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Submarine Shore-Connected Sand Bank Monitored by Means of Satellite Images in the External Zone of Bahía Blanca Estuary, Argentina

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ABSTRACT

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The evolution of an extensive shore-connected sand bank bordering the Navigation Channel along an area larger than 10 km in the external zone of Bahía Blanca Estuary 15 years ago was indicative of a potential danger to the most important deep harbor system in Argentina. The analysis of bathymetric and side scan sonar surveys recently carried out indicates that this bank evolution occurred at a lower speed than what was expected. However, and as this potential danger to the only access channel to the harbor system still remains valid, the need to carry out frequent bank monitoring is imperative. Satellite images adequately processed and corresponding to different tidal stages, together with studies on tidal circulation in this area, show that during certain tidal stages, submarine banks located in the external zone of the estuary can be adequately visualized. Thus, satellite images become an important tool for bank monitoring on account of the fact that the qualitative analysis of the evolution of subtidal geomorphology can be done more regularly as well as at lower costs with respect to periodic bathymetric surveys.

ADDITIONAL INDEX WORDS: *Bathymetric and side scan sonar surveys, suspended sediment, geomorphology, remote sensing.*

INTRODUCTION

Bahía Blanca Estuary, which is located in the southwestern area of the province of Buenos Aires, Argentina, contains one of the most important harbor complexes and therefore plays a crucial role in the economy of the country. The area consists of a system of tidal channels of different dimensions, which are separated by islands and extended tidal flats, and it is constantly influenced by winds and tidal currents which give a complex dynamics to the zone. The navigability of a large part of the Access Channel to the Harbor Complex as well as of the mooring sites of the system, is maintained artificially by dredging at 13-m depth.

In the external zone of the estuary (Figure 1) there is a submarine shore-connected sand bank called Largo Bank bordering the Navigation Channel westwards. The presence of this bank produced an acceleration on the ebb currents in the Access Channel, permitting the navigability all along an area larger than 10 km without dredging. However, based on the analysis of these changes in the geomorphological features, GÓMEZ and PERILLO (1992) proposed a hypothesis of tidal currents circulation for the migration of this sand bank, according to which, the bank evolves in such a way that it may seriously affect the Navigation Channel. GÓMEZ and PERILLO (1992) also claimed that Largo Bank sides are dominated by unbalanced opposite tidal currents, a phenomenon which promotes its eastward advancement and induces the development of an ebb-oriented sinus immediately north of the bank core. These authors also claimed that in agreement with the development of the new ebb-oriented sinus, the maximum current velocities at the Navigation Channel may progressively decrease because this sinus deviates a large part of the ebb currents.

Such decrement in current maxima velocities could be eventually translated into a sedimentation increment on the Navigation Channel, and in a speeding-up of Largo Bank migration rate, thus eventually affecting the economy of the harbor system. As a result, in order to prevent the potential starting-up of such negative interaction from occurring, the need to conduct frequent geomorphological surveys of the area becomes imperative.

In this paper, the results of a bathymetric and side scan sonar survey carried out in 2001 are not only discussed but also compared with the forecast done by GÓMEZ and PERILLO (1992). Once the tidal circulation pattern of the area is confirmed, the possibility of using remote sensing as a cheaper and easy way of monitoring bank evolution is analyzed.

The applicability and the utility of satellite-generated images in coastal and estuarine environments have been recently attested. In fact, several studies have demonstrated their usefulness mainly in detecting changes as well as in mapping

