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EFFICIENT DREDGING STRATEGY FOR CHANNEL MAINTENANCE OF THE GUADIANA EBB-DELTA

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Abstract

A simplified version of the Inlet Reservoir Model is implemented at the Guadiana ebb delta to define efficient maintenance strategy of the entrance channel. The model is first applied typically to the outer shoal area, reproducing successfully the observed post-jetty volume evolution known from 16 bathymetric grids spanning 47 years. However, the volume of the outer shoal area is too large to be significantly impacted by small dredging-induced variations. Hence, the model is applied to a smaller dredged channel area. Observations indicate that this area reached an equilibrium volume, supporting the suitability of the model to simulate its volumetric evolution (similar to typical model applications). The calibrated model was then used to explore various dredged volume scenario considering a channel volume threshold for safe navigation. The efficiency of each scenario was evaluated based on a dredging performance rate representing the dredged volume normalized to the lifetime of the intervention (i.e., until another dredging is required). Results suggest that the best (cheapest) strategy would consist in dredging a volume of 100,000 m^3 that would maintain navigability in the channel during 6 years.

Key words: ebb-delta, dredging, management, jetty, morphodynamics, Inlet Reservoir Model.

1. Introduction

Ebb-tidal deltas are dynamic features with varying morphology resulting from the complex interplay between waves, tides, river discharge and sediment supply (Boothroyd, 1985; Chang, 1997; de Swart and Zimmerman, 2009; FitzGerald, 1996; FitzGerald et al., 2002; Hayes, 1980). These interactions often produce large morphological modifications over the course of seasons to decades, characterized typically by changes in the position and depth of the inlet channel and by the development and migration of shoals over the swash platform (e.g., Burningham and French, 2006; Cheung et al., 2007; Cooper et al., 2007; Elias and van der Spek, 2006; FitzGerald, 1984; FitzGerald et al., 2002; Gaudiano and Kana, 2001; Hume and Herdendorf, 1992; Oertel, 1977; Siegle et al., 2004). These spatial and temporal morphological variations can render navigation hazardous. As such, the position of the inlet is often stabilized by jetties.

It has been largely documented that jetties disrupt the dynamic equilibrium between the historical (unaltered) ebb-tidal delta morphology and the prevailing hydrodynamic conditions (Komar, 1996; Kraus, 2009; Oost et al., 2012). Inlets typically respond to jetty construction with the collapse of parts of the historical delta where the inlet channel does not migrate anymore, such as wave-induced onshore transport is no longer countered by ebb tidal flows over the long term (Garel et al., 2014; Hansen and Knowles, 1988; Kraus, 2006; Pope, 1991). Besides, the confinement of the flow between the jetties results in the development of a modern ebb delta in the seaward stream of the stabilized estuarine ebb jet (Buijsman et al., 2003; Hansen and Knowles, 1988; Kraus, 2006; Pope, 1991). The growth of the modern ebb delta is accompanied with the formation of complex morphological features resulting from preferred sand transport pathways across the inlet (see Carr and Kraus, 2001). At a decadal to centennial time scale, the fraction of input sediment trapped in the system is progressively reduced as the delta evolves towards a mature stage increasing bypassing efficiency (Byrnes and Hiland, 1995; Gaudiano and Kana, 2001; Kraus, 2006).

The development of (modern) ebb deltas – and particularly of the outer shoal – often makes navigation difficult. The cross-section of the entrance channel is generally maintained regularly by dredging to ensure navigability. The volume of sediment to be dredged is generally based on target depth and financial considerations, more rarely on scientific knowledge. In particular, the outer shoal response to dredging, and more specifically the relation between dredged volume and associated minimum frequency of maintenance operations, is not established. Many jettied inlets are affected by shoaling issues and

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require frequent dredging operations to which they have their very own response. This calls for the implementation of scientifically based tools for the determination of cost-effective long term dredging strategies.

In the present study an analytical model simulating ebb shoal evolution - the Inlet Reservoir Model (IRM) – is implemented at a case study (the Guadiana ebb delta). Based on volume and bypass rates estimations, the model was developed to support inlet management through the prediction of large scale morphological changes (Kraus, 2000). Here, a simplified version of the model is adapted to address specifically the dredging issue at the case study. The objective is to show that the proposed approach can provide some guidance for the selection of effective inlet channel maintenance dredging schemes.

