the bottom and back. In each profile the measurements started and finished on a level near the surface (between 0.2 and 0.4 m). The stations were occupied sequentially along the tidal cycle starting with station A, then station B and ending at station C, next station B and later A were occupied. At the end of the measurement period, station B was occupied twice as much as the other end stations (Table 1).

Table 1.
Geographical location of the measurement sites in La Lista Channel.

Radium of curvature (R)	538.5 m
Width channel (w)	314 m
Meander length (L)	2860 m
Arc lenght (A)	1000 m

The tidal current velocities were decomposed into a longitudinal component (U) with reference to the main axis of the channel (positive in the ebb direction), and a transverse component (V) positive to the right, looking toward the mouth of the channel. The depth was normalized considering a standard depth so that 0 and 1 correspond to surface and bottom, respectively. The current values were interpolated considering both a standard depth and a standard hour (Perillo and Piccolo, 1997).

RESULTS AND DISCUSSIONS

Bathymetry

La Lista channel has an East-West general trend. The channel varies in width between 1 km at its mouth and 300 m at its head. The topographic characteristics derived from the bathymetric survey are shown in Figure 3. The maximum depth values were located on the convex bank, near the inflection zone situated to the East of the meander axis (Figure 4). The maximum depth measured was 7 m. Another inflection zone was located toward the West of the meander axis, with the smaller depths (> 1 m). At the meander curve the maximum values were measured on the concave bank whereas, on the convex bank an accumulation area was detected. Figure 3 also shows some negative bathymetric values related to tidal flats situated above the datum plane.

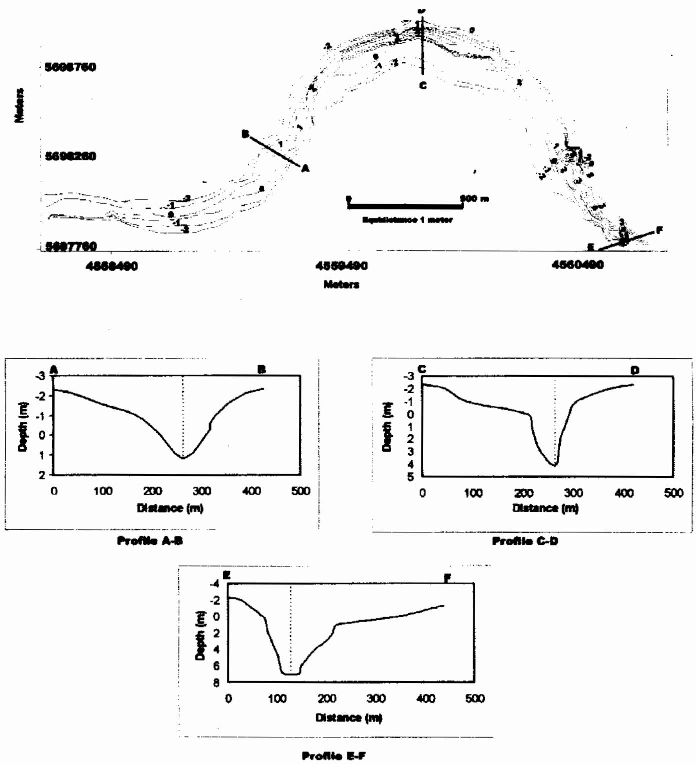

Figure 3. *General bathymetry and profiles of La Lista Channel represented by Gauss-Krugger system of coordinates (m).*

Isobaths show a displacement towards the East of the meander axis in direction of the ebb currents. An asymmetry between the flood and the ebb currents can also be observed. These situations suggest that the ebb currents would have the largest influence in the channel morphology. Three cross section profiles are described in order to summarise the topographic characteristics of the meander; profile C-D was located at the meander curve and the other two were made on the inflection zones (profiles A-B and E-F, respectively).

Figure 4. *La Lista Channel meander geometry.*

Profile C-D shows a high slope on its concave bank and an accumulation sector on the convex bank. Profile E-F, situated Eastward of the meander axis shows an inverse situation having the larger slopes on its convex bank and an accumulation sector in its concave bank. Finally, profile A-B shows similarities in both banks but with depth and slope values slightly larger on the concave bank.

