Assessment of three dredging plans for a wave-dominated inlet

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Many small wave-dominated inlets are naturally unstable and require regular dredging. To mitigate the costs of these operations, the dredged channels should be designed to bring the inlet close to equilibrium and minimise flood dominance. However, it is often unclear how to optimise the configuration of the channels. This study focuses on a small lagoon on the western Portuguese coast that has been subject to frequent and diverse interventions. A process-based morphodynamic model is applied to compare the dredging plan that has been followed for the last 15 years with two new alternatives. These alternative dredging plans increase the tidal prism and reduce flood dominance, mainly due to the higher channel cross-section. Secondary transverse channels do not affect the morphodynamics significantly. For future dredging operations, it is suggested that the bottom depth of the main natural channel be dredged to chart datum and a secondary channel be added to the previous channel with the same bottom depth and half of the channel width.

Notation

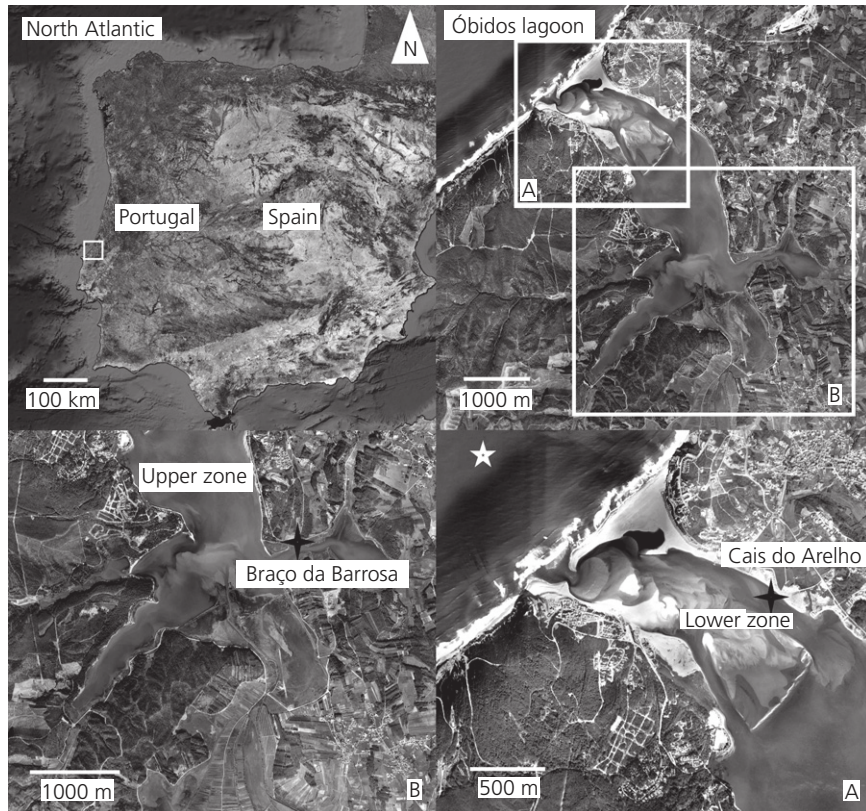|	
d_{50}	sediment median grain diameter
H_s	significant wave height
h	still-water depth (m)
Q_i	sand flux along the axis i ($(m^3/s)/m$)
T_p	wave peak period
Δh	bed update (m)
ε	dimensionless diffusion coefficient
λ	porosity (dimensionless)

1. Introduction

Shallow coastal lagoons with wave-dominated inlets are commonly found in micro-tidal or meso-tidal coasts with a very energetic wave regime (Hayes, 1979; Hayes and FitzGerald, 2013). Worldwide, their economic and environmental importance has been growing since several activities are concentrated in these coastal areas, such as construction development on the barrier islands, aquaculture, fishing and recreational activities. However, these coastal lagoons frequently close due to sediments transported landwards during storms or the littoral drift when the ebb currents are weak (Bertin *et al.*, 2009; Ranasinghe and Pattiaratchi, 2003) or when the fluvial discharge is of minor importance (Elwany *et al.*, 1998; Shuttleworth *et al.*, 2005). Inlet closure prevents navigation, deteriorates water quality and promotes marginal inundations.

Common solutions are artificial opening (Pacheco *et al.*, 2011), maintenance dredging and, in some cases, a single- or double-jetty system (Keshtpoor *et al.*, 2015; Zippel and Thomson, 2015). However, dredging operations are expensive, and jetties have high visual and environmental impacts. The long-term impact of dredging operations should therefore be optimised.

This study focuses on the Óbidos lagoon, located on the western Portuguese coast (Figure 1). This coastal lagoon is connected to the sea through a wave-dominated inlet where the combination of waves and tidal currents frequently induces closure or shoaling of the inlet mouth. Such closures prevent water renewal, which degrades water quality and causes marginal inundations, while migration of the inlet mouth to the northern and southern margins puts neighbouring constructions at risk. Several emergency solutions have been employed in past decades to bring the inlet close to equilibrium (Oliveira *et al.*, 2006). Overall, and despite all the efforts, keeping the inlet open requires frequent large-scale dredging operations, as illustrated by the recent closures in January 2014 and March and April 2015.