2. Study site

The study area encompasses the ebb delta of the Guadiana estuary, at the southern border between Spain and Portugal (Figure 1). The tidal regime in the area is semi-diurnal with a mean range of 2 m. Offshore wave climate is dominated by W-SW wave direction (71% occurrence) and SE sea waves (23% of occurrences) of moderate energy, with yearly average significant wave height and peak period of 1 m and 8.2 s, respectively (Costa et al., 2001). According to these hydrodynamic parameters and referring to the terminology of Hayes (1979), the Guadiana is a mixed-energy, tide-dominated inlet (Morales, 1997). Wave's conditions produce a dominant eastward littoral transport which average rate is estimated to be less than 110,000 m^3/yr (Santos et al., 2014). River-borne material is also supplied to the ebb delta during river floods, yielding an approximate average rate of 100,000 m^3/yr for the period 1980-2000 (Portela, 2006); however, this source has been reduced by 2 orders of magnitude with the closure of the Alqueva dam in 2002 near the estuary head (Garel and Ferreira, 2011).

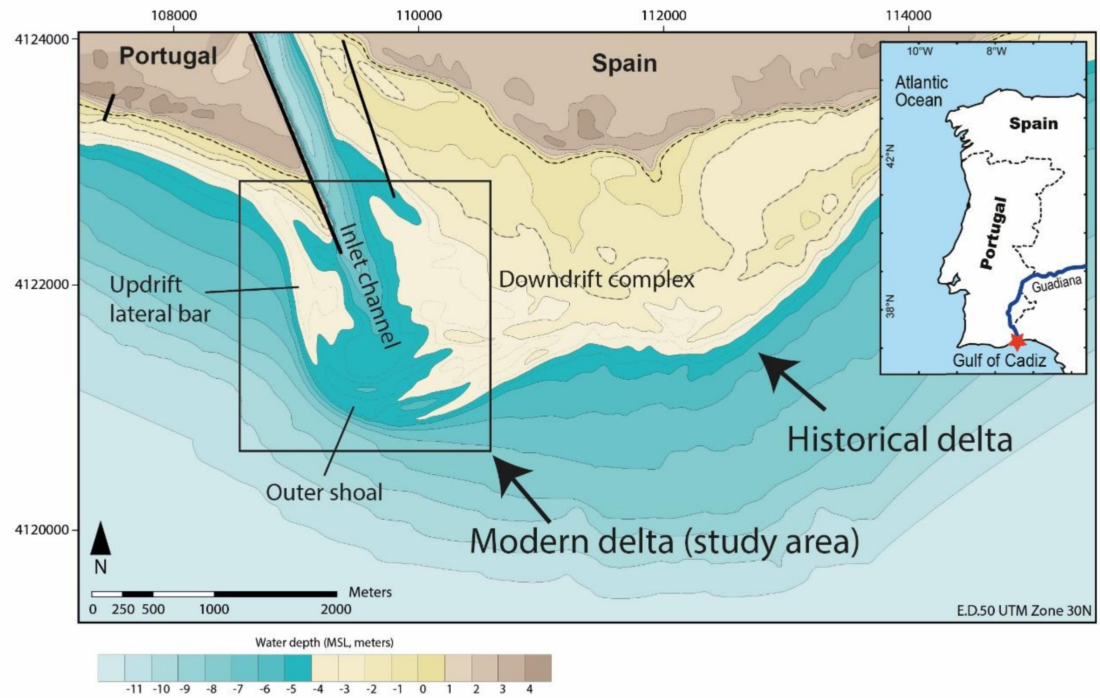

Figure 1. Composite topo-bathymetric map of the Guadiana estuary mouth area with indication of the main morphological elements of the ebb delta (as in 2014). For general location, see the red star in the inset.

Before 1974, the ebb delta of the Guadiana was broad, asymmetric eastwards and characterized by the presence of a large sandy shoal (the O'Bril bank), accumulating the littoral drift on the western margin of the estuary mouth (Gonzalez et al., 2001). Under the course of decades, the bank was undergoing cyclical periods of growth, rotation and breaching that was making estuary boat access hazardous and intricate. A pair of parallel jetties (the eastern one being emerged at spring low tide, only) was built in

1972–1974 to stabilize the entrance channel and to improve navigability. In response, the eastern part of the historical delta has collapsed while a modern ebb delta has formed off the mouth (Garel et al., 2014). The modern delta is characterized by an updrift bar and outer shoal (or ebb shoal proper) which delineate a major pathway for sand transport across the inlet. These morphological features developed rapidly due to a large contribution of local sand eroded from the O'Bril bank (Garel et al., 2015). The downdrift area consists of a broad complex including landward migrating shoals which are relict of the historical delta (Figure 1).