Tidal currents

The tidal elevation was determined every minute during the whole measurement period related to spring conditions. Tidal curve is very asymmetric with low water slack very short in duration. The total amplitude was of 4.1 m. The velocity profiles (U and V) measured at each station are presented in figures 5, 6 and 7. These profiles show that the velocity at any time during the tidal cycle is quasi logarithmic. This assumption was valid for other sites in the estuary for more than 90 % of the time (Perillo and Sequeira, 1989; Perillo and Cuadrado, 1991). The tidal wave is quasi stationary and the maximum currents were measured in a period of 2 h after slack water. The maximum velocities were measured during the ebb period at all stations.

Velocity profile distribution U and V during a complete tidal cycle at station A (Figure 5) indicates that the longitudinal component reached peak velocities (63 cm s^{-1}) at mid depth during ebb coincident with maximum values of V (60.2 cm s^{-1}) towards the right. This clearly demonstrates that a secondary flow coming from the northern flats deviates the general direction of the ebb current. During the flood, maximum longitudinal velocities (38.2 cm s^{-1}) concentrate near the surface, and transversals currents show a similar behaviour, having northward flows up to 23.5 cm s^{-1} along all this period.

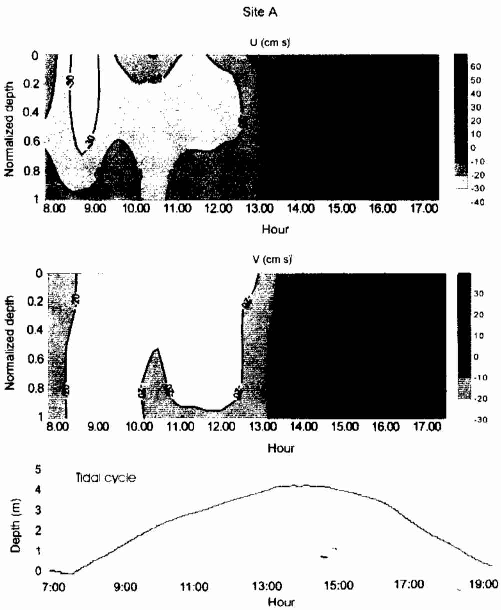

Figure 5. *Tidal current velocities in the Site A, during the tidal cycle (Velocity values are positive to the ebb direction).*

Station B, located on the meander curve, shows notable differences between ebb and flood longitudinal velocities (Figure 6). During ebb, maximum longitudinal currents (up to 86 cm s^{-1}) concentrated in a very short time (within 1 h) near the surface, whereas flood currents were more homogeneous (about 40 cm s^{-1}) and distributed over a longer period. Similar behaviour was observed for the lateral flow with water moving towards the North during flood and to the south during ebb. Station C (Figure 7) presented almost the same circulation pattern although peak velocities were lower in both, ebb (70 cm s^{-1}) and flood (40 cm s^{-1}) conditions. Specially, during ebb, superficial current acceleration was observed.

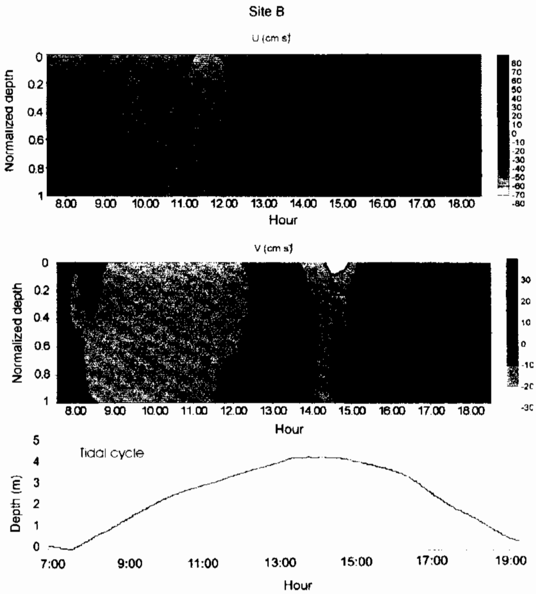

Figure 6. *Tidal current velocities in the Site B, during the tidal cycle (Velocity values are positive to the ebb direction).*

Polar distributions of current velocities for each station are shown in figure 8 considering three different levels of normalized depth (near surface, mid depth and near bottom). Comparison of the vector directions for each station in depth clearly shows that the upper flows vary widely in direction while at mid depth and bottom, vectors are more concentrated and have a general reversing direction. The degree of dispersion observed in the upper portions of the flow