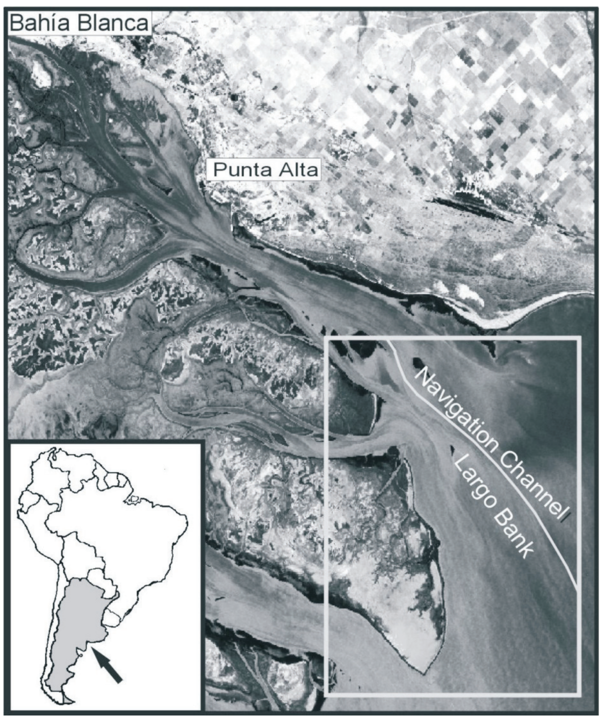

Figure 1. Location map showing the study area.

coastal regions, swamp vegetation, fluvial and tidal channels, erosion-accretion of beaches and sandbanks, turbidity front or plumes as well as bodies of water of different qualities (RESTREPO, 1997). However, the deeper waters are not always related to low turbidity. The direct identification of submerged topography through satellite images in Bahía Blanca Estuary becomes therefore uncertain because its high water turbidity changes according to the tidal stage and climatic conditions. The present study makes it clear that it is necessary to previously learn about the local tidal circulation to be able to further proceed with the observation and correct interpretation of the tidal current directions at the water surface through satellite images. In the satellite images corresponding to different tidal conditions, the tidal currents can be visualized by means of differences in the suspended sediment concentration (SSC), and SSC can be directly correlated with depth depending on the tidal stage.

METHODOLOGY

Geomorphology

In order to identify the evolution of the studied zone since 1986, a new bathymetric survey was carried out in 2001. Bathymetric profiles were taken using a 208 kHz Bathy -500 MF echosounder, and a SatLoc GPS, operating differentially in real-time, was used as navigation system (4-m error). An EG&G SMS 960 side scan sonar operating at 150 and 100 m range was used in order to identify as well as to define sea bottom features and sediment changes. Bathymetric tracks were made crossing the area in the direction of maximum morphological variation with a distance of 500 or 200 m between them, and data were corrected to the *Datum* Plane employing tidal records from the oceanographic tower tidal gauge located in the external zone of the estuary. The *Datum* Plane for nautical charts in Argentina is defined as the level of average spring low tides minus one standard deviation. For this area, the *Datum* Plane is located 1.88 m below mean sea level. All maps, which were made at an original scale of 1:20.000, are shown in Gauss-Krüger projection.

The bathymetric data obtained during the 2001 survey were compared with the data from the 1986 survey. Differences in water depths were obtained using the overlapping portions of each pair of charts at all intersections of a common rectangular grid with 100 m of side length. A residual chart was constructed with these differences. Because of the error in the reading of the echosounder records, the differences smaller than 20 cm, either erosional or depositional, were considered as no change.

Satellite Images Geoprocessing

In order to superpose different images and any other thematic map as the bathymetry, the satellite images were georeferenced by transforming the original images coordinates (Path and Row) into the Gauss Krüger coordinate system. To this end, it was necessary to define some reference point (control points) easily identified on the base map and the image that was being georeferenced. In the present study, a topographic map scaled 1:50.000 was used as a base map. On the base map, thirty-two control points easily identified and homogeneously distributed on the images were chosen. An adjust function based on the first degree polynomial was finally applied considering a maximum acceptable error of 1 pixel in the location of each control point, with errors calculated between 0.4 and 0.35 pixels.

The image working window was selected combining two spectral bands in the visible portion in order to visualize different sediment concentrations as well as one infrared band to enhance sharpness within the water mass. The so-called "Normalized Difference Water Index" (NDWI) proposed by MC FEETERS (1996) was applied on the images in order to detect areas with different SSC. However, and due to the similarity in the spectral responses between the tidal flat areas and shallow water, the methodology proposed by ÁNGELES (2001) was applied in order to obtain a better discrimination between both targets.