Bruneau *et al.* (2011) suggest that the Óbidos lagoon inlet has two stable equilibrium states. However, the authors believe that these equilibrium states should be regarded as preferential states, which are more persistent than others, rather than

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Figure 1. The Óbidos lagoon: location, place names and
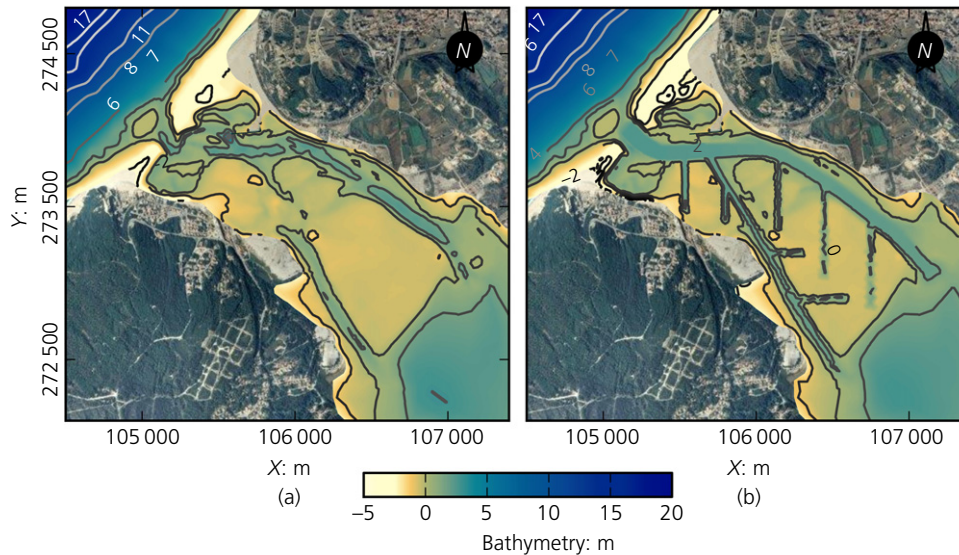monitoring stations (adapted from the free version of
GoogleEarthPro)

perennial. A similar concept was put forward by Hinwood and
McLean (2015) and Hinwood et al. (2012), who proposed
using the concept of attractors to describe a transient – yet per-
sistent – state of a tidal inlet. One of the equilibrium states pro-
posed by Bruneau et al. (2011) has a shorter inlet channel. It
therefore has the potential for lower tidal dissipation, larger
tidal prisms and higher stability.

The most common human interventions adopted in past
decades were dredging operations to reposition the inlet in a
central location and to shorten and deepen the inlet channel.
Combined with dredging operations, several rows of sandbags
were also placed along the margins to restrict the movement of
the inlet mouth, thereby protecting constructions located on
the margins. Moreover, a 200 m long sheet-pile curtain was
built near the northern margin to stabilise the position of the
inlet channel (Vieira, 2001). More traditional engineering sol-
utions comprising two jetties were proposed, but were never
implemented, mainly due to interruption of the littoral drift
and the high visual impact (Fortunato and Oliveira, 2007a).
A major dredging plan $(15 \times 10^6 \ \mathrm{m}^3)$ was subsequently

proposed in order to increase the lagoon surface area and, con-
sequently, the tidal prism. However, this solution proved unfea-
sible due to its cost and doubts raised about its efficacy
(Fortunato and Oliveira, 2007a).

The dredging operations implemented in the last 15 years were
made in accordance with a dredging plan proposed by the
Danish Hydraulic Institute (DHI) (Vieira, 2001), which aimed
at creating a stable inlet channel (Figure 2(a)). The dredging
plan constitutes one main dredged channel with a variable
width. At the upstream part of the flood delta, this channel is
close to the northern margin and is 70 m wide. It is dredged
1·0 m above the chart datum (CD, corresponding approxi-
mately to the lower spring low tide of the coast). Near the
inlet mouth, the channel is located in a central position. Here,
it has a width of 80 m and is dredged 0·5 m above the CD.
Connection with the upstream trench is made with a meander
around the sheet-pile curtain. At the meander, the bottom
depth is dredged 1·0 m above the CD and the channel is
100 m wide. This channel was dredged in 1999, 2001, 2003
and 2013. In spite of these large-scale operations, several

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Figure 2. Bathymetries relative to mean sea level, 2 m above CD.
(a) Dredging solution proposed by the DHI and (b) dredging
solution proposed by Fortunato and Oliveira (2007a) without the
guiding wall

smaller interventions were also required in these years to
prevent or correct the closure of the inlet and the destruction
of marginal constructions. The closure of the inlet in 2014,
only months after dredging of the channel, shows that this
operation constitutes a temporary solution.

Fortunato and Oliveira (2007a) proposed an innovative solution
to stabilise the Óbidos lagoon inlet, comprising a partially sub-
merged guiding wall and a new dredging plan. Figure 2(b)
shows the same solution as presented by Fortunato and Oliveira
(2007a) but without the guiding wall. This dredging plan
constitutes two main dredged channels and seven transverse
channels dredged over tidal flats that are 2·0 m above CD.
These transverse channels aim at reducing the ebb duration
(Fortunato and Oliveira, 2004) and removing sediments from
the ever-growing flood delta. The width of the northern main
channel varies between 70 m upstream and 100 m at the inlet,
and the southern channel has a constant width of 30 m. The
seven transverse channels are 25 m wide. Their total combined
length is 3 km, and they should be dredged with an angle of
~45° to the main channels to maximise the seaward residual
sediment fluxes (Fortunato and Oliveira, 2004). The lateral
slopes of all channels are 1:10. The channel near the inlet
should be dredged 0·5 m below the CD and the remaining
channels to the CD due to dredge vessel specifications.

