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A possible solution to Rosales Harbour excessive Siltation Rate (Bahía Blanca Estuary, Argentina)

Diana G. Cuadrado†‡, Eduardo A. Gómez†, Jorge O. Pierini† and Gisela A. Federici†

†Instituto Argentino de Oceanografía
CC 804, Camino La Carrindanga km 7
8000 Bahía Blanca
Argentina
cuadrado@criba.edu.ar

‡Departamento de Geología
Universidad Nacional del Sur
San Juan 670
8000 Bahía Blanca
Argentina

ABSTRACT

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Puerto Rosales is the most external port in the Bahía Blanca harbour system, but it could never be fully developed as other ports of the system because an abnormally high siltation rate. Trying to diminish the harbour sediment income but not based on previous studies, in 1995 some modifications were introduced into the environment, increasing the siltation rate by about 600%. Suspended sediment concentration (SSC) profiles carried out through different wind conditions indicated that the source for the excessive SSC is the erosion of the neighboring tidal flats by locally generated waves. Also locally generated waves are responsible for an inward estuary littoral drift of sand about 4 m depth, exceeding the opposite net sediment transport rate caused by tidal currents. The more economically way to reduce the harbour excessive siltation rate would be to prevent the passage of water from where high SSC generates by constructing an eastward continuous barrier through the entire intertidal area. In order to avoid negative interactions between this barrier and tidal currents, a hydrodynamic mathematical model evaluated by field measurements is applied under different wind conditions. Three barrier lengths are tested, recognizing which one better behaves in order to prevent the passage of water from the intertidal areas and the growth of deposits of the sand transported by the littoral drift and/or the inward income of sand harbour by residual currents.

ADDITIONAL INDEX WORDS: *Tidal flat, Man-made modifications, Hydrodynamic model.*

INTRODUCTION

The study of sediment dynamic processes on tidal flats has in recent years received increasing attention worldwide (e.g., FLEMMING and BARTHOLOMÄ, 1995; PERILLO, 1995; BLACK *et al.*, 1998), as well as the cohesive sediment transport processes in coastal zones, especially in estuaries. These kinds of studies have an important impact on the environment and the economy as the majority of the cities and industries are located there, and where recreational, fishing and port activities are developed.

Whether dredging is done to create new channels or to deepen or maintain existing channels and berths, the driving force behind a dredging project is to improve navigation conditions for commerce transport and in a lesser extent for recreation. Ports that may want to grow and expand their capabilities look to deepen the navigational channels that connect them to the sea so that deeper draft vessels carrying more cargo can make their way to them. These navigation channels are economic lifelines not only for individual ports but also for the local, regional, and national economies.

Rosales Harbour is the most external port of the Bahía Blanca Complex, the major deep harbour system of Argentina. Its design and present disposition are an adaptation of the first works done in order to construct the largest harbour of the region, interrupted and abandoned in 1916. The mooring sites and the access channel, which communicate this harbour to the Principal Channel, are located on the east side of a 2 km length N-S stone shore-connected breakwater. Eastward the breakwater there is an extensive intertidal zone (2 km long approximately) conformed by muddy tidal flats, meanwhile westward a contrasting subtidal area is located (Figure 1).

The Rosales Harbour location has the advantage that enables vessels to save 20 km when entering the system harbour and that, contrary to what occurs at the internal estuary ports, the neighboring portion of Principal Channel reaches natural depths greater than 20 m. Due to its external location, the harbour area is simultaneously affected by internal estuarine processes as tidal currents, and by frequent southeastern storm waves. In despite the natural advantages Rosales Harbour has when is compared with those more internally located, historically remained most of the time not operative due to an excessively high siltation rate (MELO, *et al.*, 1997), providing only services for small fishing boats at present.