Digital image processing is related to the application of several procedures on remotely sensed images (enhancement, arithmetic operations, classifications, etc.) to improve their visualization with the aim of extracting as much information as possible (ANGELES, 2001). According to MATHER (1987), three processes can be followed in order to enhance satellite images: sharpness alteration, transformation techniques, and filtered methods. Geoprocessing techniques were applied using the software SPRING v.5.1 developed by the Image Processing Division (DPI) of the National Institute for Space Research (INPE) in Brazil. Image processing was performed in several

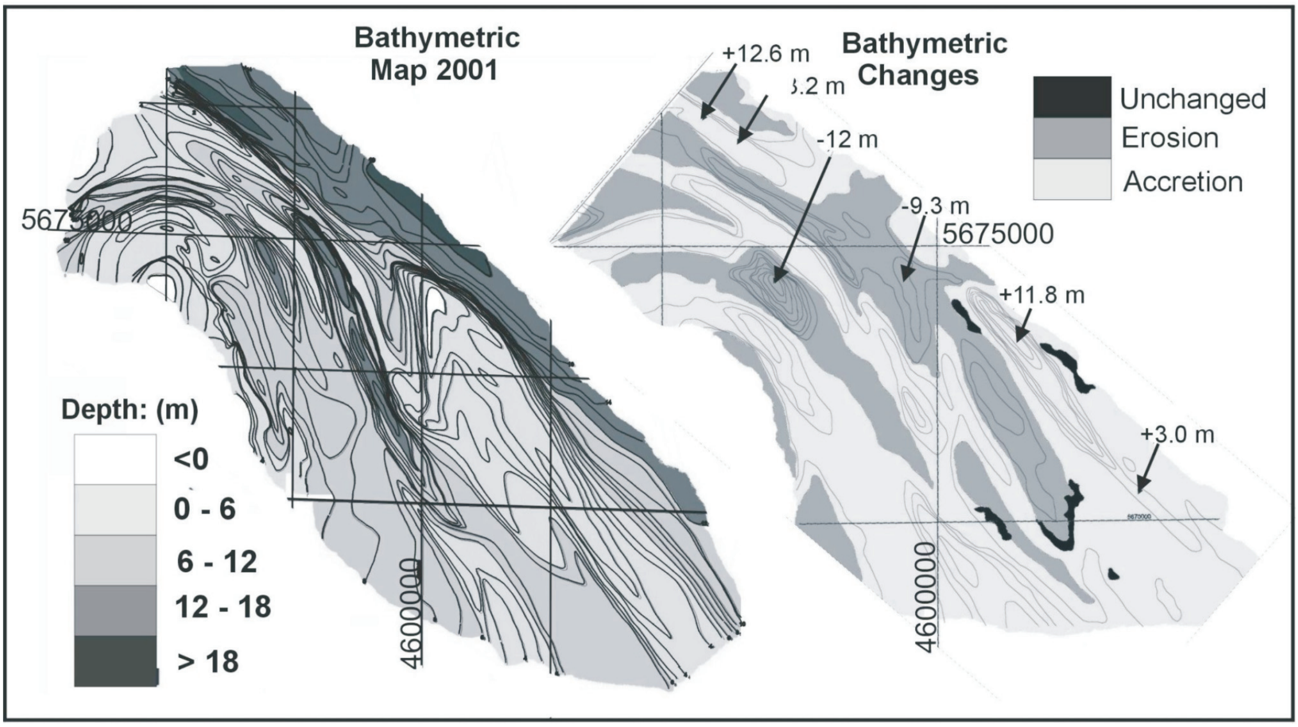

Figure 2. a) Bathymetric survey carried out in 2001 and b) Bathymetric comparison for the 1986-2001 period.

stages following similar methodologies used by CHUVIECO (1990), and RESTREPO (1997).

NDWI is concerned with the delimitation of water features on multi-spectral images. It was applied on the images used in this work in order to detect the different areas of suspended sediment concentrations. NDWI uses electromagnetic radiation corresponding to the near infrared and the visible green light wavelength, enhancing the water features with respect to soil and terrestrial forest features.

When NDWI is applied, the water bodies on the image have positive values while the other coverages (forest, exposed soil, etc.) have either negative or 0 values. This is due to the forest and exposed soil higher energy reflectance in the near infrared, in relation to the energy reflected by the green (MC FEETERS, 1996).

