Case Study: Promoting the Stability of the Óbidos Lagoon Inlet

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Abstract: The stabilization of tidal inlets by jetties interrupts the littoral drift and has negative visual impacts. This paper proposes an innovative solution to improve the stability of a tidal inlet (the Óbidos Lagoon, Portugal) and minimize maintenance dredging, while avoiding the disadvantages of the traditional solution. The new solution has two key features. First, transverse channels are dredged over the tidal flats to promote ebb dominance, thereby improving the ability of the lagoon to flush out incoming sediments. Second, a partially submerged guiding wall near the southern shoreline, together with the existing guiding wall in the northern shore, prevents the movement of the inlet channel and concentrates the ebb flow in the channel. Analyses with empirical, numerical, and analytical models indicate that the solution improves the stability of the tidal inlet and reduces the accretion in the system.

DOI: 10.1061/(ASCE)0733-9429(2007)133:7(816)

CE Database subject headings: Morphology; Sand; Portugal; Inlets, waterways; Lagoons; Case reports.

Introduction

Coastal lagoons are semienclosed water bodies, characterized by small river flows and the influence of tides. These systems are typically shallow, with high salinities, and are separated from the ocean by sand spits or barrier islands. They are connected to the ocean by constricted inlets, which may be seasonally closed. These systems are often very productive biologically, due to their shallow depths. However, the often partial stability of their inlets can disrupt the ecosystems. Low water renewal rates can deteriorate water quality and prevent the role of the lagoons as nurseries.

The ecological and economic value of coastal lagoons and their vulnerability have long called for human interventions (Mehta 1996). Many of their inlets are protected by jetties, the traditional solution to stabilize the inlets and reduce the inflow of coastal sediments. However, these structures meet with increasing opposition, because they interrupt the littoral drift and they have negative visual impacts. Hence, new approaches are required to improve the stability of the tidal inlets.

The Óbidos Lagoon (Fig. 1), located in western Portugal, has a surface area of 4.4 km^2 at mean sea level (8.0 km^2 at high spring tide) and a maximum depth around 4 m below mean sea level. This small surface area, the small fresh water inflows, and the strong littoral drift have led to inlet closures since at least the 15th Century (Henriques 1992), with adverse effects on water quality. More recently, constructions on the lagoon's shores have been threatened or damaged by the migration of the inlet. Both problems led to the proposal of two large interventions to stabilize the inlet in the past two decades. The first was based on the construction of jetties (Hidrotécnica Portuguesa 1991), and the second on a drastic increase of the tidal prism (Vieira 2001). However, both solutions were abandoned as subsequent studies found them ineffective and showed their negative environmental impacts. Small interventions (inlet repositioning, dredging of the main channel, and emergency sand bags walls) have avoided major problems, but have only provided temporary solutions. A guiding wall was also built near the northern shore, but only solved the problems partially. The study described herein aims at developing a permanent, complete solution to the lagoon, satisfactory for all stakeholders.

Given the limited accuracy of the various approaches to simulate morphodynamics, various models are used, including empirical (O'Brian 1969; Allersma 1994), analytical (Fortunato and Oliveira 2005), and numerical models (Zhang et al. 2004; Oliveira and Fortunato 2002; Fortunato and Oliveira 2004a).

This paper is divided into three sections besides this introduction. The second section describes the characteristics, the evolution and the problems of the Óbidos Lagoon, as well as the previous solutions. The new solution is described in the next section. The paper closes with some concluding remarks.

Óbidos Lagoon: Characteristics, Problems, and Solutions

Description of the System

The Óbidos Lagoon consists in two regions with distinct morphological and sedimentary characteristics (Fig. 1). The lower lagoon, connected to the Atlantic Ocean, is composed of several channels cutting through large sand banks. Velocities in this region often exceed 1 m/s and the bottom sediments are mainly sands. The upper lagoon, with a surface area of 3.6 km^2 at mean sea level (5.3 km^2 at high spring tide), has low velocities and muddy bottom sediments (Freitas 1989a).

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Note. Discussion open until December 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 17, 2006; approved on November 30, 2006. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 133, No. 7, July 1, 2007. ©ASCE, ISSN 0733-9429/2007/7-816–824/$25.00.