The outer bar is formed by several sub-parallel bars which development has reduced locally the depth of the entrance channel to less than 3 m (all depths referred to the hydrographic zero, 2 m below mean sea level), justifying dredging operations performed in 1987 and 2015. Details about the 1987 dredging were not available. In 2015, a sand volume of 0.063 Mm^3 was dredged in the channel to reach a minimum target depth of 3.5 m, for a total cost of 850,000 €. The dredged channel was 1,250 m long and 60 m wide.

3. Material and Methods

3.1. Bathymetric data

The recent morphological evolution of the Guadiana ebb delta was evaluated based on a series of 16 bathymetric maps ranging from 1969 to 2016 (Table 1). The original material (raw data, grids or maps) were converted into ED50 UTM29N projection system and standardized to a grid of 25 m resolution. All the grids include the inlet channel and the whole outer shoal, except the ones of 2001, 2003 and 2012 (channel only).

Table 1. List and attributes of the bathymetric maps of the Guadiana ebb-delta used in the present study.

Year	Source	Data
1969	Ministry of Public Works, Hydrography Section	Digitalised topo-bathymetric map 1/5000
1973	Ministry of Public Works, Hydrography Section	Digitalised topo-bathymetric map 1/5000
1977	Port and Maritime Transport Institute (IPTM)	Digitalised topo-bathymetric map 1/5000
1982	Port and Maritime Transport Institute (IPTM)	Digitalised topo-bathymetric map 1/5000
1986	Ministry of Public Works, Transport and Communications (*MOPTC)*	Digitalised topo-bathymetric map 1/5000
1988	Ministry of Public Works, Transport and Communications (*MOPTC)*	Digitalised topo-bathymetric map 1/5000
1992	Port and Maritime Transport Institute (IPTM)	Digitalised topo-bathymetric map 1/5000
1995	Hydrographic Institute (IH)	Gridded data 50 m-cell size
2001	Port and Maritime Transport Institute (IPTM)	Single beam data 20 m transect interval
2003	Port and Maritime Transport Institute (IPTM)	Single beam data 20 to 40 m transect interval
2005	Hydrographic Institute (IH)	Gridded data 25 m-cell size
2010	Hydrographic Institute (IH)	Gridded data 25 m-cell size
2012	J.M.A. Morales (Huelva University)	Gridded data 100 m-cell size
2014	Algarve University (UAlg)	Single beam data 50 m transect interval
2015	Algarve University (UAlg)	Single beam data 50 m transect interval
2016	Algarve University (UAlg)	Single beam data 50 m transect interval

Garel et al. (2015) previously discussed the volumetric evolution of the outer shoal, considering a fixed area that included a large part of the inlet channel. A more accurate definition of this feature is provided in the present contribution. The shoal is considered to include the subparallel bars shallower than 2 m that connect to the lateral (updrift and downdrift) areas (Figure 2, red areas). The seaward limit of this shoal corresponds to the -3 m contour line, which delineates well the external lobe of the delta. The landward limit is set between the most landward mouth bar and the tip of the inlet channel defined by the 3 m isocontour. The outer shoal area defined in this way is not fixed but is rather allowed to expand over years as the delta migrates seaward (as typically observed at other systems).

The morphological evolution of the outer shoal is characterized based on its total surface area, volume and offshore distance. The offshore distance is measured between the tip of the west jetty and the most seaward 3 m isocontour, in the jetty direction (see 2003 and 2005 in Figure 2). The volume is obtained by subtracting the bathymetric grid of 1969 (i.e., the reference surface before jetties' construction, where developed the modern ebb delta) to a grid subset matching the outer shoal area.

3.2. The Inlet Reservoir Model

The IRM is an analytical model that describes the volumetric evolution of tidal inlet deltas and evaluates the associated bypassing rate based on mass conservation (Kraus, 2000; Kraus, 2002). The delta is divided in distinct morphological elements that correspond to different deposition areas (reservoirs) embracing the main transport pathways across the inlet. For example, at typical wave-dominated inlets, these elements can consist of the outer shoal, the downdrift and updrift (if present) lateral bars and the attachment bars that connect the lateral bars to the beach. Depending of the sediment transport pathways at the study site, more complex morphological schemes can be designed (e.g., Dabees and Kraus, 2008). The IRM model is based on the assumption that each morphological feature has an equilibrium volume corresponding to a maximum sand-retention capacity that is limited by wave action and cannot be exceeded. Each feature passes on an increasing volume of sand to the next one as it develops, until it reaches equilibrium in volume. Then all additional sediment arriving to that feature is transported to the next feature(s), and so forth until sediment exits the area (for example when it reaches the downdrift beach). The volumetric evolution of each morphological element is described as:

$$V(t) = V_e \times \left(1 - e^{\left(\frac{-Q_{in}}{V_e} \times t\right)}\right) \tag{1}$$

In Equation (1), V is the volume of the considered feature, V_e is its equilibrium volume, Q_{in} is the rate of sediment input and t is the time (0 at the start of the delta construction, for example after island breaching or jetty construction). For additional details, see Kraus (2002).