Not based on any previous studies and with the objective of diminishing the harbour siltation rate, some modifications on the eastward intertidal area were introduced into the environment during the 1995 dredging. With the idea of blocking the sediment passage to the harbour, two vessels and the dredged materials were located as a discontinue barrier at the mid and the mid-upper

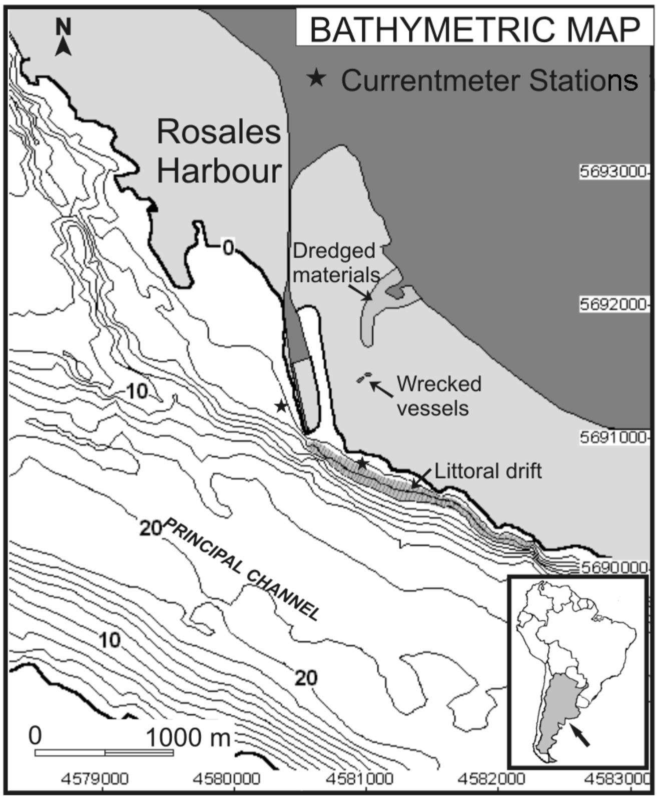

Figure 1. Study zone showing the modifications made in the surroundings of Puerto Rosales. Littoral drift and currentmeter stations are also shown. The coordinates are in Gauss Krüger projection.

portion of the tidal flat, respectively. The cohesive dredged materials were originally dammed by cloth hoses filled with sand, which failed in a short time leading to the remobilization of the contained cohesive materials.

In the present study the way in which the interaction among coastal constructions and natural occurring processes, and how the facilities of Rosales Harbour are seriously affected, is analyzed. It is also shown how modifications introduced into the environment ignoring the involved processes led to a serious worsening of the problem. Once the concerned processes are studied and analyzed, a solution evaluated through a hydrodynamic mathematical model is proposed; eventually testing which alternative would better behave.

METHODOLOGY

In the field works done in the present study, a 14 m long vessel and a Zodiac type boat positioned with a differential GPS Satloc operating in real time (3 m error) were employed. The bathymetric survey of the entire zone was done by means of an echosounder Bathy 500 MF, performing the bathymetric tracks transversally to the dominant morphology (300-200 m spacing), and reducing to a 100-50 m interval at some particular places. All maps were made using a Gauss-Krüger projection. Depth information was referred to the local Datum Plane by means of the tidal records from the tidal gauges of Rosales and Belgrano harbours. In order to recognize and define sea bottom features characteristics and sediment changes on the Principal Channel, an EG&G SMS 960 side scan sonar operating at 150 and 100 m range was employed. Superficial bottom samples from the harbour, surrounding areas and Principal Channel were also obtained and analyzed by standard procedures.

At the northern Principal Channel flank, tidal currents were continuously recorded at a frequency of 0.5 Hz during two complete tidal cycles by deploying two Interocean currentmeters (model 135) at 7 m depth and at both sides of the Rosales Harbour access channel entrance. The currentmeters were located 1 m above the bottom in order to compute the currents ability to transport sediment as bed-load. An hourly profiling of suspended sediment concentration (SSC), by means of an OBS (Optical Backscatter Sensor), and tidal currents (with a Valeport current meter) at five vertical levels were carried out during a complete tidal cycle at two stations located 550 m apart, at the mooring sites and in the access channel. After profiling, SSC in $mg\ l^{-1}$ were obtained in laboratory calibrating the OBS lectures against different concentrations attained with local sediments.