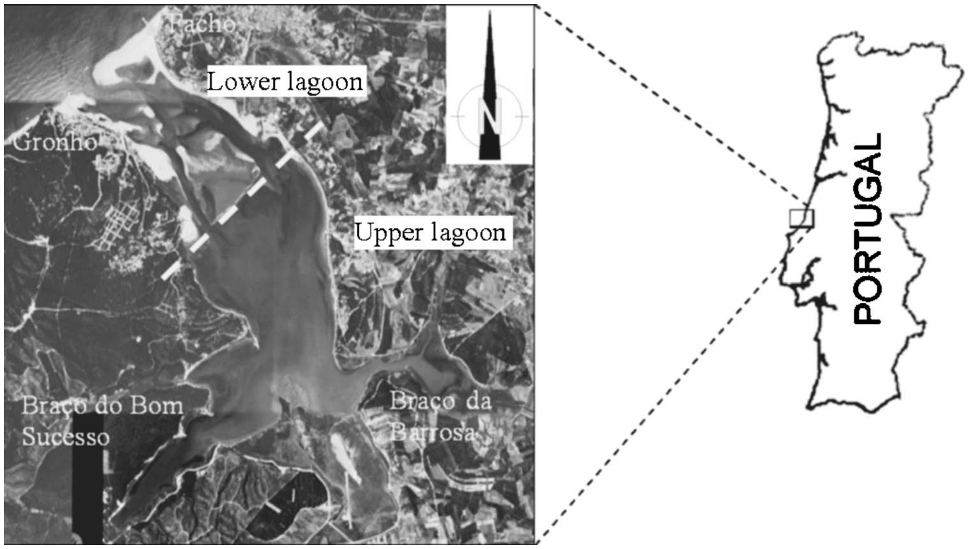

Fig. 1. Óbidos Lagoon: location and place names

The wave regime in front of the lagoon is very energetic, with significant wave heights exceeding 1 m during 88% of the time. Dominant wave directions are almost perpendicular to the beach, which faces 315°N, and wave periods range from 5 to 20 s (Oliveira et al. 2006). As a result, the net drift is negligible relative to the total littoral drift of about 10^6 m^3/year (Vicente and Clímaco 1994). These characteristics of the littoral drift lead to a wandering inlet, with unpredictable movements, as shown by aerial photographs from 1947 to 2004. Tidal ranges vary between 2 and 4 m at the coast, and between 1 and 2 m inside the lagoon (Oliveira et al. 2004).

Although wave action is limited to a few hundred meters upstream of the mouth, it affects significantly the morphodynamics, hence the tidal propagation inside the lagoon. Waves generate the littoral drift, which promote the inflow of marine sand into the inlet, and resuspend sediments, which can then be carried by the tidal flow. Because the maximum ebb occurs at lower tidal levels that the maximum flood, wave-induced resuspension is stronger on ebb, promoting sediment flushing from the inlet. However, the first effect is dominant in the Óbidos Lagoon, as is usually the case. The sedimentation of the inlet throat and of the lower channel during the maritime winter leads to a 50% reduction in the M2 tidal amplitude and an enhancement of the flood dominance. This trend is reverted during maritime summer, and can be further improved by dredging (Oliveira et al. 2006). Freshwater plays a minor role, with average flows on the order of 3 m^3/s (Vão 1991), which are less than 5% of the average tidal prism scaled by the M2 period (Rego 2004).

The channels and the sandbanks are very dynamic. Meanders form, evolve, and disappear in a few months (Oliveira et al. 2004) and the inlet throat continuously migrates along the 1,400 m littoral barrier (Fig. 2). Overall, the lower lagoon exhibits a clear tendency for accretion, on the order of a few centimeters per year (Oliveira et al. 2006). While the frequent dredging operations compensate for this accretion in the channels, the depth of the sand banks has been decreasing a few centimeters per year.

The upper lagoon consists of shallow basin, with an average depth of 0.6 m relative to the Hydrographic vertical datum, two elongated bays (the Braço da Barrosa and the Braço do Bom Sucesso) and a small embayment in the South. Because velocities are small, sediments coming from various tributaries tend to settle in this part of the lagoon, contributing to the progressive reduction of the average depth and the surface area (Freitas 1989b; Henriques 1992). Land reclamation for salt ponds and to deposit dredging spoils has also contributed to reduce the surface area of the lagoon in the past.

Environmental Problems

The lagoon's problems are mostly related to its morphological evolution. The progressive accretion of the upper lagoon hampers navigation and threatens to separate the lateral bays from the lagoon's main body. For instance, the accretion in the lagoon between June 2000 and September 2004 was 10 cm on average (in spite of the dredging operations), and reached about 1 m in some areas. Also, large residence times, combined with the disposal of untreated sewage waters in the recent past, degrade water quality, in particular, in the lateral bays. The accretion of the inlet also contributes to large residence times (up to several years), further promoting the degradation of water quality (Oliveira et al. 2006). However, because efforts to redirect wastewater effluents to a marine outfall were still ongoing at the time of this study, water quality problems were not addressed.

In the lower lagoon, the instability of the inlet constitutes the major problem. This behavior is due to various factors. The length (over 2 km) and depth (about 2 m below mean sea level) of the main (northern) channel that connects the body of the lagoon to the sea damp the tidal amplitudes. The meandering and migration of this channel, as well as the ebb and flood sandbanks, further promote this damping (Oliveira et al. 2006). Together with the declining surface area of the lagoon, this damping is responsible for a small tidal prism and for a limited ability of the tides to flush out the incoming sediments. Residence times in the system vary from a few hours in the lower channels and near the inlet's throat to several years in the upper bays.