3.3. Implementation of the model

At first order, the main morphological elements of the Guadiana ebb delta are the outer shoal, a lateral updrift bar and a downdrift complex area (Figure 1). Amongst those, only the outer shoal is affected by dredging operations to maintain the entrance channel, which are the scope of the present paper. Hence, a simplified version of the IRM model is implemented focusing exclusively on the outer shoal area (previously defined in Section 3.1). The sediment input rate into the shoal (Q_{in}) corresponds to the littoral transport, plus any other contribution, such as river export or input from the adjacent elements. Given the large uncertainty about this rate, model simulations were performed considering low (100,000 m^3/yr) and high (300,000 m^3/yr) estimates. The equilibrium volume V_e was then obtained by fitting Eq(1) to the outer shoal volume observations.

Application of the IRM model to simulate the outer shoal evolution, as described above, is useful to evaluate the model performance at the case study but is not suitable for the analysis of channel dredging effects. Indeed, the volume of the outer shoal (order of Mm^3) is too large to be significantly affected by the small volumetric variations induced by channel dredging (which are 2 orders of magnitude smaller). Thus, the model was also applied to a smaller area restricted to the inlet channel, to specifically study its response to dredging operations (Figure 2, green areas). It is assumed that this feature can be considered as a morphological element, reaching toward an equilibrium volume controlled not only by waves but also by tidal currents. The channel area was defined as the region affected by the dredging performed in 2015, which was explicitly identified on the bathymetric survey performed only one month after the intervention (see 2015 in Figure 2). The position of the area over each bathymetric map was modified to account for the migration of the inlet channel; however, its size (150 x 835 m) was kept constant as it is not expected to expand laterally through time (contrarily to the outer shoal area). In support, the channel dredged in 1986 is included in the defined area (see 1988 in Figure 2). The channel area is a sub-element of the outer shoal area and receives as such an unknown fraction (rather than the totality) of the sediment inputs Q_{in}. Thus, both the V_e and Q_{in} were estimated by fitting Equation (1) to the observed volume of deposits within the channel area (obtained with the same approach as for the outer shoal area).