The purpose of this study was twofold. First, three
dredging plans designed to optimise the configuration of a
wave-dominated inlet were compared. The second objective
was to investigate the impact of adding transverse channels.
The three dredging plans are the dredging plan proposed by
the DHI (hereafter called DP1), the scheme proposed by
Fortunato and Oliveira (2007a) without the guiding wall (here-
after DP2) and a variant of the latter, comprising a single
transverse channel (hereafter DP3).

Section 2 of this paper characterises and describes the Óbidos
lagoon. Section 3 presents the morphodynamic model used.
Section 4 covers verification of the morphological evolutions
simulated by the morphodynamic model and an assessment
of the two proposed dredging plans, comparing both with the
dredging plan used in the last decade. Section 5 summarises
the main conclusions.

2. Description of the study site

2.1 Geomorphological characterisation

The Óbidos lagoon is a shallow coastal system located on
the western Portuguese coast with a narrow (<100 m) wave-
dominated inlet that comprises the connection between the
lagoon and the open sea. The average depth is 2·5 m below
CD. It has a maximum width of 1·8 km, and the total distance
between the inlet and the main tributaries is 4·5 km (Freitas
et al., 1992). Morphologically, the Óbidos lagoon can be
divided into an upper and a lower zone (Figure 1). The upper
zone consists of cohesive sediments, while in the lower zone,

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the vast majority of sediments are sands with a sediment median grain diameter (d_{50}) ranging from 0·4 to 0·8 mm (Bruneau *et al.*, 2011). In the lower zone, the combined effects of waves and tidal currents lead to a complex system of meanders and sand banks (Figure 1). At the inlet, these effects induce morphological evolutions that can occur on monthly time scales (Oliveira *et al.*, 2006). During the maritime summer, the sediments are mainly transported by tidal currents, and the Óbidos lagoon is naturally capable of maintaining its inlet opened, even displaying a natural tendency for enlargement. However, the very energetic wave regime characterised by large swell waves during the maritime winter leads to the transport of a substantial amount of sediments landwards, which often induces the inlet's closure (Bruneau *et al.*, 2011).

2.2 Hydrodynamic forcing

The tidal regime is semi-diurnal with tidal ranges between 2 and 4 m at the coast and 1–2 m inside the lagoon (Oliveira *et al.*, 2006). The wave climate is mild to severe and can be briefly summarised by a significant wave height (H_s) larger than 1 m 88% of the time, and occasionally reaching 6 m in the maritime winter (Bruneau *et al.*, 2011). The mean wave direction (MWD) is confined to a sector between 255 and 345°N but the most frequent MWD is 315°N (perpendicular to the coastline). The wave peak period (T_p) varies between 5 and 20 s (Bertin *et al.*, 2009). The fluvial discharge is concentrated in three main tributaries – Vala do Ameal, Arnóia and Cal. The freshwater input is negligible because it only represents 5% of the tidal prism scaled by the M_2 period (Oliveira *et al.*, 2006). Therefore, the Óbidos lagoon may be considered a well-mixed lagoon.

2.3 Environmental data

In 2001, a comprehensive monitoring campaign was carried out. Between July and November 2001, the wave parameters in front of the inlet and the water levels inside the lagoon were recorded along with two bathymetric surveys inside the lagoon. The wave characteristics were intermittently recorded by the Portuguese Hydrographic Institute (IH, 2001) from July to September 2001 in front of the Óbidos lagoon inlet. These data were obtained using an acoustic Doppler current profiler deployed at 23 m depth (CD). Water levels were measured by two tidal gauges, one located near the inlet (at Cais do Arelho) and the other at the upstream boundary of the lagoon (at Braço da Barrosa). These tidal gauges had a sample period of 6 min and measured the sea surface elevations between July and November 2001. The bathymetric surveys were performed by boat inside the lagoon in July 2001 and in November 2001.

3. Methodology

3.1 Description of the morphodynamic model

The morphodynamic model used simulates the non-cohesive sediment dynamics and the morphological changes in estuaries and coastal inlets under the combined effect of waves and tidal currents. The model comprises the wave propagation model WWM-II (Roland *et al.*, 2012), the circulation model Selfe (Zhang and Baptista, 2008) and the sediment transport and bottom evolution model Sed2D (Dodet, 2013). In order to provide flexibility and efficiency, these models share the same unstructured grid, which allows adaptation to complex coastal environments, and are fully parallelised.

WWM-II solves the wave action equation that describes the evolution of the wave spectrum over time and geographical and spectral spaces. The relevant physical processes in shallow waters are included in the model, such as wave shoaling, bottom-induced refraction and breaking, bottom friction, triad wave–wave interactions and current-induced wave blocking and refraction. The outputs of WWM-II are used to compute the gradients of radiation stresses necessary to force Selfe and to evaluate the sediment fluxes in Sed2D.

The version of Selfe used in this work solves the 2DH shallow-water equations with the Boussinesq approximation. The bottom friction is determined using a Manning friction law with a spatially variable coefficient. The water levels and tidal currents obtained by Selfe are fed back into WWM-II to calculate the current-induced wave shoaling and refraction and into Sed2D to calculate the sediment fluxes.