Past Solutions

Several engineering solutions have been implemented in the Óbidos Lagoon over the last two decades to promote tidal flushing, avoid inlet throat closure, protect the shores and stabilize the lower lagoon channels. In the past decade, the northern channel

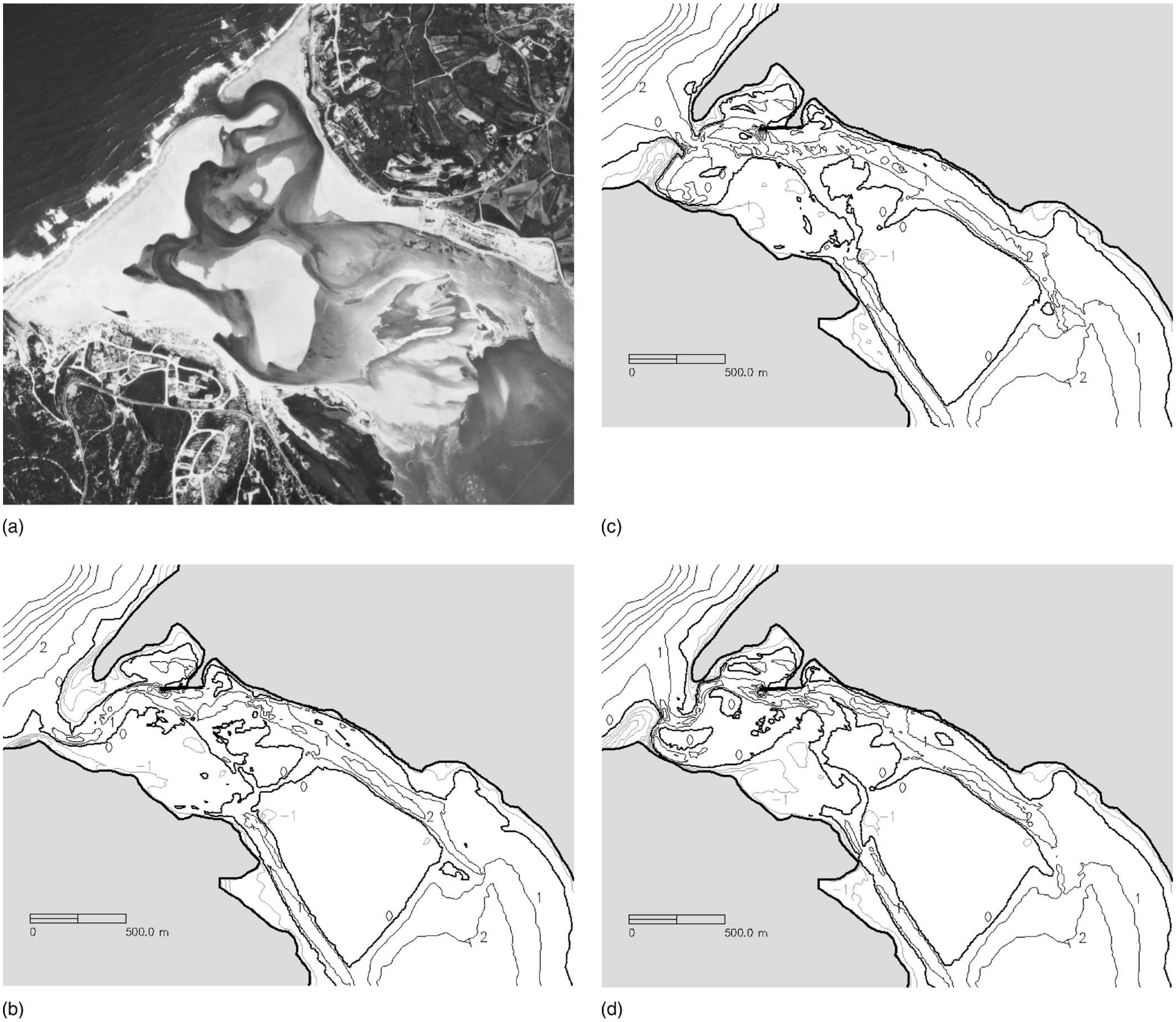

Fig. 2. Examples of configurations of the lower Óbidos Lagoon: (a) 1980; (b) November 2000; (c) July 2001; and (d) October 2002. Bathymetries are in meters, relative to mean sea level, with positive values downward.

has been dredged and the inlet mouth repositioned in 1995, 1999, 2001, and 2003. In 1995, the southern channel was also dredged. As dredging alone failed to avoid channel migration, which damaged constructions in the northern shore in the winter of 1993/1994, a guiding wall was built near the northern shoreline in 1999. The inlet mouth never returned to the northern third of the littoral barrier since this construction, suggesting that this structure is effective. However, the short time elapsed since the construction prevents definitive conclusions.

The southward migration of the inlet has also occurred in the past few years, leading to recurring placement of emergency sandbag walls (Fortunato and Oliveira 2004b). However, these sandbag walls need to be repaired often, as their foundations are eroded by tidal currents and the sandbags fall into the channel.

Because the present status of the lagoon is maintained only through emergency operations, more effective and permanent solutions have been sought. Application of the Bruun criterion, based on the ratio between the tidal prism and the annual volume of sediments that enters the lagoon, indicates that the inlet is unstable (Vieira 2001). Previous proposed solutions have therefore attempted to increase this ratio by reducing the inflow of sediments or by increasing the tidal prism. Building two parallel jetties was proposed to reduce the maintenance dredging of the northern channel (Hidrotécnica Portuguesa 1991). However, this solution was abandoned after subsequent studies. As the head of the jetties would be located in the surf zone, the flooding tides would carry a heavier load of sediments than in the present conditions, thereby increasing the accretion of the lagoon. In addition, the interruption of the littoral drift by the jetties was also argued against this solution (Beja Neves et al. 1996). As an alternative, Vieira (2001) proposed a drastic increase of the lagoon's surface area. This solution would increase the tidal prism and promote ebb dominance through a vast dredging plan (about 15×10^6 m^3), which would double the lagoon's surface area at mean sea level and increase the cross section of the main channel. Although this solution would significantly increase the tidal prism, thereby improving the inlet's stability, the application of Bruun's inlet stability criterion showed that the stability of the inlet would remain marginal. Further, the disposal of the large volume of dredging spoils, mostly mud, remained an unsolved problem (Fortunato et al. 2002).