Consequently, NDWI has values of 0 and 1. To avoid negative values in the index, the resulting values were multiplied by a scale factor (e.g. 255). However, as a result of the similarity in the spectral responses between the areas corresponding to the tidal flats and the shallow water zones, a 'gain' of 128 and an 'offset' of 127 were applied in the present study for a better discrimination between both targets.

RESULTS

Geomorphology

The bathymetric comparison corresponding to the 1986-2001 period (Figure 2) shows that those areas with depths larger than 18 m in 1986 were reduced in 2001. Almost the entire portion of the Navigation Channel neighboring the Largo Bank underwent accretion. Southwards the bank core, the Navigation Channel showed an average accretion of 3 m.

During the 15 years that elapsed between the periods compared in the present study, the bank core moved more than 1 km eastward (towards the Navigation Channel) with a maximum accretion of 11.8 m, increasing also the steepness of its eastward slope. The bank core and its southern portion, composed of fine-to-medium sand (Figure 3a), exhibited a general widening while its connection to the shore (the bank northern portion) underwent a significant general erosion.

As it is shown in Figure 3b, the bank connection to the shore is mainly composed of compacted cohesive sediments. The ebb-oriented sinus located immediately north of the bank core shows a significant enlargement and a depth increment of up to 9.3 m at its mouth.

Satellite Images

Four satellite images representing different tidal stages corresponding to the sensor Thematic Mapper (TM) on board of the Landsat-7 satellite were chosen (Figure 4). All the images analyzed exhibit a different degree of proper correlation between SSC and the submarine geomorphology as it is shown - as an example - in two cross sections in the study area (Figure 5). These cross-sections reveal that the highest apparent reflectance is proportional to water depth. However, the values registered under ebb conditions show more reflectance power in all areas, either covered by water or emergent.

DISCUSSIONS

The bathymetric changes registered in the 1986-2001 period corroborate the hypothesis by GÓMEZ and PERILLO (1992). That is, there is a remarkable eastward growth of the Largo Bank, a widening and deepening of the ebb-oriented sinus, and an appreciable increase in sedimentation at the Navigation Channel. Yet, the morphological modifications corresponding to the 1986-2001 period occurred at a slower rate than what was expected from the 1983-1986 period. This de-acceleration could be related to a differential erodibility rate of the materials of the area. According to the side scan sonar records in the present study, the core of the northern portion of Largo Bank is composed of ancient compacted cohesive sediments having the same characteristics as those of the submarine outcrops determined within the study area in several places where erosive processes occur (GÓMEZ and PERILLO, 1995). Compacted cohesive sediments do not easily erode in contrast to the fine-to-medium sand of which the banks of the area are mainly composed.

Due to this geological control, the deepening of the ebb-oriented sinus as well as the erosion of Largo Bank northern portion and the consequent eastward migration rate of the bank central portion, could have been delayed with respect to what it was expected from the 1983-1986 period. In spite of this delay in the evolution of the bank, the data collected in 2001 indicate that the potential risk for the Navigation Channel is still valid. Thus, frequent monitoring of the bank evolution should be done in order to avoid in advance further negative consequences for the economy of the harbor system.

Despite the apparent good correlation shown in Figure 5, it should be pointed out that the differences in reflectance are not directly related to the differences in water depth but to the differences in suspended sediment concentrations (SSC). Higher superficial SSC values, which could be observed on the images, are produced at shallow depths, where superficial water agitation interacts with un-consolidated cohesive materials (silt and clay). As a result, in an almost current-free environment, lower SSC values are directly related with a larger depth and *vice versa*. Almost the same process occurs in an environment with permanent unidirectional currents, such as rivers and estuaries with a large fresh water input. In these environments, superficial SSC sources are usually upstream located and maximum current speeds, which occur at maximum depths, normally exhibit relative lower SSC than that in the shallower areas.

In an environment dominated by tidal currents, where a dynamical equilibrium between tidal currents and morphology occurs, the differences in reflectance may be directly correlated with superficial tidal currents (and water depth), depending on the relative position of SSC generative areas and the tidal stage.

