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Key parameters of the sediment surface morphodynamics in an estuary – An assessment of model solutions

D.M.R. Sampath *, T. Boski

CIMA - Centro de Investigação Marinha e Ambiental, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

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ABSTRACT

Large-scale geomorphological evolution of an estuarine system was simulated by means of a hybrid estuarine sedimentation model (HESM) applied to the Guadiana Estuary, in Southwest Iberia. The model simulates the decadal-scale morphodynamics of the system under environmental forcing, using a set of analytical solutions to simplified equations of tidal wave propagation in shallow waters, constrained by empirical knowledge of estuarine sedimentary dynamics and topography. The key controlling parameters of the model are bed friction (f), current velocity power of the erosion rate function (N), and sea-level rise rate. An assessment of sensitivity of the simulated sediment surface elevation (SSE) change to these controlling parameters was performed. The model predicted the spatial differentiation of accretion and erosion, the latter especially marked in the mudflats within mean sea level and low tide level and accretion was mainly in a subtidal channel. The average SSE change mutually depended on both the friction coefficient and power of the current velocity. Analysis of the average annual SSE change suggests that the state of intertidal and subtidal compartments of the estuarine system vary differently according to the dominant processes (erosion and accretion). As the Guadiana estuarine system shows dominant erosional behaviour in the context of sea-level rise and sediment supply reduction after the closure of the Alqueva Dam, the most plausible sets of parameter values for the Guadiana Estuary are $N = 1.8$ and $f = 0.8f_0$, or $N = 2$ and $f = f_0$, where f_0 is the empirically estimated value. For these sets of parameter values, the relative errors in SSE change did not exceed ±20% in 73% of simulation cells in the studied area. Such a limit of accuracy can be acceptable for an idealized modelling of coastal evolution in response to uncertain sea-level rise scenarios in the context of reduced sediment supply due to flow regulation. Therefore, the idealized but cost-effective HESM model will be suitable for estimating the morphological impacts of sea-level rise on estuarine systems on a decadal timescale.

1. Introduction

Coastal systems that integrate different geological features are continuously reshaped by the combined action of wind, waves, tides, storms, and sea-level rise (SLR), undergoing morphological evolution over different spatial and temporal scales (Reeve et al., 2016). The multiple interactions and feedback between nonlinear and stochastic physical processes result in highly complex evolutionary trends (Southgate et al., 2003). Beyond the centennial timescale, coastal systems associated with estuaries evolve due to two dominant processes: sea-level change and basin infilling due to the SLR-induced increase in sediment accommodation space (Cowell et al., 2003; Stolper et al., 2005; Towned et al., 2007; Ranasinghe et al., 2013). Back-barrier basins tend to achieve equilibrium by accommodating sediments brought in by rivers or coastal currents carrying the products of shoreface erosion (Ranasinghe et al., 2013). If the sediment supply is limited due to natural or anthropogenic causes, water depth in estuarine channels will increase, pushing the intertidal zone to an upper landward position. The consequences of this process are twofold: flooding of mudflats and salt marshes, and increased erosion (Sampath and Boski, 2016).

The Intergovernmental Panel on Climate Change (IPCC, 2013) forecasts indicate an almost unavoidable acceleration of mean sea-level rise (MSLR) during this century, forced by increased mass transfer from ice sheets to the oceans (Paolo et al., 2015; Seo et al., 2015) and the thermosteric effect. The accelerating pace (IPCC, 2013; Dangendorf et al., 2017) of this eustatic process may overcome the resilience of ecological and socio-economic systems in coastal zones. As the IPCC (2014) report emphasized, forecasting coastal evolution and subsequent impacts on natural systems and infrastructure at appropriate timescales is of paramount importance for policy formulation for integrated coastal zone management, mitigation, and adaptation actions. Thus, there is increasing interest in modelling the bathymetric evolution of estuaries in response to SLR, specifically to predict future trends over periods of ≈100 years (Lane, 2004). Many researchers have approached this problem by developing different models of varying complexities, for accurately predicting morphological evolution in estuarine systems in response to projected scenarios of SLR and acute human interventions

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* Corresponding author.
E-mail address: rmudiyanselage@ualg.pt (D.M.R. Sampath).

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in river catchments (e.g. Cowell et al., 2003, 2006; Stolper et al., 2005; Karunarathna et al., 2008; Ranasinghe et al., 2012; Reeve et al., 2016).