The siltation rate of Rosales Harbour and the evolution through time after harbour dredging were obtained by comparisons of successive bathymetric charts from the 1972-1995, 1995-2000 and 2000-2001 periods. Local wind analysis was carried out over a one year period recorded by a meteorological automatic station located at Rosales Harbour facilities.

At Rosales Harbour and the neighboring portion of the Principal Channel area, a finite-differences hydrodynamic numerical model solving the deep-integrated shallow water equations with mobile boundary conditions (Pierini and Perillo, 2003) was finally employed.

At the moment, after several research contributions (Reid and Bodine, 1968; Leendertse, 1970, 1987; Benque *et al.*, 1982; Stelling, 1984; Stelling, *et al.*, 1986; Falconer, 1986; Falconer and Owens, 1987; Falconer and Chen, 1991; Casulli and Cheng, 1993; Balzano, 1998), only methods based on the Eulerian discretization approach seem to have been used in industrial numerical models for simulation of such processes in real world applications. The numerical model used in this study is based on the depth integrated shallow water equations with tidal flats boundary conditions (Balzano, 1998)

In order to stabilize the model solution, it was run over 30 days. Small values of the mean-quadratic relative error between predicted and observed velocity vectors and tidal height measured at the field were obtained, indicating the good quality of the results.

RESULTS AND DISCUSSION

The side scan sonar survey carried out on the northern Principal Channel flank showed the presence of 0.7 m height (8-18 m wavelength) flood-oriented 2D dunes field at an average depth of 4 m, indicating a net sediment transport as bed load inward the estuary. Westward of the breakwater this dune field is abruptly interrupted (Figure 2).

All tidal current deployments showed a reversing direction parallel to the isobaths and an ebb current net dominance. Westward to the breakwater maximum water speeds were in the order of 60 $m\ s^{-1}$, while on the eastern side maximum values reached 40 $m\ s^{-1}$. With this information, computation of the potential net sand transport of tidal currents were obtained trough the Gadd *et al.* (1978) reformulation of Bagnold (1963) equation, according to suggestions given by Amos et al. (1993).

A potential net bed transport of sand of 18.98 $m^3\ m^{-1}\ yr^{-1}$ in the N 150º ebb direction on the western side of the breakwater it was obtained, while a 0.015 $m^3\ m^{-1}\ yr^{-1}$ value was computed in the N 110º ebb direction on the eastern side.

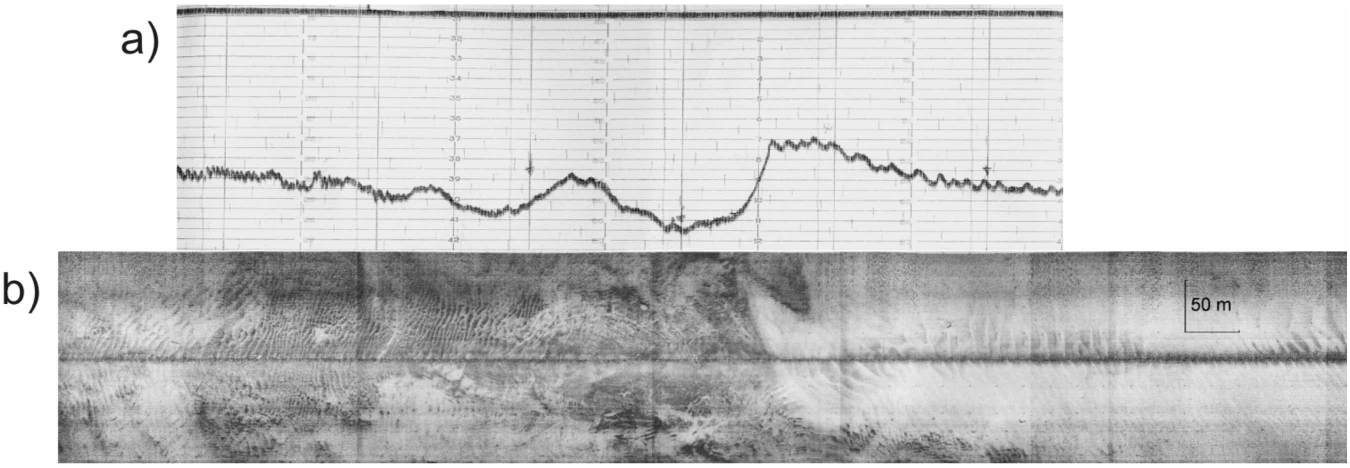

Figure 2. a) Echo echo sounder record and b) the corresponding side scan sonar sonograph along the northern margin of the Principal Channel, close to the breakwater of Rosales Harbour. The littoral drift showed in Figure 1 can be seen as the 2D dune on the right side of the sonograph.