Following Fortunato and Oliveira (2004), Sed2D solves the Exner equation (Equation 1) with a node-centred finite-volume technique to update the bottom bathymetry

1. $$\Delta h = \frac{1}{1-\lambda} \nabla \left[Q + \varepsilon(1-\lambda) \left(|Q_x| \frac{\partial h}{\partial x} + |Q_y| \frac{\partial h}{\partial y} \right) \right]$$

where h is the water depth, λ is the porosity, ε is a dimensionless diffusion coefficient and Q is the sand flux computed with one of the available semi-empirical formulas. The sediment transport formula of Van Rijn (2007a, 2007b), which accounts for bed load, suspended load and wave–current interaction, was used to compute the sediment fluxes over the domain.

3.2 Modelling set-up

The unstructured grid, generated in the paper by Bruneau *et al.* (2011), has 29 398 nodes and 57 880 elements with a spatial resolution between 1600 m at the ocean boundary and 6 m at the inlet. The initial bathymetry of July 2001 (Figure 2 (a)) was measured by the Portuguese Hydrographic Institute (IH, 2001) soon after the dredging plan proposed by the DHI was implemented in May/June 2001.

The offshore boundary conditions are provided by regional models. The wave model WaveWatchIII (hereafter WW3)

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(Tolman, 2009) is run in two nested grids, following Dodet *et al.* (2010), and provides the two-dimensional wave spectrum every 3 h. Tidal elevations for the major 20 tidal constituents are computed with a regional application of Selfe (Fortunato *et al.*, 2016). The atmospheric pressure is considered constant with a value of 1015 HPa since the estimated standard deviation was 3 HPa during the period between July and November 2001.

Deep-water effects, namely white capping and quadruplet wave–wave interactions, were not considered in the local wave model to reduce the computational effort. The wind forcing was neglected due to computational time constraints because the domain in the analysis is small, with a fetch of 11 km over an area of 210 km^2. The reduction of the computational costs also led to restricting the frequency and direction bins to 12. To model the horizontal turbulence, a spatial constant eddy viscosity coefficient of 1 m^2/s was adopted.

Solving the Exner equation can cause spurious morphological oscillations. To circumvent these effects, the use of filters is common in such models. Sed2D has three built-in filters: an extrema filter, a slope filter and a diffusive filter. The extrema filter eliminates local extrema while preserving mass by averaging the depth at nodes with local extrema and neighbours (Fortunato and Oliveira, 2000). The slope filter mimics gravity effects on steep bottoms to prevent large gradients on the wet and dry zones (Roelvink *et al.*, 2009). The diffusive filter aims to prevent the development of numerical oscillations by adding diffusion along the flow direction (Fortunato and Oliveira, 2007b). The median grain diameter was chosen in accordance with the sampling analysis described above, following Bruneau *et al.* (2011).

4. Morphodynamic model simulations

4.1 Morphodynamic model verification

To verify the wave model, a simulation of 95 d, with a 3 d ramp period, was performed between 1 July and 30 September 2001. The wave model was run alone since the wave buoy is located deep enough (around 23 m depth) where waves do not interact with bottom bathymetry or the ambient currents. The verification of the coupled wave and hydrodynamic models was assessed with a simulation of 21 d with a ramp period of 1 d between 17 July and 6 August 2001. This temporal interval was chosen to validate the coupled model because it was considered small enough for the morphological evolutions to be neglected. Finally, to evaluate the predictions of the full morphodynamic model, a simulation of 156 d from July to November 2001, with 3 d of ramp period, was made and the results were compared with the bathymetric data collected in November 2001. The coefficients used in the morphodynamic model are presented in Table 1.

Coefficient	Setting
WWM-ll	
WWM-II time step	300 s
Direction bins	12 (southwest to northeast)
Frequency bins	12 (0·2–0·05 Hz)
Bottom friction coefficient	0·067 m^2/s^3
Wave breaking coefficient	0·78
Selfe	
Selfe time step	20 s
Horizontal eddy viscosity	1 m^2/s
Water depth for wetting and drying	0·01 m
Manning coefficient	Spatially variable (Bruneau *et al.*, 2011)
Sed2D	
Sed2D time step	20 s
Diffusion coefficient	2
Maximum slope for wet/dry elements	11/45°

Table 1. Coefficients used in the morphodynamic model

	H_s: m	T_p: s	MWD: degrees
WWM-II			
RMSE	0·39	1·43	18·1
ME	−0·22	0·02	9·4
SI: %	31	15	—

	Cais do Arelho	Braço da Barrosa
WWM-II and Selfe		
RMSE: m	0·18	0·12
ME: m	−0·05	0·01
Skill	0·91	0·94

	Bathymetry of November 2001
WWM-II, Selfe and Sed2D	
BSS	0·47

Table 2. Statistical error measures of the morphodynamic model

The statistical error measures used to verify the wave model were the root mean square error (RMSE), the mean error (ME) and the scatter index (SI), as in the paper by Teles *et al.* (2012). The results (Table 2) are in line with the results published by other authors (Dodet *et al.*, 2013; Teles *et al.*, 2012). They show fairly good behaviour and agreement between

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simulations and observations: the wave model underestimated H_s by 0·22 m, the T_p was well reproduced with an SI of 15% and the MWD had an average error of 9·4°.

The coupling between the wave and the hydrodynamic model was validated through a comparison of the simulated and measured water levels for two tidal gauges inside the lagoon. The statistical error measures evaluated were the RMSE, the ME and the skill, as in the paper by Dias *et al.* (2009). The good reproduction of the water levels inside the lagoon (Table 2) was made evident by the values of the above-mentioned statistical errors. Both comparisons described provided a sufficient level of confidence to continue with the additional morphodynamic module.