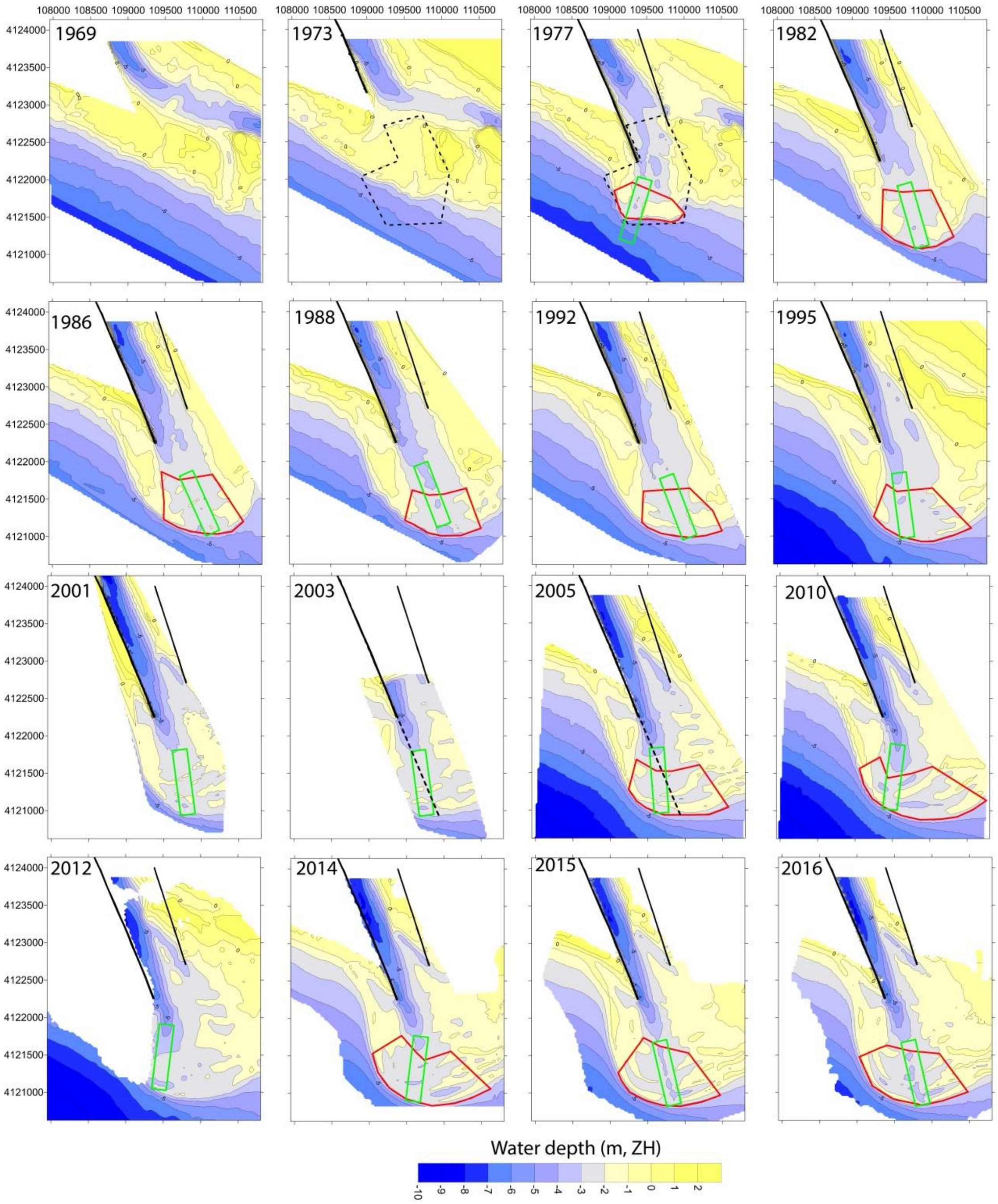

Figure 2. Bathymetric evolution of the modern ebb delta from 1969 (pre-jetty situation) to 2016 with localization of the outer shoal area (red) and channel area (green box). The dashed box in 1973-1977 represents the area where the sediment balance between the newly formed inlet channel and outer shoal was computed (section 4.1.2). The offshore distance of the ebb shoal is computed along the dashed line represented in the 2003 and 2005 maps.

The calibrated model was then used to simulate the channel area response to prospective dredging of various sand volumes. Dredging efficiency was evaluated based on a performance rate (m^3/yr), which is the (model input) dredged volume normalized to the corresponding (model output) lifetime of the operation (until another dredging is required): Thus, this parameter is not the rate at which the channel recovers its pre-dredging volume. The most efficient dredging strategy corresponds to the weakest performance rate (small dredged volume but long effectiveness of the operation). Knowing the price of a dredging operation (e.g., in €/m^3), the performance rate is also indicative of the annual cost (m^3/yr) of a maintenance strategy.

4. Results and discussion

4.1 Outer shoal area

4.1.1 Evolution

Overall, the morphological evolution of the outer shoal is characterized by two periods, with a rapid increase of the measured parameters (offshore distance, area and volume) during the 1st decade after jetty installation, followed by a significantly slower development afterwards (Figure 3). For instance, ebb jets produced offshore migration of the seaward flank of the O'Bril bank (1969, 1973) and of the newly formed shoal until 1982 at a rate of ~80 m/yr. Since then, a strong linear correlation (r^2 = 0.96) indicates a relatively steady migration at a rate of 7.5 m/yr. The ongoing growth of the shoal is well-evidenced by volume variations. For example, the shoal gained about 0.6 Mm^3 in between 2005 and 2016, reaching about 2.7 Mm^3. These observations clearly indicate that the outer shoal is not currently at equilibrium.

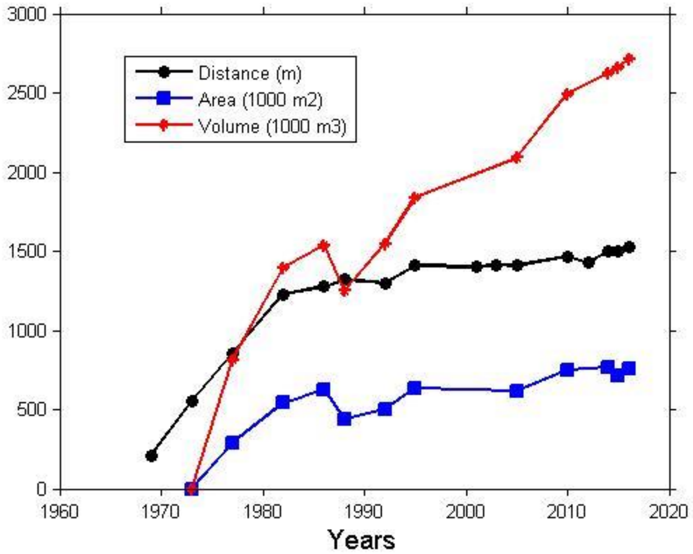

Figure 3. Evolution of the outer shoal expressed as offshore distance (m, black), total area (thousands of m^2, blue) and volume with reference to the 1969 bathymetry (thousands of m^3, red).