The computed potential net sand transport direction (outward the estuary) was opposite to that exhibited by the bed forms on the 2D dunes field (inward the estuary), indicating that the dune field is not being generated by tidal currents. The littoral drift, computed through the USACE (2002) method from the local wind information, the available fetch and bathymetry, gave an inward potential sand transport of 11,777.23 m^3 m^{-1} yr^{-1}, which is much greater than the ability of tidal currents to transport sand. However, the westward interruption of the 2D dunes field at the breakwater vicinity indicates that the amount of sand available to be transported by the littoral drift is smaller, or at least equal, to the potential net sand transport of the tidal currents on the western side, as once the transported sand overpasses the breakwater is washed away by the strong ebb currents occurring here.

The mean-averaged depth within Rosales Harbour for the 1972-1990 period showed an exponential decay with time, beginning at -8 m immediately after the harbour dredging, reaching an almost constant value of 0.78 m below the Datum Plane after 18 years (CUADRADO *et al.*, 1996). During the 1995-2000 period, the mean-averaged depth after a 6 m dredging followed the same form of decay but at a noticeable increased speed as a -0.74 m depth was reached after only 47 months. The same increased tendency was also manifested after a 4 m dredging during the 2000- 2001 period. When data from the three analyzed periods are compared on the bases of a common depth range (3.5-1.75 m), it is noted that the siltation lasted 4.33 years, 16 months and 9 months for the 1972-1995, 1995-2000 and 2000-2001 periods, respectively. This information evidences that, unlike expected results, the changes introduced into the environment during the 1995 dredging have had a negative and dramatic impact on the harbour interests.

As well as in any enclosed dock, sediment settling is promoted within Rosales Harbour because the area is protected from the wave action and small tidal current speed occurs. So, the excess on the siltation rate observed at this harbour when it is compared with other enclosed or semi-enclosed docks of the harbour system should be attributed to the SSC source. It is well-known that the hydrodynamic of intertidal flats results from the combination of several forcings, mainly the tidal currents, the waves and associated winds and drainage (LE HIR *et al.*, 2000; EISMA, 1997). Naturally, local winds generate waves that are likely to resuspend sediment, so that the correlation between the wind and wave episodes should be accounted for. The results from the SSC profiling in both station inside the harbour, showed that during the flood, the bottom concentration increased from 35 to 100 mg l^{-1}. Such SSC growth was only related to the increase of tidal current velocities, as the N-NW local winds blowing during such period did not affected the harbour area. However, it was observed that when wind direction changed to the maximum fetch direction (SE) at 7.5 m s^{-1}, the distribution and the magnitude of the SSC was strongly modified, reaching values up to 240 mg l^{-1} (FEDERICI *et al.*, 2000, 2001). Such important SSC increase should be attributed to the erosive action of locally generated waves that resuspends cohesive materials (silt and clay) from the extensive tidal flats neighboring the Rosales Harbour area. The observed remarkable increase in the harbour siltation rate after the environment modifications introduced during the 1995 dredging agree with the explanation proposed above. By reflection of the incoming waves, the presence of the wrecked vessels almost double the waves height, increasing tidal flat erosion and so the SSC of the water entering to the harbour. The remobilization of the dredged cohesive materials due to the failure of its contention should also have contributed to a significant SSC increment.