The morphodynamic simulation between July and November 2001 was assessed with the Brier-skill score (BSS) proposed by Sutherland *et al.* (2004). The simulated DP1 bathymetry was compared against the measured bathymetry in November 2001 (Bertin *et al.*, 2009; Bruneau *et al.*, 2011). According to Sutherland *et al.* (2004), a BSS error of 0·3–0·5 corresponds to 'good agreement'. The values obtained for BSS (Table 2) thus indicate that the morphodynamic model predictions showed good agreement with the morphological evolutions in the Óbidos lagoon. The inlet migration to the southern margin in November 2001, seen in the bathymetric survey, was not reproduced by the model. This behaviour is attributed to the high d_{50} at the northern margin required to stabilise the morphodynamic model and to the absence of the swash transport that reduces the longshore sediment transport. Also, the cut-off to 12 frequency bins to reduce the computational time, and the related loss of the energy associated with the frequencies above 0·2 Hz, could decrease the wave energy near the inlet mouth.

The ability of the morphodynamic model to reproduce the inlet enlargement and infilling was tested with the methodology proposed by Bertin *et al.* (2009). The amplitude of the tidal constituent M_2 was calculated at the Cais do Arelho tidal gauge using both model results and data. The growth of the tidal amplitude in the maritime summer and its reduction in the autumn were successfully reproduced by the model, although with a lag of 15 d (Figure 3). This lag can be associated with uncertainty of the exact date of the initial bathymetry, which is unknown. This comprehensive verification of the morphodynamic model displayed a good capability to predict the morphological evolution of the Óbidos lagoon. Therefore, it is an appropriate tool to assess the morphodynamic evolution of the three dredging plans.

4.2 Morphological simulations of the three dredging plans

The morphological evolution of the lagoon from 1 July until 27 November 2001 for the three dredging plans displayed
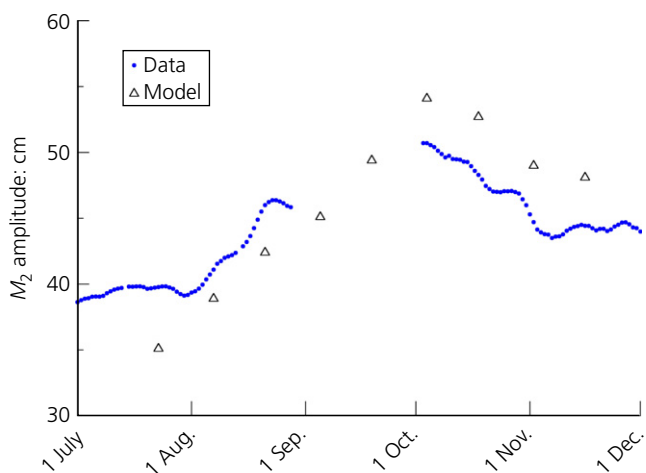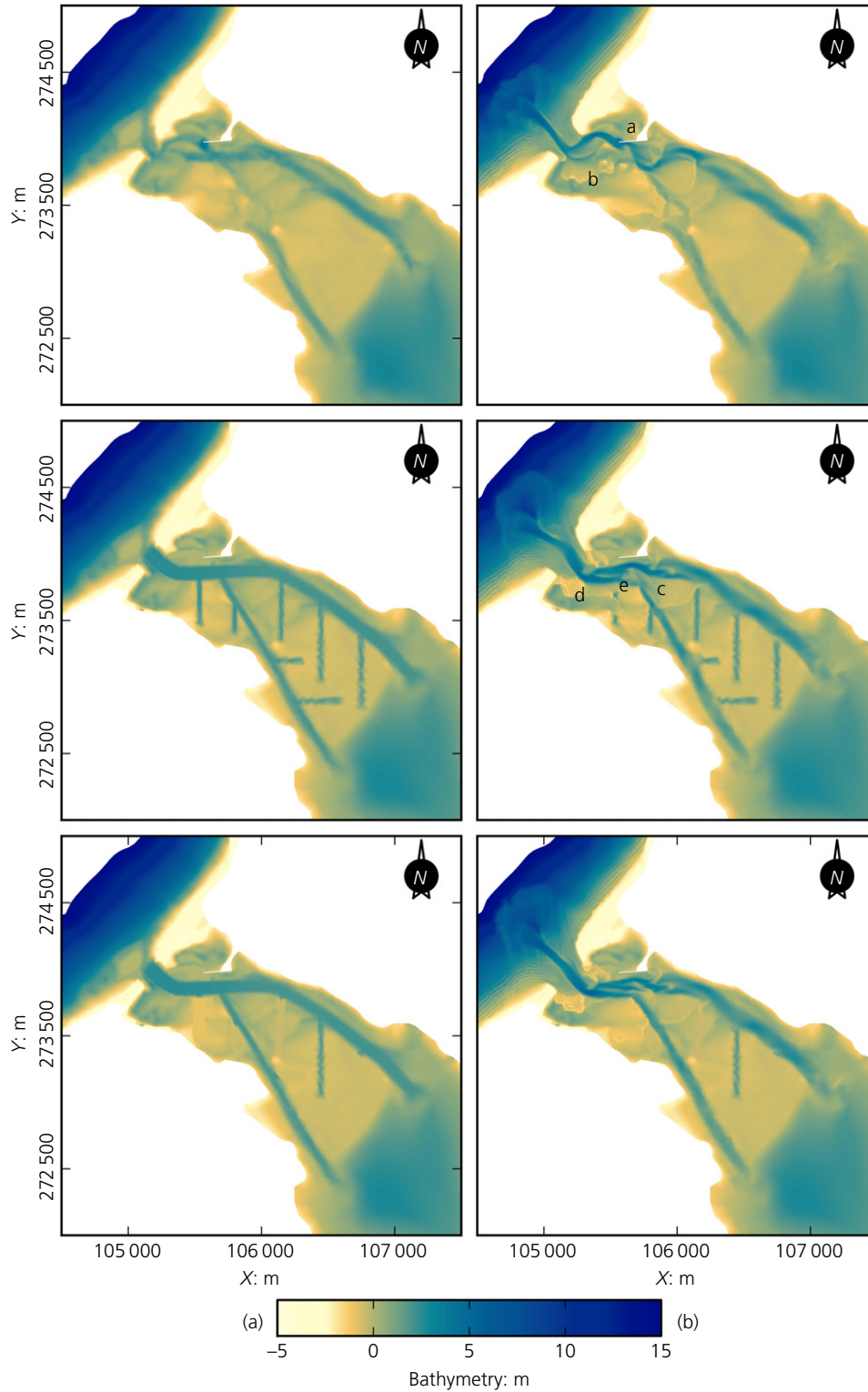
Figure 3. Evolution of the M_2 amplitude in Cais do Arelho from July to December 2001