The present study constitutes, therefore, the third attempt to develop an overall solution to stabilize the inlet. Its primary objective is to guarantee the stability of the inlet, while minimizing maintenance dredging. Other expectations from stakeholders included the maintenance of a beach on each side of the littoral barrier and the protection of the lagoon's shores. Finally, the interruption of the littoral drift would be unacceptable, due to potential impacts on nearby coastal beaches, and the volume of muddy dredging spoils would have to be small.

Stabilization of the Óbidos Lagoon Inlet

Screening Analysis of Potential Solutions

A screening analysis was first performed to narrow the range of potential solutions. Solutions similar to the ones already proposed for the Óbidos Lagoon (jetties and increase of the lagoon's surface area) were not considered, as they had already been rejected for this particular system. The remaining solutions could be grouped into two classes: dredging operations and hard structures.

The first class of solutions includes repositioning the inlet mouth, changing the number, length and cross-section of the lower lagoon channels, and dredging the sand banks. Repositioning the inlet mouth updrift of the ebb sand bank has been proposed (e.g., Rosati and Kraus 1999) as a solution to counteract the migration of an inlet and to avoid inlet closure due to the shoreward movement of the bank ("bulldozer effect"). However, in coasts with a small net drift, this approach is ineffective because the inlets migrate in both directions. Also, past inlet repositioning in this system proved ephemeral. Therefore, this solution was discarded.

The number of channels in the lower lagoon may influence the morphodynamic behavior of the inlet. While fewer channels should have a higher ability to flush out incoming sediments and be more resilient, the slow evolution of the south channel, dredged in 1995, suggests that it may be marginally stable. Therefore, the optimal number of channels was analyzed in detail. The channels could also be shortened by dredging the upstream part of the flood sandbanks. This approach could increase the tidal prism both by reducing the damping of the tide along the channel, and by increasing the surface area of the lagoon. Finally, the cross section of the northern channel was originally determined by the application of the empirical relationship between the tidal prism and the equilibrium cross section (O'Brian 1969). However, this channel is being dredged with a smaller cross-section. In addition, an analysis of the behavior of the channel after these dredging operations suggests that the present cross-section is too small, indicating that this issue should be revisited (Oliveira et al. 2006).

Tidal flats are known to enhance ebb dominance in estuaries and lagoons, thereby reducing accretion (e.g., Friedrichs and Aubrey 1988). In the scope of this project, the feasibility of maximizing ebb dominance through dredging the tidal flats was analyzed. An analytical model was developed for this purpose (Fortunato and Oliveira 2005), and numerical simulations for a synthetic lagoon confirmed and extended the initial conclusions (Fortunato and Oliveira 2004b). The application of this concept to the Óbidos Lagoon is presented in the next section.

The second class of solutions, those based on hard structures, is very limited. Some of these solutions require simultaneously the presence of jetties (e.g., sand traps—Seabergh 2002), and were therefore rejected. The only solution considered was the construction of a guiding wall near the southern shore to prevent inlet migration in that direction. The apparent good behavior of the guiding wall in the northern shore was a strong argument toward the consideration of this solution.

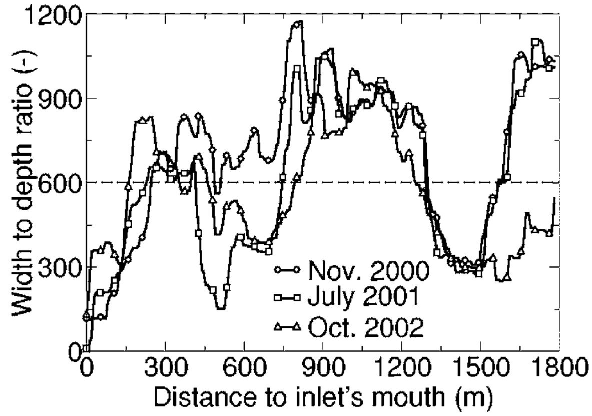

Fig. 3. Application of the empirical model of Allersma (1994) to three bathymetries of the Óbidos Lagoon, which relates the ratio between the channel width and the average depth to the number of channels. The number of channels should be 1 when the ratio is below 600 and 2 when the ratio is between 600 and 1,200.

Although guiding walls contribute toward a rigidization of an inherently dynamic natural system, they are far more flexible than other hard structures, allowing the system to adapt, in a limited way, to the new geometry. The evolution of the bathymetry near the existing guiding wall illustrates this flexibility, since the northern channel is able to meander and shift in different areas, but its northward displacement is limited by the guiding wall.