Relatively strong erosion of the outer shoal occurred between 1986 and 1988, with a volume loss of 0.3 Mm^3 (Figure 3). These years correspond to a dry period with no major storms indicating that river floods or increased wave activity are not the cause of this erosive event. Noting that both the area and volume decrease, but not the distance, this event could be partly related to inaccurate delimitation of the shoal area. Yet, a decrease of 0.16 Mm^3 is still observed when the outer shoal of 1986 is considered to compute the volume in 1988. The volume loss could also be partly due to the dredging operation in 1986, although the dredged volume was unlikely more than 0.1 Mm^3.

4.1.2 Model results

Considering a low sediment input rate (Q_{in} = 100,000 m^3/yr), a good fit (r^2 = 0.87) is obtained between Eq(1) and shoal volume observations (Figure 4a, black line). Only the initial shoal evolution (1977, 1982 and 1986) is not well reproduced, with observations well-above the model predictions. The estimated equilibrium volume V_e is 4.5 Mm^3. With a high sediment input rate (Q_{in} = 300,000 m^3/yr), the fit is relatively poor (Figure 4a, blue line). In particular, the model predicts that the outer shoal reached equilibrium (2.3 Mm^3) around the year 2000, in contradiction with observations. On the other hand, the initial development of the shoal (until 1986) is better represented than with low sediment inputs. Overall, these results indicate significant variations in the sediment input rates between the first decade after jetty installation (strong rate) and afterward (low rate).

The decrease in the sediment input rate to the outer shoal after 1986 results from a weaker total contribution of the littoral sediment transport, river export and local sources. However, the littoral transport contribution should progressively increase - rather than decrease – during the first years after inlet stabilization due to jetty impoundment. A significant decrease in the river export contribution after 1986 is also hardly supported by river discharge observations, as flood patterns in 1974-1986 were not markedly distinct from other periods (the largest flood events of the studied period occurred in 1996-1998). On the other hand, the importance of local sources for the incipient modern delta development through erosion of the O'Bril bank has been previously documented (Garel et al., 2015). In support, the volume eroded by ebb jets in the new inlet channel (1.16 Mm^3) is largely superior to the volume of the newly formed outer shoal (0.75 Mm^3) in between 1973 and 1977 (see 1973-1977 in Figure 2). This source was largely exhausted in 1986 with the complete erosion of the O'Bril bank in the studied area (see 1982 in Figure 2; see also Figure 3 in Garel et al., 2015). The two identified periods with distinct ebb shoal volume evolution (1974-1986 and later on) are therefore attributed primarily to a strong decrease of the local source contribution.

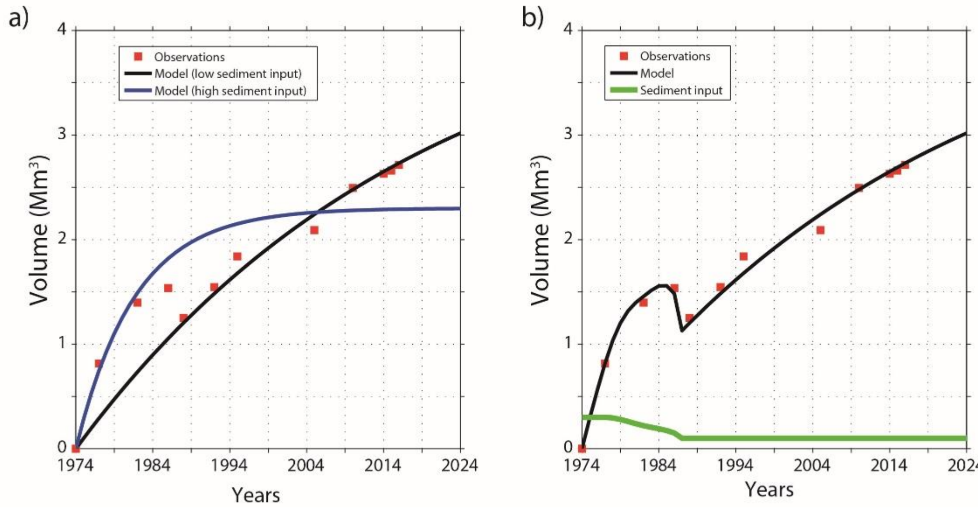

Figure 4. Volume observations (red squares, m^3) and model results (m^3) for the outer shoal area considering (a) a constant low (black line) and high (blue line) sediment input rates and (b) temporally variable sediment input rates (red line); the variable input rate is also indicated (green line, m^3/yr).