some distinct behaviours (Figure 4). The northern main channel in DP1 displayed an unstable behaviour near the sheet-pile curtain because two meanders were formed (mark a). Moreover, strong sedimentation occurred in the sand bank south of the inlet transitional channel, which promoted the accretion of the downstream part of the flood delta (mark b).

The morphological evolutions of DP2 and DP3 were very similar to each other, but fairly different from DP1 (Figure 4). Both scenarios exhibited a stable northern main channel, without significant meanders. The transitional channel remained in a more central location. Dredging the main southern channel limits further accretion in the sand bank located between the two main channels (mark c). Also, the accretion at the beginning of the flood delta became restricted to a feature similar to a sand spit on the southern barrier island (mark d). After 5 months, DP2 and DP3 displayed a 40% wider and 25% deeper transitional channel when compared with DP1. These results reflect the characteristics of an ebb-dominated inlet with a more stable and wider transitional channel, where the ebb currents are the main agents that transport sediments seawards. Therefore, DP2 and DP3 presented a more stable morphological evolution than DP1.

The three transverse channels connected to the southern main channel increased the sediment transport along the south channel. At its downstream end, a sand bank similar to a flood delta developed, which will consequently constrict the main northern channel (mark e). They also increased the sediment transport near the connections with the southern main channel. This increase can allow a meander formation. The

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Figure 4. Bathymetries relative to mean sea level, 2 m above CD.
(a) Initial bathymetry for DP1 (top), DP2 (middle) and DP3
(bottom). (b) Simulated bathymetry past 5 months for DP1 (top),
DP2 (middle) and DP3 (bottom)

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westernmost transverse channel in DP2 was fully accreted after 5 months, probably because it is approximately perpendicular to the northern main channel. Therefore, the qualitative comparison between DP2 and DP3 results suggest a less stable behaviour of the southern main channel when the transverse channels are present.

4.3 Hydrodynamic characteristics of the three dredging plans

The tidal prism is the volume of water that enters a lagoon during flood. In general, the stability of an inlet increases with the tidal prism (Bruun and Gerritsen, 1960). Time series of tidal prisms were computed for the three simulations. The results show that both DP2 and DP3 increase the tidal prism by roughly 50% relative to DP1 (Figure 5). However, this increase declines over time, suggesting that DP2 and DP3 lead to higher accretion rates than DP1. The benefits of these plans are therefore temporary. A rough estimate of the time scale of adjustment by a simple linear extrapolation of the trends in Figure 5 (thick lines) suggests that this period will be of the order of 1–2 years.

Sediments deposited inside coastal lagoons are transported seawards mainly by ebb currents. These currents are stronger if ebbs are shorter than floods. The differences between ebb and flood durations and the maximum ebb or flood velocities were calculated at two locations: inside the lagoon and near Cais do Arelho (Table 3). The ebb–flood differences between DP2 and DP3 are small, with an increase of 2% of the maximum ebb velocity at Cais do Arelho. These velocities are
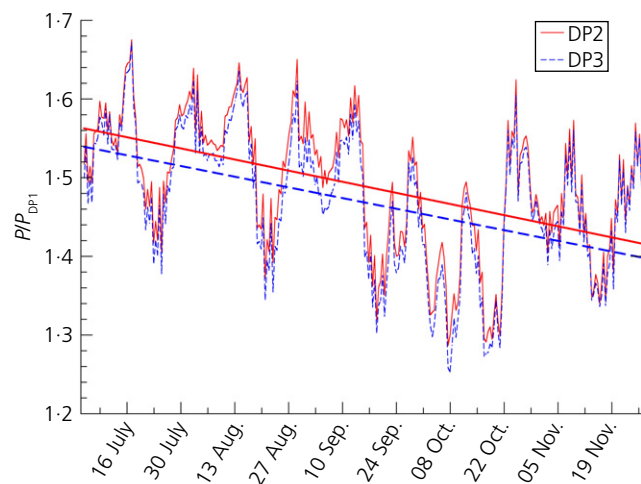
high enough to keep the main northern channel near Cais do Arelho stable for every dredging plan, thereby flushing out the sediments accumulated in that channel. Also, the differences in ebb and flood durations of DP2 and DP3 compared with DP1 were reduced on average by 25% at the central zone of the Óbidos lagoon and by 63% at Cais do Arelho. Therefore, the results show that DP2 and DP3 promote ebb dominance relative to DP1: the flood durations increase and the ebb velocities increase.