The screening analysis suggests the following general approach to develop a solution. First, dredging strategies are sought to improve the ability of the system to flush out incoming sediments (e.g., by increasing the tidal prism or promoting ebb dominance). These strategies include defining the number, orientation and cross section of channels and the interventions over the tidal flats. This analysis is carried out using six bathymetries measured between 2000 and 2002, which represent different configurations of the lower lagoon. Then, hard structures are considered to ensure that the gains obtained by the dredging operations are not short lived (e.g., due to inlet migration). These two steps are described next.

Dredging Strategy

The number of channels in the lower lagoon was defined using an empirical model, data analysis and numerical simulations. The empirical model relates the number of channels across an estuary with the width to depth ratio (Allersma 1994). Application of this model to the various bathymetries of the Óbidos Lagoon listed previously indicates that there should be a single channel downstream of the existing guiding wall, and one or two channels upstream (Fig. 3). The analysis of historical maps and aerial photographs of the lagoon confirms in general the conclusions from the empirical model. Although there is always a single inlet mouth, the number of channels varies between one and three. When three channels exist, at least one appears to be a trace of a formerly active channel that conveys little flow [Fig. 2(a)]. Presently, two channels coexist upstream of the guiding wall. The

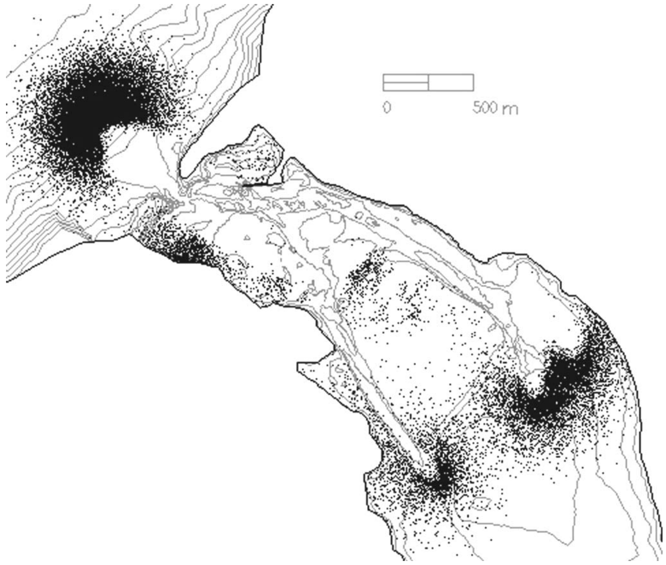

Fig. 4. Simulation of the fate of sand particles released in the beginning of flood at the mouth of the inlet. Each dot represents the settling location of a particle.

northern one is dredged regularly, while the southern one was last dredged in 1995. Numerical simulations indicate that the percentage of the tidal prism conveyed by the southern channel is slowly declining since 1995 (Oliveira et al. 2006), suggesting that it is marginally unstable. However, the presence of a spawning area for shellfish (Freire et al. 2004) in this channel recommends its maintenance.

Simulations with the quasi-three-dimensional particle tracking model VELApart (Oliveira and Fortunato 2002) were used to verify the advantages of shortening the channels. VELApart computes the trajectory of individual sediment particles carried by the flow, considering all the major processes: horizontal advection, horizontal and vertical diffusion and settling velocity. Trajectories are computed on a finite element grid, using a Runge-Kutta method for horizontal advection (Oliveira and Baptista 1997), a random walk method for diffusion (Dimou and Adams 1993) and a forward Euler method for the vertical advection terms. The application of this model to the Óbidos Lagoon is described in Oliveira et al. (2006). Results showed that sand particles released at the inlet mouth at the beginning of flood settle near the connection between the channels and the upper lagoon at the end of flood (Fig. 4). These results suggest that dredging the upstream part of the sand banks to reduce the length of the channels would be a temporary solution, as the banks would grow again to their present length.

The alignment of the channels was defined based on the analysis of the available bathymetries and aerial photographs. These data indicate that there has been a lasting channel for at least a century in the upstream half of the lower lagoon (Girard 1915), while in the downstream half of the lower lagoon, the position of the channel(s) varied significantly. However, since the construction of the guiding wall in 1999, the position and orientation of the northern channel has been stable upstream of this wall. Similarly, the upstream half of the south channel has lasted for a decade, while the downstream half of this channel is barely visible in the 2000 bathymetry [Fig. 2(b)]. Instead, the southern channel has extended almost rectilinearly to intersect the northern channel near the guiding wall. Based on these observations, the northern channel was defined with the same alignment that has been dredged in recent years, while the southern channel was redefined as a rectilinear channel, connecting the upper lagoon to the northern channel, near the guiding wall.

The definition of the cross section of both channels was determined iteratively, using the hydrodynamic model ELCIRC (Zhang et al. 2004) and the empirical relation between the tidal prism and the cross-section (Jarrett 1976). ELCIRC solves the three-dimensional baroclinic shallow water equations using triangular finite volumes and Eulerian-Lagrangian techniques. Because the lagoon is well mixed, the model is run in two-dimensional (2D) barotropic mode here. The procedure consisted in running the hydrodynamic model for a specific cross-section distribution along the channels and computing the tidal prisms at selected cross sections from both channels. These volumes were then used to determine a new set of cross sections, and the procedure was repeated. The convergence of this procedure requires that the energy dissipation at the inlet mouth is not allowed to decrease by indefinitely increasing the cross section. Therefore, the inlet mouth was fixed with the depths measured in July 2001, just after a dredging operation [Fig. 2(c)]. As this configuration exhibits the largest width and cross section of all available bathymetries, it seems unlikely that a larger cross section can be stable. The lateral slopes of the trapezoidal cross sections were set to 1:10, as in the existing channels. The channels are dredged to chart datum, except downstream of the existing guiding wall where they are 0.5 m deeper. Their width is 30 m for the southern channel, and increases from 70 m upstream to 100 m at the mouth for the northern channel.