Based on the above results and discussion, the model was updated with a variable sediment input rate, decreasing during the first decade after jetty installation from a high (300,000 m^3/yr) to a low (100,000 m^3/yr) value (Figure 4b, green line). The (low) Q_{in} was kept constant after 1986, and its corresponding equilibrium volume V_e (4.5 Mm^3) was considered for model simulation. The model outputs match remarkably the observations, including the erosive period in 1986-1988 (Figure 4b, black line). Thus, an additional potential explanation for this erosive event is a strong reduction of the local supply to the outer shoal (resulting in temporally weaker sediment inputs than sediment outputs). It should be noted however that the model does not embed any erosive mechanism, but rather represents the expected volume of the shoal for each year in function of Q_{in}. The origin of this volume loss should be verified based on additional analyses (which are out of the scope of the present study).

4.2. Channel area

4.2.1. Evolution

Initially rapid sand accumulation within the channel area progressively slowed down and finally stabilized between 0.33 and 0.36 Mm^3 since 2001 (Figure 5, red line). The largest channel volume was in 2005, when the channel was almost totally obstructed by bars shallower than 2 m water depth (Figure 2). The area lost a volume of 37,200 m^3 in between 1986 and 1988 due (at least partly) to channel dredging and (probably) the general erosion observed previously at the outer shoal. More than the double of this volume deposited in the area during the following 4 years (1988-1992), indicating rapid recovery. By contrast, the 2015 dredging was associated to a smaller volume decrease (17,800 m^3) between 2014 and 2015. The reason why such a small volume loss is observed in regards to the reported dredged volume (63,000 m^3) is unclear.

Some potential explanations include large volumetric increase in the area between the 2014 survey and dredging, rapid infilling (although the 2015 survey was performed only one month after dredging) and inaccurate dredged volume report. In any case, the channel continued to erode slightly in 2015-2016, confirming that the dredging did not disturb significantly the area.

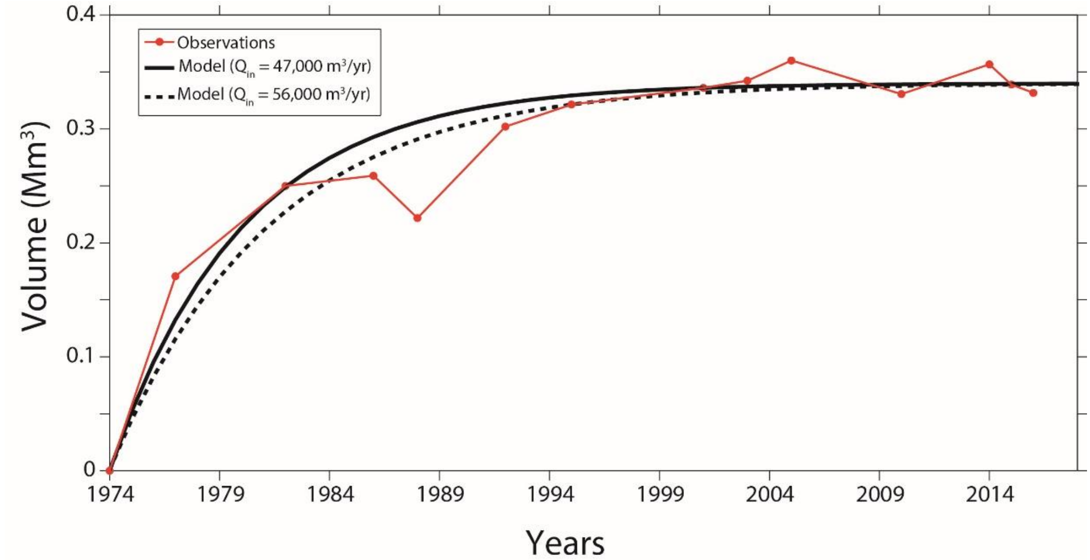

Figure 5. Volumetric evolution (Mm^3) of the channel area from 1974 to 2016 (red) and results of the model simulations with Q_{in}=47,000 m^3/yr (dashed black line) and Q_{in}=56,000 m^3/yr (solid black line).