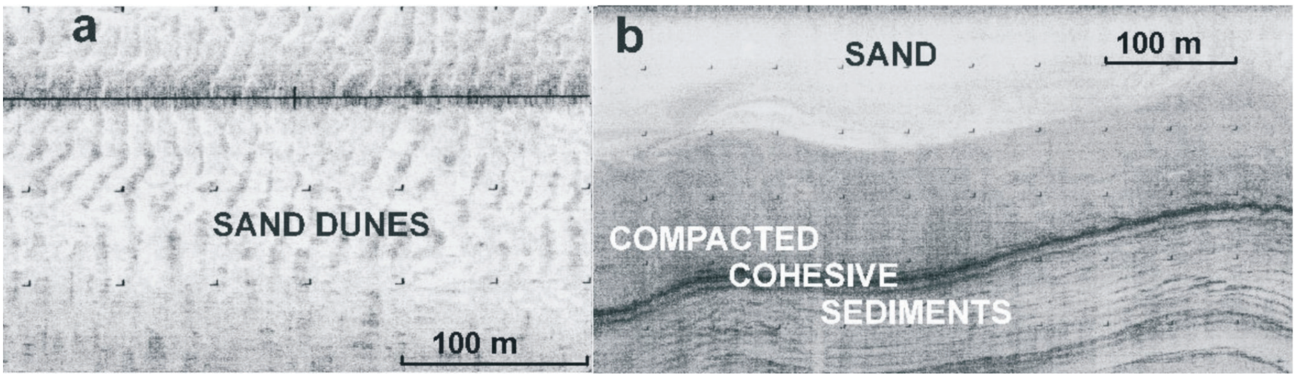

Figure 3. Side scan sonar records showing the sand dunes from the bank core (a) and the compacted cohesive sediments cropping out at the bank connection to the shore (b).