To evaluate the impact of these changes in the dredging operations, hydrodynamic simulations were compared for the July 2001 bathymetry (immediately after the current dredging operation) and the proposed dredging changes. M2 amplitudes and tidal prisms at the mouth were increased by 25 and 20%, respectively.

The definition of the dredging operations over the tidal flats to promote ebb dominance was done in three steps. First, the analytical model of Fortunato and Oliveira (2005) was used to determine the approximate depth of the tidal flats that maximizes ebb dominance. Then, this depth was fine-tuned using 2D hydrodynamic and sediment transport models. Finally, recognizing that dredging all the sand banks at a constant depth is difficult to implement and could have negative effects on the ecosystems, alternative strategies to dredge the same volume were sought and evaluated using the same numerical models.

Fortunato and Oliveira (2005) provide analytical solutions for the dimensionless rate of deformation of the tidal wave, $F=\Delta t_{ef}(gh)^{0.5}/L$, where Δt_{ef}=difference between ebb and flood durations; g=gravity; h=channel depth; and L=its length. The model is based on the difference in celerities of the tidal wave at high and low tide, and depends on the characteristics of the channels, the tidal flats and the tidal amplitude. Application of this model to the physical characteristics of the lower Óbidos Lagoon indicates that ebb dominance is maximal when the tidal flats are close to mean water level (about 0–40 cm above mean sea level) (Fig. 5).

The optimal depth of the tidal flats was verified with the hydrodynamic model, based on the proposed channels superimposed on the July 2001 bathymetry. Results show that dredging the sand banks to 2 m above chart datum (i.e., approximately to mean sea level) significantly reduces the ebb durations, although ebbs remain longer than floods (Fig. 6). This operation would also lead to a 10% increase in the tidal prism relative to the solution with

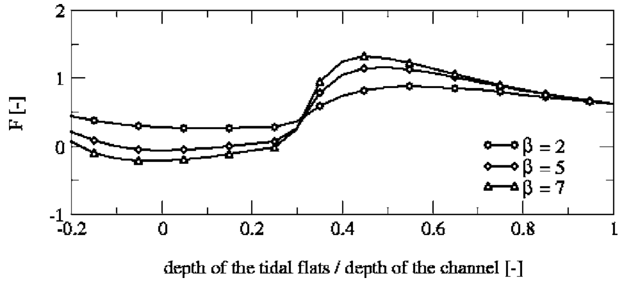

Fig. 5. Application of the analytical model of Fortunato and Oliveira (2005) to optimize the depth of the tidal flats. Parameter β represents the ratio between the width of the tidal flats and the width of the channel. $F=\Delta t_{ef}(gh)^{0.5}/L$ represents the dimensionless rate of deformation of the tidal wave, where Δt_{ef}=difference between ebb and flood durations; g=is gravity; h=channel depth; and L=its length.

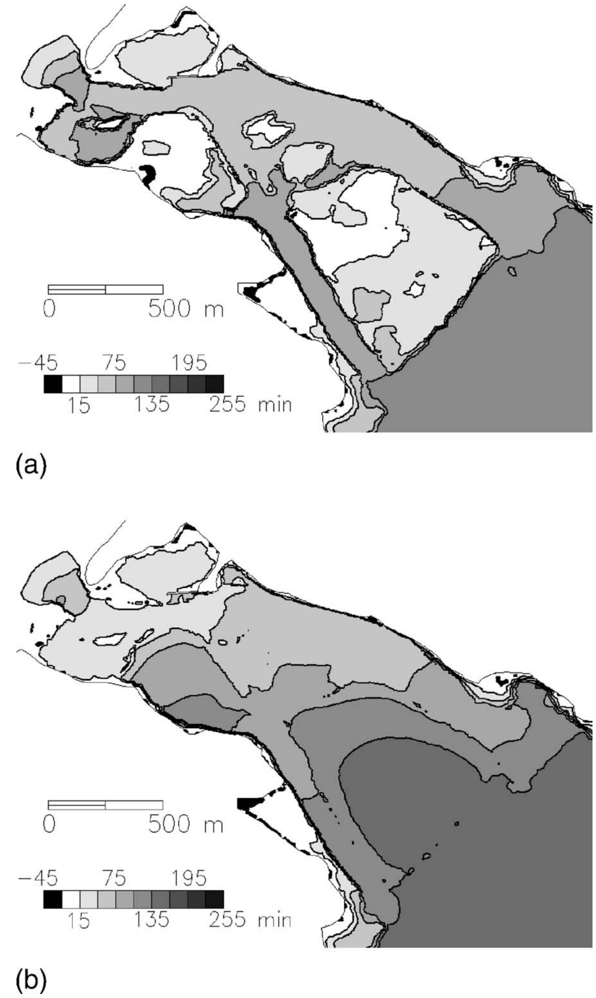

Fig. 6. Differences between ebb and flood durations computed with ELCIRC: (a) sandbanks at present bathymetry; (b) sand banks dredged to 2 m above chart datum

the proposed channels alone, which should further contribute to stabilize the tidal inlet. The total volume to be dredged is 420,000 m^3 of predominantly sandy material.