Therefore, as the source of excessive SSC entering to the

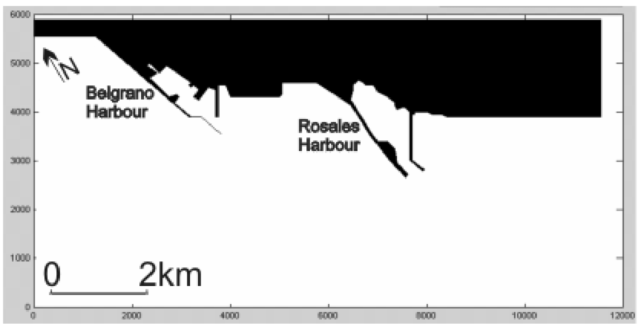

Figure 3. Zone where the hydrodynamic model was applied on a 50 m side grid.

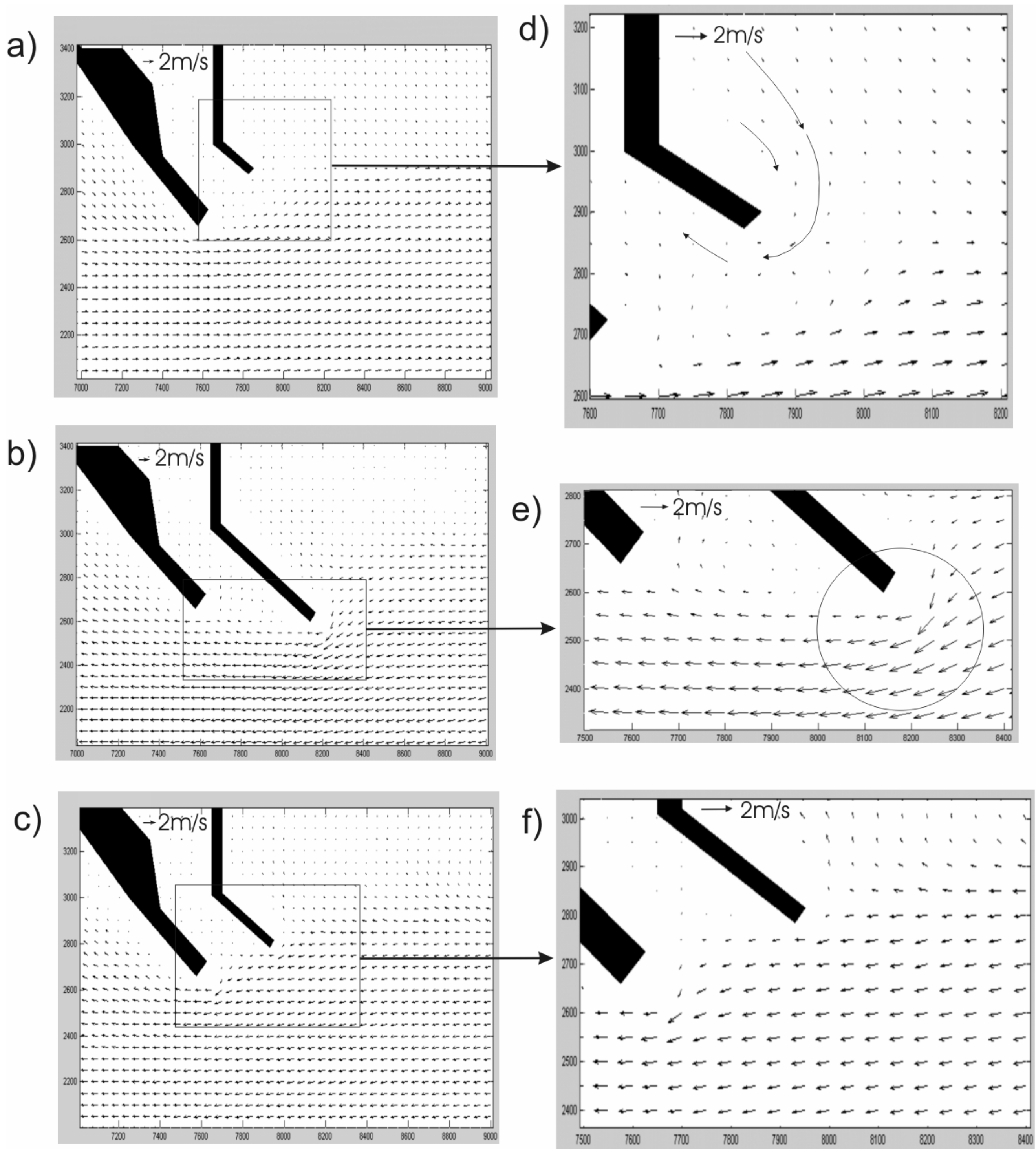

Figure 4. Model results with different lengths of barriers. a) Option I. Short barrier during the mid ebb tide with SE wind. b) Option II. Large barrier during the mid flood tide. c) Option III. Intermediate barrier during the mid flood tide with SE wind. d) Zoom area of (a). e) Zoom area of (b). f) Zoom area of (c).

harbour was identified, the possible way to diminish the Rosales Harbour siltation rate would be to avoid the erosion of the neighbouring tidal flats or prevent the passage into the harbour area of water from where the excessive SSC is generated. Given the extension of the tidal flats, the later option seems to be more feasible and economically sounding, and it should be attained by means of the construction of an adequate eastwards continuous fence through the entire intertidal area. However, the design and extension of such barrier would interact negatively with tidal currents and the sand transported by littoral drift at the harbour entrance, generating further problems. So, in order to evaluate and avoid or diminish such potential negative interactions, the behaviour of different barrier extensions were tested by a hydrodynamic mathematical model.

In shallow coastal water bodies like harbours, estuaries, lagoons, and such experiencing tidal oscillation of the free surface, the extent of areas subjected to alternating wetting and drying, the tidal flat, can be of the same order of magnitude as the permanently submerged areas (FALCONER, 1986; CASULLI and CHENG, 1983; UMGIESSER, *et al.*, 1988; BALZANO, 1998). Thus, the reproduction of the covering/uncovering of the tidal flats is an important feature of numerical tidal flow models based on shallow water equations. Accurate simulation of free surface flows on domains with moving boundaries is needed in several engineering applications, including tidal flat predictions.