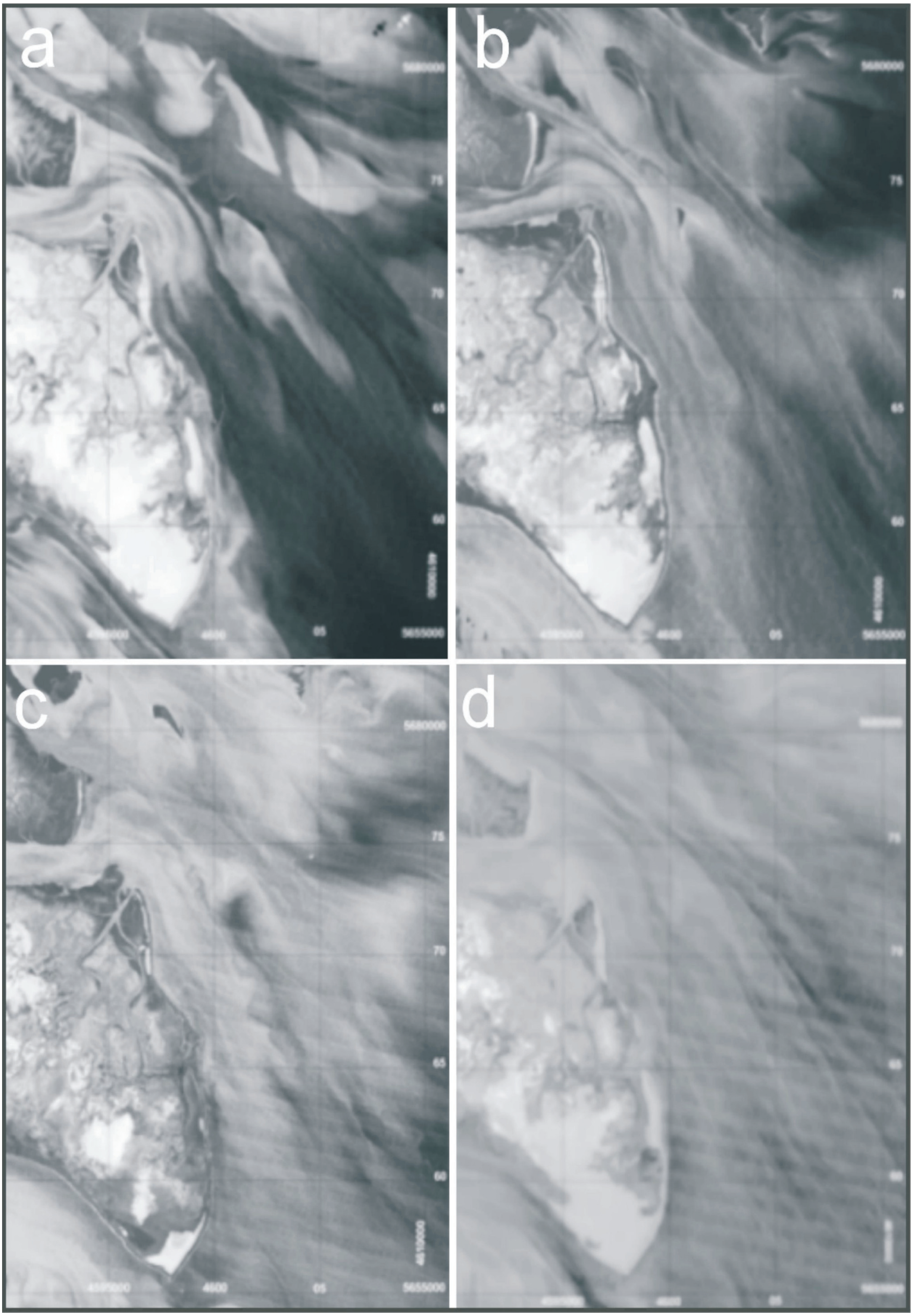

Figure 4. Selected satellite images. (a) Middle ebb tide, (b) Low tide, (c) Middle flood tide and (d) High tide.

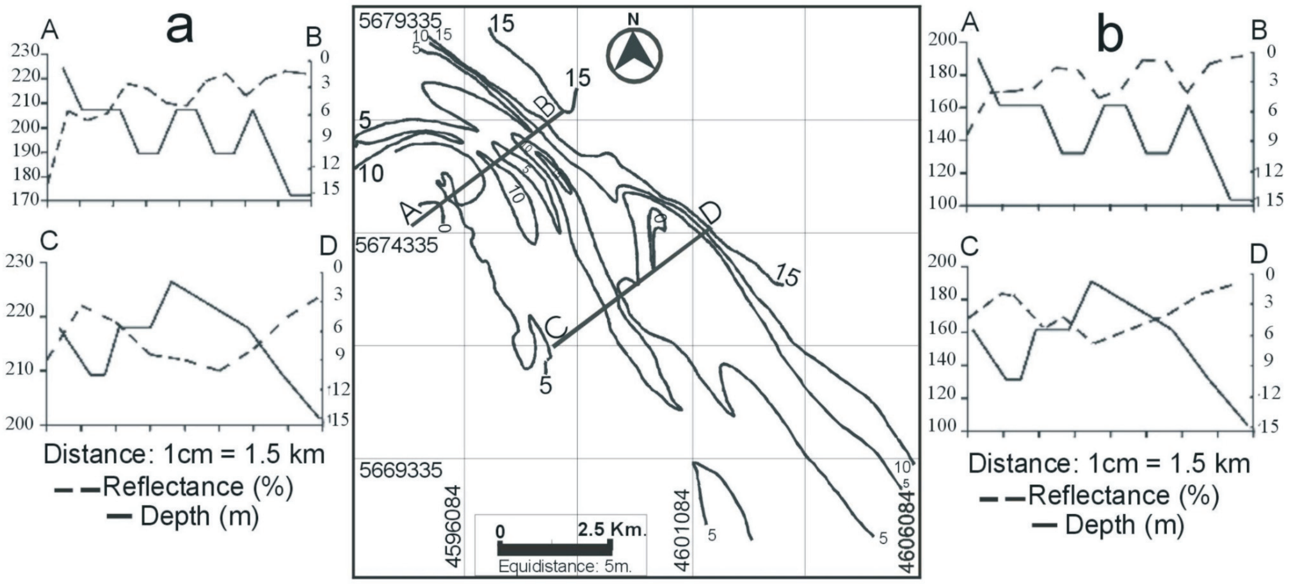

Figure 5. Cross sections showing the reflectance-depth relationship for (a) middle low tide and (b) low tide.