Given the practical difficulties associated with dredging an extensive area close to mean sea level, alternative dredging strategies were sought. The creation of lateral channels over the sand banks emerged as a promising approach. In the short run, the transverse channels should promote the dewatering of the sand banks on ebb, hence favoring shorter ebbs. In the long run, these channels can act as sediment traps, collecting sediments from the sand bank, and reducing the accretion of the main channels. Hence, if the volume of sand determined above is removed from these lateral channels, this solution may naturally revert to the first one. The volume to be dredged was therefore set to 420,000 m^3. The cross-section of the channels was determined based on the expected characteristics of the dredging equipment, which limited the width of the channels and depth of dredging to minimum values of 25 and 2 m, respectively. Seven channels were defined over the sand banks, spaced by 300 m, and with a total combined length of 3 km (Fig. 7). Preliminary simulations for a schematic lagoon with dimensions similar to the Óbidos Lagoon determined that the angle between the main and secondary channels should be around 45° (Fortunato and Oliveira 2004b), to maximize residual ebb sediment fluxes.

Sediment transport simulations were performed with the model SAND2D (Fortunato and Oliveira 2004a). SAND2D computes the time-averaged sediment fluxes using the empirical equilibrium formulas. The Ackers and White (1973) formula was used here for its robustness (Pinto et al. 2006). Details on the application of this model to the Óbidos Lagoon are given in Oliveira et al. (2004).

The proposed dredging solution increases the tidal prism at the mouth of the lagoon by 22% relative to the one obtained with the July 2001 bathymetry. Simulations with the sand transport model SAND2D also indicate that the transverse channels improve the ability of the inlet to flush out sediments, and are therefore expected to reduce accretion in the inlet (Fig. 8). Although the gains are both relatively modest compared with those obtained by dredging the tidal flats at a constant depth, the disadvantages of the latter solution recommend the lateral channels dredging. They avoid the sedimentation of the banks by mobilizing the fine sediments trapped there on ebb. This sedimentation reduces the lagoon's area, promotes flood dominance and may in the long run transform the sand banks into dry land. As the lateral channels avoid this sedimentation and promote ebb dominance, they are a relevant part of the overall solution.

Preventing Inlet Throat Migration

Bathymetric data and aerial photos indicate that meanders can form downstream of the guiding wall and disappear naturally in a few months (Oliveira et al. 2004, 2006). This process is therefore expected to continue in spite of the dredging operations proposed earlier.

The development of these meanders has negative consequences for the stability of the lagoon. On the one hand, the meanders increase the length of the channels and reduce the tidal prism, decreasing the ability of the channel to flush out incoming sediments. On the other hand, the meanders cause the southward migration of the channel and the inlet mouth, jeopardizing the marginal constructions and reducing the southern beach.

In order to prevent the movement of the downstream part of the channel and the inlet's mouth, a new guiding wall, 300 m long and parallel to the channel, was proposed (Fig. 7). The downstream end of the guiding wall is determined by the alignment of the two rocky cliffs that limit the littoral barrier, Facho and Gronho (Fig. 1). This positioning of the seaward limit of the

Fig. 7. Final solution, including the main channels, the transverse channels, and the guiding wall

guiding wall prevents the interruption of the littoral drift by this structure, thus minimizing its impact on the adjacent coastline. The upstream limit of the guiding wall is defined close to the downstream limit of the existing guiding wall, based on the existing knowledge of where meanders form.

The crest of the guiding wall is defined separately for two different stretches. The downstream third of the wall must protect the littoral barrier from wave and currents action. Hence, overtopping must be avoided, and the crest of the structure is determined accordingly. In contrast, the function of the upstream part of the wall is to prevent the meandering and migration of the channel, thus avoiding overtopping is not a requirement. In addition, the guiding wall should promote sediment flushing from the lagoon. On ebb, the guiding wall should concentrate the currents in the channel, to maximize velocities and promote sediment flushing. Overtopping on ebb should therefore be avoided. In contrast, flood velocities should be minimized, which can be achieved by allowing the overtopping of the guiding wall. The definition of the crest of the upstream part of the guiding wall takes advantage of the difference between the tidal level at maximum ebb and flood close to the inlet mouth (Fig. 9). This definition of the crest also minimizes its visual impact, since the upstream two thirds of the structure are submerged during part of the tidal cycle.