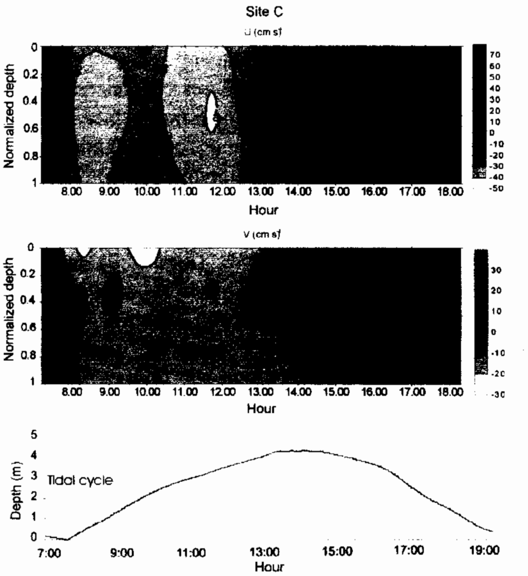

Figure 7. *Tidal current velocities in the Site C, during the tidal cycle (Velocity values are positive to the ebb direction).*

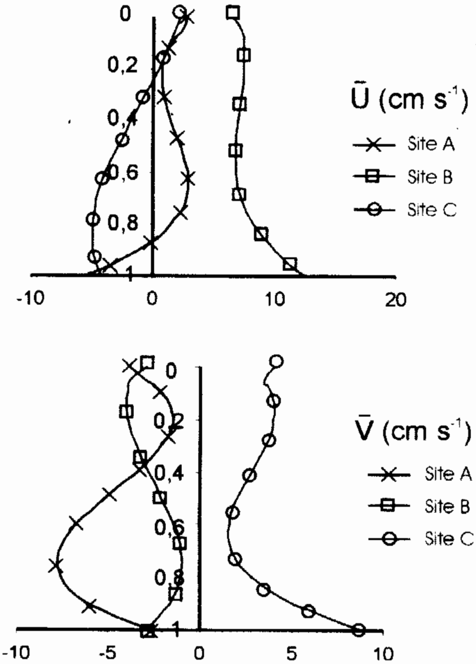

Figure 9. *Profiles show the average values of both U and V component for each level of normalized depth in the 3 measurement sites considered.*

are influenced by the process of inundation and drying of the adjacent flats. Secondary superficial currents having directions both normal and oblique to the main channel direction can displace the actual current in the channel, especially when the latter is relatively small. This occurs near high and low tide conditions.

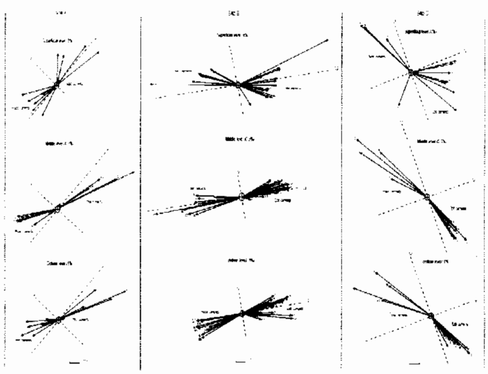

Figure 8. *Polar diagrams of current velocities (longitudinal U and transverse V) obtained in the sites of measurement considering three levels of normalized depth (0, 0.5 and 1 %). The vector number indicates the order in wich each vector was obtained.*

As indicated, directions at lower levels in the water column appear more concentrated along the specific main direction. There are certain fluctuations, however, but their angles never reach 30º, which is typical of most channels. Direction concentration was more effective during the ebb, indicating that, once the current is concentrated in the channel, velocities are stronger and less prone to be modified by lateral flows. Whereas, flooding starts concentrated within the channel, and while the water level increases, so does the cross-section area and velocity decreases, then lateral flows become significant.

Residual velocity profiles corresponding to the three sites A, B and C (Figure 9) were calculated by averaging over the tidal cycle velocity values interpolated to a series of predefined normalized depths. At the central station (B), the mean longitudinal component has a greater influence than the mean transverse component. However, in stations

A and C the inverse situation was perceived. Moreover, in both end stations a similar behaviour in the vertical distribution of the mean transverse component was observed. This behaviour reveals that the flood currents have a dominance in depth whereas the ebb currents have a dominance at a superficial level. In relation to the mean longitudinal component an inverse behaviour was observed, mostly in a normalized depth situated between 0.2 and 1, due to the flow conditions, the meander morphology and the cross section asymmetry (Figure 10).