This model was applied on the area showed in Figure 3 covering 6x12 km with a grid of 50x50 m, considering three different barrier lengths. The shorter barrier (Option I) extent to the Datum Plane (0 m), the longest one (Option II) reaches 7 m depth and the third one (Option III) reaches 4 m depth. Model results for mid flood or ebb tidal conditions for the three tested options are shown in Figure 4. The most economically Option I does not interact with tidal currents (Figure 4a and d) but an income to the harbour entrance of water from the intertidal areas it is observed during ebb. Therefore, Option I would prevent most of the passage of water into the harbour area from the neighboring tidal flats but it would not totally be avoided, particularly when S-SE winds are blowing (maximum SSC generation). Option II (Figure 4b) totally impedes the passage of water from the intertidal areas but it strongly interacts with tidal currents. During ebb, there is no change in the current velocities at the breakwater extreme. However, flood currents suffer acceleration and deceleration before and after passing the breakwater (Figure 4e). This fact may erode the sand transported by littoral drift eastwards the fence depositing it at the harbour entrance. This would promote an embankment with a potential influx of sand into the harbour area. With Option III (Figure 4c), the passage of water through the harbour entrance from the intertidal zone is totally impeded, while interactions between the proposed fence length and tidal currents are minimized, even when wind blows from the SE (Figure 4c and f). Thus, Option III seems to be the most likely choice.

CONCLUSIONS

The high suspended sediment concentration of the water incoming into the harbour area is the responsible for the abnormally high siltation rate historically occurring at Rosales Harbour. These concentrations are originated when wind blowing from SE promotes the erosion of the intertidal areas by locally generated waves. Far from reducing the problem, the modifications introduced into the environment in 1995 increased the sediment availability, raising dramatically the harbour siltation rate.

In order to avoid the income of water with high suspended sediment concentration into the harbour area from where it is generated, the construction of a continuous barrier through the entire intertidal area is proposed. This barrier should be constructed up to the 4 m depth, as a shorter extension would allow the passage of water from the westward tidal flats through the harbour entrance; while a longer one may promote a sand bank generation at the harbour entrance by the interaction with the littoral drift.

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