Conclusions

The traditional approach to stabilize tidal inlets, the construction of jetties, meets with increasing criticism because it interrupts the coastal drift, causing erosion problems downdrift. New solutions to stabilize tidal inlets must therefore be developed. The proposed solution for the Óbidos Lagoon meets the demands from the stakeholders by: (1) guarantying the stability of the inlet; (2) minimizing maintenance dredging; (3) not significantly affecting fishing and shellfish harvesting; (4) having a small visual impact; (5) guarantying an ocean beach on the southern sandspit; and (6) protecting this shore. Two of the aspects of the solution proposed

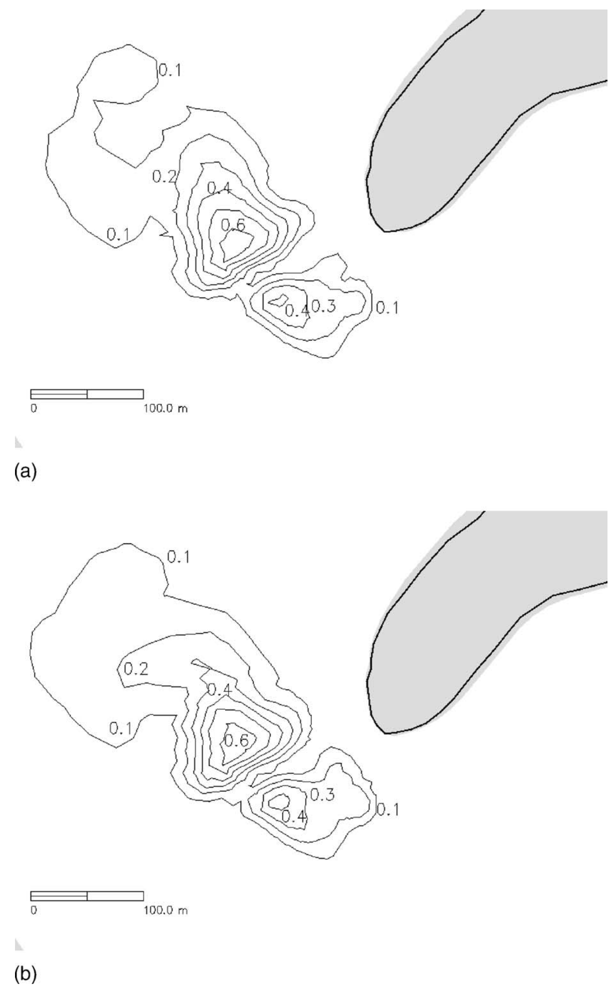

Fig. 8. Magnitudes of the residual sediment flux (kg/m/s) at the inlet mouth for the configurations with: (a) the main channels alone; (b) the main and the transverse channels. All fluxes are directed seaward.

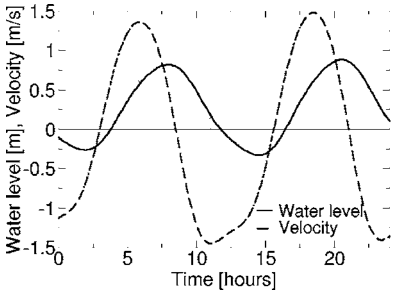

Fig. 9. Computed water level and east–west velocity close to the inlet mouth. On average, water levels are 60 cm higher at maximum flood than at maximum ebb.

herein for the Óbidos Lagoon can also be applicable to other coastal systems.

First, a dredging strategy is proposed to minimize flood dominance, or maximize ebb dominance. Optimizing tidal asymmetry is expected to have long-term benefits for the sediment budget of the lagoon, although existing knowledge on how the long-term evolution of coastal lagoons depends on tidal asymmetry is qualitative, at best. The efficiency of the dredging strategy depends on the extent and depth of the existing tidal flats. Even when the efficiency of this strategy is limited, it can provide guidance on how best to remove sediments from a coastal system undergoing accretion.

Second, a guiding wall was proposed to limit the migration of the inlet channel and mouth. This solution is akin to the traditional jetties, because it helps preventing the movement of the channels and concentrating the ebb flow in the channels, but minimizes their visual impacts and their effects on the coastline. In addition, the inlet mouth retains some degree of freedom, which allows it to adapt to the environmental conditions. For instance, if the ebb sandbank migrates shoreward due to wave action, thereby contributing to the closure of the inlet, the inlet can still migrate northward and remain open. Although the solution is not entirely new (e.g., Druery and Nielsen 1981), it was shown that the choice of the crest of the structure could be optimized by taking advantage of the difference between the tidal level at maximum ebb and flood that occurs in coastal lagoons.

The development and analysis of the engineering solution presented herein was based on a suite of models and approaches. Although various coastal area morphodynamic models have been developed in recent years (e.g., Zyserman and Johnson 2002; Grunnet et al. 2004; Fortunato and Oliveira 2004a), and some tidal inlets have been modeled successfully (e.g., Cayocca 2001), these models still suffer from numerical problems, difficulties in representing all the relevant physical forcings and excessive parameterization of physical processes. Hence, a combination of numerical, analytical and empirical models, such as the one presented herein, is the most reliable way to evaluate engineering works in coastal inlets and can provide the best confidence in the final solution.

Acknowledgments

This work was funded by INAG, project "Revision of the environmental management plan for the Óbidos Lagoon" and LNEC, projects "Long-term evolution of estuarine morphology" and "Short-term morphodynamics of tidal inlets." The writers would like to thank INAG for the permission to publish this work and Professor A.M. Baptista (Center for Coastal and Land-Margin Research, Oregon Health and Science University) for the model ELCIRC. The writers are also grateful to their colleagues who participated in the INAG project, Mr. J. Rego for his participation in the analysis of the hydrodynamics of the Óbidos Lagoon, and Mr. Lourival Trovisco for treating the aerial photographs.

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