A comparison between a typical meandering river cross section (unidirectional flow) with the meander cross section in La Lista (bidirectional flow) is presented in figure 10. The comparison is based on the distribution of velocity profiles during a complete tidal cycle and the position of the stations in the meander. Similarities in relation to their morphological characteristics can be observed. However, the current dynamic is very different in the tidal channel due to its bidirectional flow condition.

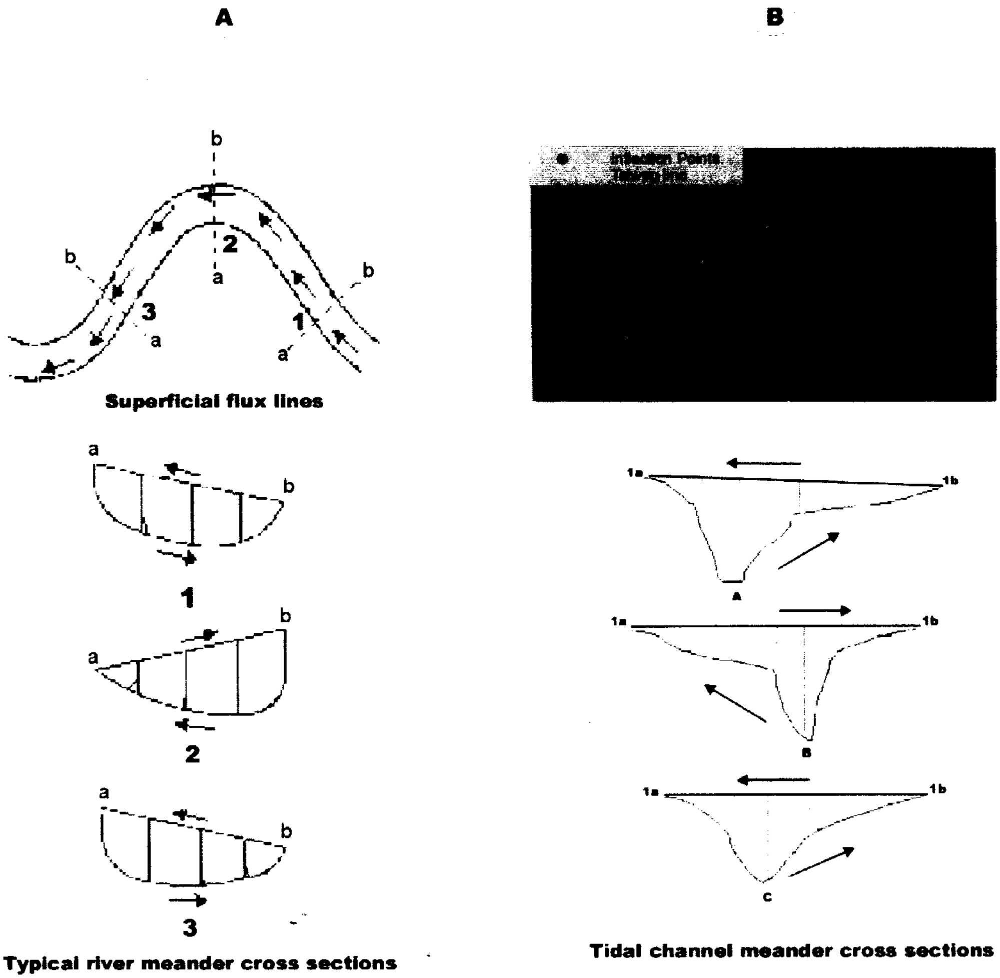

Figure 10.
Comparison between characteristic profiles of: A) a typical river meander, according to Leopold et al., 1964 and B) a tidal channel meander.