4.2.2. Model results and dredging scenarios

A very good fit (r^2=0.92) is obtained between observations and Eq(1), with Q_{in} of 47,000 m^3/yr and V_e of 340,000 m^3 (Figure 5, dashed black line). A similar V_e and slightly higher Q_{in} (56,000 m^3/yr) are obtained (r^2 =0.97) when the erosive event observed in 1988 is discarded (Figure 5, solid black line) The model results indicate that local sources contributed less to the initial development of the channel in comparison to the outer shoal (however, this area was not allowed to expand laterally contrarily to the outer shoal area).

Based on above results, the model simulations of dredging scenarios were performed considering an equilibrium volume of 340,000 m^3, and constant sediment input rate of 56,000 m^3/yr (for which the best fit was obtained). A channel area with sand volume less than 300,000 m^3 was considered as maintained (i.e., safe for navigation). This limit was selected because it corresponds to a volume loss of 40,000 m^3 (compared to V_e) which is larger than the observed variability of the channel volume over the last 15 years and slightly below the volume dredged in 2015 (63,000 m^3, which is considered to be close to the minimum required as parts of the channel were already shallower than 2.5 m in 2016).

The model was run considering dredged volumes ranging from 40,000 to 340,000 m^3 in 2020 (Figure 6a). Yet, the selected year of dredging has no influence on the model outputs since the channel volume is at equilibrium. Results indicate that the weakest performance rate - and thus the most efficient strategy – is achieved for a dredged volume of 100,000 m^3 (Figure 6b). This operation would reduce the channel volume from 340,000 m3 (present V_e) to 240,000 m^3. To maintain safe navigation conditions (i.e. channel volume < 300,000 m^3), the subsequent dredging operation should be conducted 6 years later (Figure 6b). Thus, the annual cost of this dredging strategy would be about 83,000€ per year, considering a price of 5 €/m^3 based on examples of previous dredging in the region (Teixeira, 2016). The dredging of any other volumes would have a higher annual cost. For instance, for a dredging of 200,000 m^3, subsequent dredging would be required 10 years later, yielding an annual cost of 100,000 €/yr.

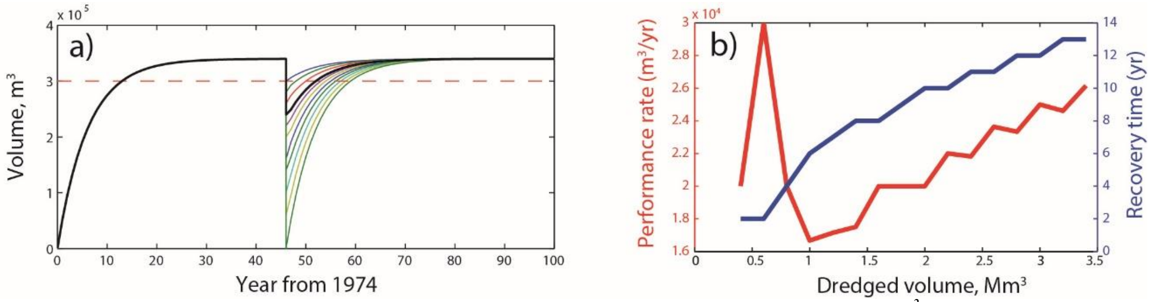

Figure 6. Model results of channel dredging simulations: a) channel volumetric evolution (m³) considering various dredged volumes in 2020 (with best scenario in thick black); b) Performance rate (m³/yr, left axis in red) and recovery time (year, right axis in blue) associated to each considered dredged volumes scenario represented in (a).

5. Conclusions

The knowledge of ebb tidal deltas morphological evolution after jetty installation is essential to plan channel maintenance strategies. In this paper, an approach for the determination of efficient dredging schemes is explored at a case study.

The method is based on a simplified version of the IRM model, applied to the outer shoal of the Guadiana ebb delta. The model successfully reproduces the volumetric evolution of this feature. However, the relatively large volume of the outer shoal is not adequate to investigate its response to small dredging-induced volume variations. Hence, the IRM model is then applied to a smaller area that includes the dredged channel in order to specifically study the response of the inlet channel to dredging operations. Volume computations based on 16 bathymetric maps indicate that this area evolved towards volume equilibrium and can be considered as a morphological element of the delta, in line with typical model applications. Calibration of the model with the volume observations yielded the average sediment input rate into the area. In turn, simulations of various dredged volume scenario were performed considering a channel volume threshold for safe navigation. Based on a dredging performance rate, the optimal strategy consists in dredging a volume of 100,000 m^3 to maintain navigability in the channel during 6 years.

Overall, the results presented in this paper suggest that the proposed approach may guide the choice of best dredging strategies at sites where sufficient bathymetric data are available. Regular (yearly) ongoing monitoring at the case study will support the validation and further development of this tool.

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