The ratio between tidal amplitudes inside and outside the lagoon (Figure 6(b)) shows a strong fortnightly behaviour for all the dredging plans. This behaviour is associated with the neap/spring tidal cycle (Figure 6(a)). On spring tides, velocities increase at the inlet, thereby increasing the dissipation of tidal energy. Conversely, the smaller velocities on neap tides reduce the damping of the tide inside the lagoon and the ratio decreases. There is no evidence of any phenomenon (storm) that affects DP2/DP3 differently from DP1 because the curves are equidistant. The small differences between the results for DP2 and DP3 suggest that the impact of the transverse channels is very small. There is also an average difference of 0·3 in the ratios between DP2/DP3 and DP1. This increase is subjacent to higher tidal prisms, which will lead to more stable dredging solutions.

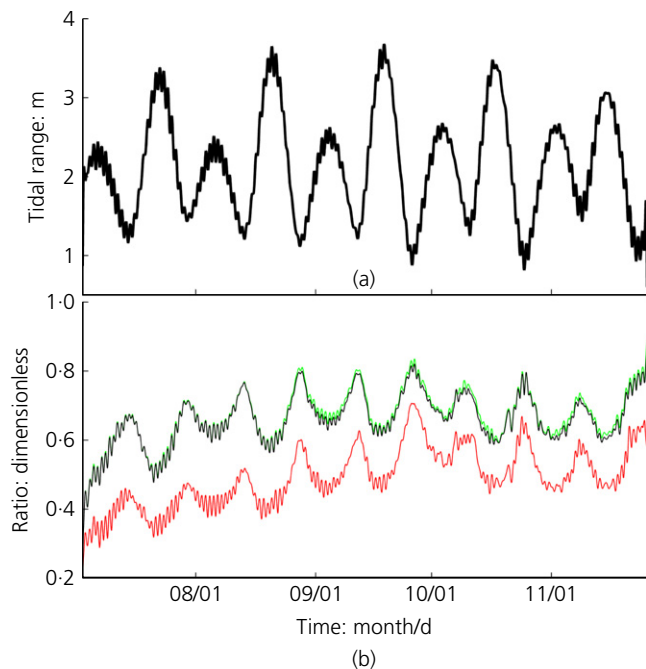### 4.4 Bathymetric differences between the three dredging plans

The differences between the initial and final bathymetries over 5 months highlight the areas of erosion and accretion inside the Óbidos lagoon for the three dredging plans (Figure 7). DP1 displays a large accretion zone at the seaward end of the flood delta, which leads to the formation of the downstream meander of the northern main channel. This meander increases the length of the inlet channel, enhances tidal dissipation and reduces the tidal prism.

Figure 5. Time series of the ratio between the tidal prisms of DP2 (solid line) and DP3 (dashed line) with the tidal prism of DP1. The thick lines represent linear regression curves

	Difference: min		
	DP1	DP2	DP3
Cais do Arelho	89	33	32
Central zone of the Óbidos lagoon	165	126	123
	Maximum velocities: m/s		
Cais do Arelho	1·22 (1·22)	1·27 (1·22)	1·24 (1·21)

Table 3. Average differences between ebb and flood durations, and maximum ebb (flood) velocities at two locations in the Óbidos lagoon during the 5-month period

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Figure 6. (a) Tidal amplitude outside the lagoon. (b) Ratio between tidal amplitude inside (at Cais do Arelho) and outside the lagoon for DP1 (lower plot), DP2 (uppermost of the top two plots) and DP3 (lower of the top two plots) from July to the end of November 2001

The addition of the southern channel in DP2 and DP3 seems to prevent the progression of the accretion landwards of the seaward end of the flood delta. Also, the main northern channel remained in a fixed position in the DP2 and DP3 simulations. In contrast, the same channel progressively developed meanders in the DP1 simulation, a clear evidence of instability. Differences between DP2 and DP3 can be observed at the southern main channel since the southern transverse channels improved the accretion in the previous channel. Therefore, the comparison suggests that the four transverse channels connected to the southern main channel promoted accretion, thereby reducing the discharge capacity of the southern main channel.

5. Conclusions

Three dredging plans designed to improve the stability of a wave-dominated inlet were assessed using a process-based morphodynamic model. The methodology presented in this study proved adequate to investigate dredging solutions and can be further used in other sites with wave-dominated inlets. Overall, this study allows the understanding of the morphological evolution of a coastal lagoon with a wave-dominated inlet with three distinct dredging plans and presents a methodology to evaluate dredging plans in wave-dominated inlets.

The results show that dredging a second main channel in the southern part of the lagoon improves the stability of the inlet. In the short term, flood dominance decreases, ebb velocities grow and the tidal prism increases. Furthermore, this channel reduces the formation of a flood delta, which leads to the meandering of the inlet channel. As this meander contributes to lengthening the inlet channel and reducing the tidal prism, avoiding its generation is particularly beneficial to the stability of the inlet. However, these benefits of the second main channel are expected to be temporary and will gradually fade away over 1 or 2 years.

