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Efficient dredging strategy in a tidal inlet based on an energetic approach

Miguel Á. Reyes-Merlo*, Miguel Ortega-Sánchez, Manuel Díez-Minguito, Miguel A. Losada

Andalusian Institute for Earth System Research, University of Granada, Avda. del Mediterráneo, s/n, 18006, Granada, Spain

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ABSTRACT

Despite relevant advances in the study of inlet morphodynamics during the last decades, there is still a lack of knowledge regarding the effects of dredging interventions into these systems and their role into the mid-term stability. In this work the case of Punta Umbría, a deeply human-altered inlet in South-western Spain, was studied. To ensure the operational capacity and safe navigation throughout the inlet, five dredging works have been done since 2002, according to three alternative navigation channels designs. Given the siltation of the dredged channels and their associated high economic and environmental impacts, regional managers are demanding a more efficient alternative in time with a longer life cycle. The objective of this study is to relate the observed morphological activity to the forcings' dynamics to quantitatively assess the morphodynamic response of the tidal inlet. To this purpose, 18 high−resolution bathymetries of the inlet were analyzed in order to compute the morphological activity of the bed. The Delft3D numerical model was implemented to reproduce the total energy flux, obtained as the sum of both tidal and wave energy fluxes. The model was then calibrated and validated with hydrodynamic measurements from a monitoring network. Results show that the spatial divergence of the total energy flux explains the observed morphological activity patterns in the inlet, where locations with larger sedimentation correspond to those with higher convergence in the total energy flux. Through the reduction of the bed slope a more efficient design was obtained, since it minimizes the divergence of the energy fluxes and hence the bed activity, in contrast to former channel designs. This methodology can be extended to other systems, and therefore improve the efficiency in time of dredging interventions in tidal inlets.

1. Introduction

The management of coastal environments is complex due to the interaction between agents and coastal features, repleted with valuable ecosystems and subjected to numerous human activities (Dyer, 1997; Savenije, 2005). Particularly, estuaries and tidal inlets are crucial both from environmental and socio-economic considerations; connections between land and open sea are fundamental for seaborne transport, fishing and recreational navigation, among others (Dean and Dalrymple, 2004; Prandle, 2009). For the maintenance and extension of these environments, dredging interventions are frequently required (Van Rijn, 2005). Apart from the associated costs and impacts, over recent decades there has been a growing concern regarding the short- and medium-term effects of these interventions, since there is a lack of deep understanding about the morphodynamic response of tidal inlets to dredging activities (De Jonge et al., 2014).

Tidal hydrodynamics and wave climate are the fundamental acting mechanisms on the morphodynamics of tidal inlets (FitzGerald and Buynevich, 2003; De Swart and Zimmerman, 2009). The assessment of long-term sediment exchange traditionally focuses on the size of the inlet cross-section and the total volume of water exchanged between the tidal basin and the open sea, being this the basis for well-known empirical relations (O'Brien, 1931; Escoffier, 1940; O'Brien, 1969; Jarret, 1976; D'Alpaos et al., 2009). The stability analysis is completed by taking into account the transport rate caused by wave action (Bruun and Gerritsen, 1966). These relationships have proven to be a useful tool for the development of conceptual models, associating the observed long-term evolution of the inlet morphology with the forcings. On the contrary, they cannot perform an stability analysis from an energetic approach or include dredging activities as a

* Corresponding author.
E-mail address: mgreyes@ugr.es (M.Á. Reyes-Merlo).

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direct human-induced forcing. Hence, there is a real need to use and combine reliable methods and tools when exploring the effects of such interventions at different spatio-temporal scales, since both a deeper evaluation of their environmental impacts and more sustainable strategies are being strongly demanded (Bray, 2008).

During the last decades relevant achievements resulted in the development of an extensive list of process-based models, applied to assess the estuarine and inlet morphodynamic evolution and equilibrium (Schuttelaars and de Swart, 1996; Lanzoni and Seminara, 2002; Stive and Wang, 2003), and the sedimentary process of dredged trenches inside these systems (Walstra et al., 1999). Considering the improvement in computing capabilities, complex 3D models were developed to study the morphological changes of these environments (Wang et al., 1995; Cayocca, 2001; Hibma et al., 2004; Bertin et al., 2005; Elias et al., 2006; Van der Wegen and Roelvink, 2008; Ridderinkhof et al., 2014; Prumm and Iglesias, 2016). These models are used to predict the estuarine and inlet response to a shift in the regime of its forcing agents (Grunnet et al., 2005), the effects of sea level rise (Dissanayake et al., 2012) and the implications of management interventions in the system (Elias and van der Spek, 2006; Moreno et al., 2010; Winterwerp and Wang, 2013; Van Maren et al., 2015; Zarzuelo et al., 2017). Some of these works analyzed the evolution of ebb-tidal deltas (Garel et al., 2014, 2015), implemented bathymetric information to predict the migration of tidal channels (Chu et al., 2013) or developed physics-based models that describe the historic morphodynamic behaviour of an estuary inlet (Karunarathna et al., 2016).