During the ebb hemicycle, superficial SSC sources are upstream located in the external zone of Bahía Blanca estuary, similarly to what it occurs in environments with permanent unidirectional currents. Differences in reflectance during such hemicycle (Figure 4a) are therefore usually related to tidal currents and depth, as it is shown in Figure 6. However, it should be pointed out that due to lateral mixing, the superficial SSC tends to laterally homogenize downstream.

As a result of sediment settling, during the ebb slack water period, the superficial SSC is gradually reduced while it is incremented with depth. This as well as the SSC lateral homogenization of the water lead to an ambiguous identification of the submerged features (Figure 4b).

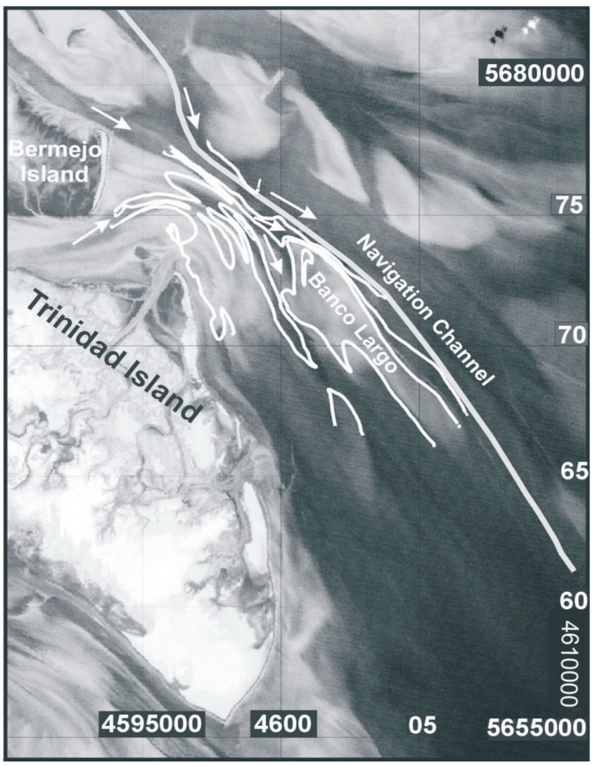

Figure 6. Satellite image during the ebb hemicycle. Note that differences in reflectance are correlated with tidal currents and depths.

During the flood hemicycle, there are no significant sources of superficial SSC upstream. This generates no lateral notable differences in reflectance to easily identify the main current directions at the bank area. Moreover, as maximum current speeds occur at the deeper zones (channels), the sub-superficial water with the relative SSC increase occurring during the preceding slack water period, is more vertically mixed with the more limpid water from the surface than from the bank crest, where minimum superficial water speeds occur. Because of the above-mentioned mechanism, during the flood hemicycle the shallower areas of the external zone of the estuary may even show a relatively low reflectivity with respect to the deeper areas, as it is observed over the Largo Bank crest in Figure 4c. During the flood hemicycle, and in contrast to what it occurs during the ebb hemicycle, these mechanisms result in a general homogeneity and/or ambiguity on the reflectance that does not allow to clearly identify the shape or even the presence of submerged features through the use of satellite images. The lateral superficial SSC homogeneity increases as the tidal cycle proceeds, reaching its maximum during the flood slack water period (Figure 4d).

CONCLUSIONS

The results obtained through the bathymetric and side scan sonar information collected in 2001 corroborate both tidal currents circulation in the study area and the forecast done in 1986. Largo Bank evolution indicates that a large part of the ebb currents that maintain maximum depths at the Navigation Channel are being diverted throughout the new channel that crosses the bank crest.

This urges the need to carry out a short-term monitoring of the bank evolution as it may negatively affect the economy of the harbor system.

The analysis of satellite images corresponding to different tidal stages indicates that the differentiation of superficial suspended sediment concentrations directly related to sea bottom morphology can only be achieved during the ebb hemicycle. However, the use of satellite images under these tidal conditions could be very useful to qualitatively monitor the evolution of the submarine banks located in the external zone of the estuary on account of the fact that this can be done more regularly and at lower costs with respect to periodic bathymetric surveys.

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