The benefits of dredging transverse secondary channels were unclear. While these channels slightly increased the tidal prism, they also promoted accretion at the main southern channel and constricted the main northern channel by creating a feature similar to a flood delta. Hence, they may have negative impacts in the long run.
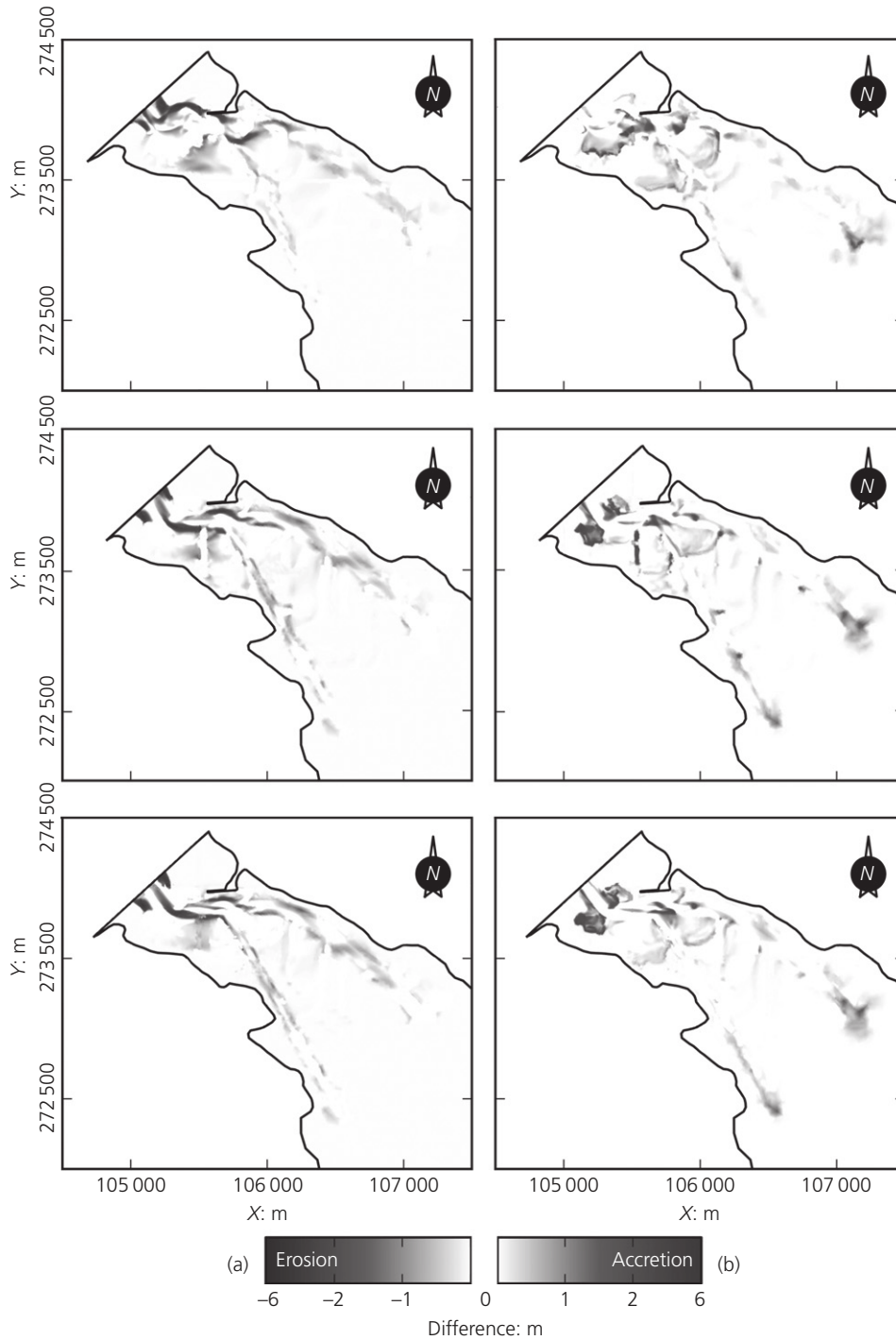
For future dredging applications in similar coastal lagoons with wave-dominated inlets, it is advisable to increase the bottom depths to the CD (approximately the lower low tide in the ocean) and the width of the main natural channel in order to improve the inlet stability by increasing the tidal prism and the ebb dominance. The secondary channel (the southern main channel in this study) should be dredged to the CD and must have a width half that of the main channel and be at an angle of ~45° to the main channel to maximise the residual ebb fluxes.

Numerical simulations were performed from July to the end of November 2001. Further studies are therefore required to understand the complex evolution cycle of the inlet, from the dredging operation to the natural closure (Fortunato *et al.*, 2014). In particular, these studies should include the winter season because the wave regime is more energetic, thereby increasing the morphological changes in wave-dominated inlets and even leading to inlet closure. The higher tidal prisms obtained by dredging larger volumes of sand are expected to keep the inlet from closing in the winter months. However, this behaviour should be verified and quantified.

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Figure 7. Erosion (a) and accretion (b) patterns between the initial and the final bathymetries for DP1 (top), DP2 (middle) and DP3 (bottom)

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