Despite previous works and to the authors' knowledge, a method that infers the bed evolution directly from the hydrodynamic magnitudes is still lacking. Hence, the objective of this study is to relate the observed morphological activity to the forcings' dynamics, in order to quantitatively assesses the morphodynamic response of the tidal inlet. This was applied to the case study of Punta Umbría, a prototypical inlet in Southwestern Spain, where the presence of many industrial and tourist activities have led to a progressive increase in the magnitude and frequency of dredging activities, especially during the last decade. This work used 18 sets of bathymetric data, taken during a 13 years period, together with a six-month set of recorded observations from a monitoring network. Through numerical modeling, the present study linked the erosion and sedimentation patterns with the divergence of both the tidal and the wave energy fluxes. Finally, a new dredging strategy was proposed as a more efficient alternative for managing the inlet in the mid-term, confronting current interventions.

2. Study area

The Punta Umbría inlet (PUI) is located in the Southwestern coast of the Iberian Peninsula, facing to the Gulf of Cádiz (Fig. 1), and it is part of the so-called Ría de Huelva estuary. The maximum transgression reached in the Flandrian (6500 BP) shaped this coastal area. Based on morphological observations, Rodríguez Vidal (1987) and Lario (1996) suggested that during this period a spit barrier arose in Punta Umbría that was cut through in ~2500 BP. The resultant natural inlet originated the channel of Punta Umbría (PU channel, Fig. 1), and favoured the formation of barrier islands, sandy capes and littoral bars. In contrast, Morales et al. (2014) documented that the most significant evolution of the sedimentary environment of the PUI occurred during the past 200 years. Observations prior to intense human interventions identified the estuary as an ebb-tidal delta system, with minor ebb channels, shoals and frontal lobes.

Two main port areas are established in the Ría de Huelva (Fig. 1): the port of Punta Umbría (P.1), inside the inlet, with fisheries and recreational activities distributed in three different wharf zones; and the Huelva harbour (P.2), inside the main channel of the Ría. The pressure of these activities forced the construction of a large jetty (Jetty I, Fig. 1), to guarantee safety access to the Port of Huelva. This infrastructure inhibited the tidal action across the ebb tidal system (Morales et al., 2014), partially blocking the eastern connection between the PU channel and the Ría de Huelva, and acting as a barrier for the predominant northwest-to-southeast littoral drift. This resulted in sediment accretion nearby the jetty and the generation of a new coastal area. The presence of this structure, in combination with the natural dynamics of the system, caused the PUI to be no longer in balance with a high tendency to close. Hence, managers built a curved jetty (Jetty II, Fig. 1) in mid 80's of the XX century at the entrance of the inlet to ensure safety access to the inland port. Different studies estimate that the long-shore sediment transport rate at the nearby coast of the inlet (up-drift Jetty II) is between $0.5-3 \times 10^5$ m^3/year (CEDEX, 2013; Reyes-Merlo et al., 2015). Since the sediment supply from rivers draining into the Gulf of Cádiz has dramatically decreased in the last century as a result of dam construction on river basins (Benavente et al., 2005), the littoral drift is the main source of sediment into the inlet. During the past decade three alternative designs of navigation channels have been sequentially dredged in the PUI: Central-drift (Cd), Down-drift (Dd) and Up-drift (Ud) (Fig. 1), with a total of five interventions (2002, 2004, 2008, 2010 and 2014). According to the records of the Regional Government through the Agencia Pública de Puertos de Andalucía (APPA), during the period 2004–2014 the total dredged volume was 4.4×10^5 m^3, with an average price of 10.39 €/m^3.

PU channel is 5.7 km long with an approximately constant width of 250 m and mean water depth of 8.5 m in the thalweg. The morphology of the PUI is characterized by a submerged sandbar leeside the curved jetty, herein referred as shoaling area or shoal (Fig. 1). This shoal is defined as the zone with water depths $\leq$1 m referred to the Lowest Astronomical Tide, in the case of the PUI $\leq$3 m referred to the Mean Sea Level (MSL). The nearshore slope in the inlet and surroundings is smooth with values $\leq$ 1/100. In the tidal flat area the material vary from fine/medium sand, with organic-rich muddy matrix, to medium/very coarse sand (Morales et al., 2014). In the inlet, medium sand (D_{50}~ 0.25 mm) dominates. Finer sands are located southwestern the entrance, changing to coarser material (including gravels) when getting closer to the mouth.

Fig. 1 also depicts the wave rose for the area. The main incoming directions are W (43%) and SW (29.2%); waves from the SE (10.9%) are relevant as well. The most common values of the significant wave height (H_s) are between 0.5 and 1 m, with peak periods from 4 to 6 s. Regarding wind, the prevailing directions are from the west-to-north sector (54.4%), dominant direction is SW (12.8%); eastern winds are also noticeable (10.3%). Usual values of wind speed are between 4 and 5 m/s. The estuary is mesotidal and the most energetic tidal constituent is the semidiurnal M_2 (12.42 h). Tidal range varies from 1.1 to 3.2 m during neap and spring tides, respectively. Depth average currents near the mouth vary from 0.9 to 0.6 m/s, depending on ebb/flood phase. According to Del Río et al. (2012), the critical threshold for the minimum storm conditions in the Gulf of Cádiz that generate damage to infrastructure or human occupation is characterized by a duration of 30 h or higher, with H_S from moderate average ($\geq$ 3.3 m) to high maximum ($\geq$ 4 m), mean or spring tide situation and average wind speed >9 m/s, approaching from the S–W and W–N quadrants. The tidal prism in the PUI is $\sim 2 \times 10^7$ m^3 (Reyes-Merlo et al., 2015). The fresh water discharge is not considered in this study, since it represents around