Velocity distribution reveals that the superficial fluid velocity is greater than the bottom fluid velocity. According to Leopold *et al.* (1964) this phenomenon is a consequence of the centrifugal acceleration derived from the helicoidal flow present in meandering channels. In the meander curve, where station B was located, the longitudinal velocity component (maximum during the ebb tide) and the comparatively weaker transverse velocity component was remarkable. The latter carried superficial water towards the concave bank whereas the bottom water flowed towards the convex bank. The transverse current velocities represent between 10 and 20% of the longitudinal current magnitudes. In the inflection zones (stations A and C) the cross section profiles are asymmetric with the deeper portions on the convex bank. Thus, the magnitude of the transverse component is larger. Inversely, in the inflection areas the longitudinal component is smaller than in the meander curve. These differences suggest the action of both acceleration and deceleration processes on the tidal currents at these sites.

Secondary tidal channels connected to the studied meander may have a certain influence on the velocity distribution in the meander. This distribution is also related to erosive and accumulation processes developed in different sections of the meander. Consequently, the larger velocities generate increasing erosion on the concave bank, following a trajectory along the thalweg line (Figure 10). The transverse flow component carried the eroded material towards the centre of the channel. However, part of this material cross the channel to settle on the convex bank.

Figure 10 also shows differences in the surface water level in the cross section profiles. In an ideal meander (Figure 10a) the water level is higher on the concave bank as a consequence of the velocity distribution whereas in a tidal channel(Figure 10b) there is practically no difference due to the bidirectional flow condition which produces a balance between the levels reached by the banks and the geomorphology (tidal flats) on which the channel is developing.

The meander geometric parameters should be considered in order to relate them to the flow characteristics. Bagnold (1960) described the flow as the ratio R/w where, R is the curvature radius and w is the channel width. He suggested that values of the ratio near 2 indicate that the channel curvature offers a very low resistance to the flow. Adopting a similar criterion, the relationship was applied to La Lista meander (Table 2) resulting equal to 1.71. According to Bagnold (1960), this result reveals that there is an increase of the flow pressure on the concave bank (external) and a flow divergence that originates an accumulation zone on the convex bank (internal). Thus the situation becomes unstable and generates an energy dissipation process due to the action of the returning secondary currents. This could be intensified by the action of secondary discharges proceeding from the near tidal flats, for instance, the presence of a secondary channel (Figure 10) which is flowing on the convex bank in the meander curve.

Table 2. *Geometrical parameters in the meander studied.*

Station	Latitude	Longitude	N° of profils in each station
A	38° 51′48" S	62° 18′ 56" W	11
B	38° 51′41" S	62° 18′ 47" W	22
C	38° 51′47" S	62° 18′ 33" W	11

CONCLUSIONS

The results obtained from the bathymetric survey reveal the general geomorphology of the study area. Maximum depth was 7 m concentrating on the convex bank and around the inflection zone located to the East of the meander axis. Whereas in the inflection zone located toward the West of the meander axis the depths measured were smaller than 1 m. On the meander curve, the great depth values were measured on its concave bank while on the convex bank an accumulation zone was detected. The stretching of the isobaths towards the East of the meander axis (ebb current direction) shows the asymmetry between the flood and the ebb currents where the former are the most important influence on the channel morphology. The meander cross section profiles were compared to typical river meander profiles. Considering the differences in the flow conditions a morphological similarity was observed, mostly in relation to the erosive and accumulation banks.

Tidal current velocities have larger values for both components during the ebb tide period. The largest value of U (86 cm s^{-1}) was measured in the station B, situated on the meander axis. The magnitude and direction of the V-component are related to acceleration process which, in turn, could be linked to both the helicoidal current dynamic characteristic of meanders, and surficial discharges proceeding from the incipient tidal channels situated near the measurement site. In the A and C stations, situated in the inflection zones, the larger longitudinal velocities measured were smaller than in station B. However, in these stations the larger transversal component velocities were detected.

As a result of the study, we observed geomorphological similarities between the tidal channel meander (bidirectional flow) and the typical river meander (unidirectional flow). However, the geomorphology of the meander is conditioned by the bidirectional flow conditions characteristic in the tidal channel. In the meander curve (station B), the ebb was important, with the transverse velocity component comparatively weaker. The latter carried the surficial water towards the concave bank whereas the bottom water flows towards the convex bank. In the inflection zones (stations A and C) the cross section profiles are asymmetric with the higher depths on the convex bank, and with the larger transverse component velocity. Conversely, in the inflection areas the longitudinal component is smaller than in the meander curve. These differences suggest the action of both acceleration and deceleration process on the tidal currents.

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