Sampath et al. (2015) introduced the Hybrid Estuarine Sedimentation Model (HESM), which was applied successfully to simulate sediment infilling and morphological evolution of the Guadiana Estuary during Holocene SLR. The HESM consists of two modules: a decadal timescale simulation module based on theoretical framework of Prandle (2009) and a centennial timescale of morphological evolution module, which embraced the behaviour-oriented approach of Stolper (2002). As an input for the second module, the first module was used to derive the decadal timescale spatial distribution of net accretion and erosion coefficients, which are relative to the representative sedimentation rate of the estuary. The representative sedimentation rate can be defined as observed average rate or a scenario for future prediction. For hindcasting, the average sedimentation rate can be estimated using radiocarbon data analysis of borehole samples. However, in this study, the decadal-scale module was used to predict the morphological evolution from 2000 to 2014. Prandle's (2009) analytical solutions to one-dimensional and cross-sectionally averaged shallow water wave equations and empirical knowledge of the Guadiana estuarine system were used to develop the decadal-scale morphological evolution module of the HESM approach (Sampath et al., 2015).

Equations of tidal motion were simplified for the first-order tidal simulations by neglecting the convective terms and by linearizing the quadratic friction term of the shallow water wave equation. Parameters such as the bed friction coefficient (f), power of the current velocity (N) of the erosion rate function, river discharge, fluvial sediment supply rate, and sea-level rise rate can be considered as major sources of uncertainty in this HESM approach. Given that these parameters are highly uncertain, a better understanding of the sensitivity of Sediment Surface Elevation (SSE) change to model controlling parameters is required to improve the reliability of predicted morphological evolution for given scenarios. Despite using the HESM approach to hindcast the estuarine evolution due to eustatic sea-level rise since 11,500 cal. yr BP, it is important to understand the ability of the decadal-scale module of HESM approach to simulate the short-term evolution of an estuarine system.

Thus, the objectives of this study were twofold: (1) to simulate the morphological evolution in the Guadiana Estuary over the period from 2000 to 2014, for which bathymetric data exist; and (2) to assess the sensitivity of SSE change to a set of selected controlling parameters. The selected model controlling parameters were bed friction coefficient (f), the power of the current velocity of the erosion rate function (N), and s SLR rate. These sensitivity analysis results can be used in long-term morphological evolution simulations to represent the uncertainty or possible ranges of input parameters. The present research complements the sensitivity study of SSE change to river discharge and fluvial sediment supply rate by Sampath and Boski (2016). The simulations, using the decadal-scale module of the HESM, were applied to the Guadiana estuarine system because it is affected by fluvial sediment starvation provoked by dams in the watershed (Wolanski et al., 2006) and vulnerable to SLR (Sampath and Boski, 2016).

2. Study area

2.1. Geographical and geological setting

The Guadiana River drainage basin is the fourth largest on the Iberian Peninsula, with an area of 66,960 km^2 (Garel et al., 2009). It is 810 km long and traverses extensive rural areas in Spain and Portugal, including the mining areas of the Iberian Pyrite Belt (Delgado et al., 2012). The Guadiana Estuary (Fig. 1) is located along the southern border between Spain and Portugal and extends for about 80 km from its mouth to the weir of Moinho dos Canais, where the tidal wave is virtually dampened (Silva et al., 2000; Garel et al., 2009). According to the physical definition for an estuary given by Dalrymple et al. (1992), the weir of Moinho dos Canais defines landward limit of the estuary. According to the definition for an estuary in chemical terms (Pritchard, 1967), however, Alcoutim township marks the estuary limit. Here, the salinity is 0.1‰ and distance from the mouth is ca. 50 km (Wolanski et al., 2006).

In terms of its antecedent morphology, the Guadiana palaeovalley is narrow, deeply incised (down to ca. 80 m below present MSL), bedrock-controlled, and experiencing the final stages of sediment infilling and incipient coastal progradation (Boski et al., 2008). The channel width at the mouth is 800 m and converges to 50 m at Moinho dos Canais. Channel depths range between 5 and 18 m, with the maxima generally observed in front of creeks (Lobo et al., 2002). The prograding system near to the river mouth is constituted by successive sandy barriers separated by salt marshes, configuring a wave-dominated delta (Morales, 1997). The estuarine system consists of extensive salt marsh areas on both sides of the inlet, occupying about 70% of the area of the lower estuary and corresponding to the last 9 km of the main channel. Salt marshes developed within the limits determined by maximum post-glacial transgression around ca. 7500 cal. yr BP (Boski et al., 2008), which created an extensive accommodation space for unhindered sedimentation during the Holocene.

A near-horizontal lateral tidal bar has developed between 2 and 4 m depth and is separated from intertidal areas by a steep slope step of 2 m (Morales et al., 2014). Water circulation within the estuary is almost exclusively confined within a narrow bypassing channel, which connects the river directly to the open littoral zone (Garel et al., 2009). The marine sector of the estuarine channel consists of successive meanders imposed by the hard geology of the substrate (Lobo et al., 2002; Morales et al., 2006, 2014). Curved sectors of the channel exhibit a section characterized by pools on the concave margins and lateral tidal bars on the convex ones (Morales, 1997; Morales et al., 2014).

Only about 7 km of the channel from the mouth is embedded in soft sediment (Garel et al., 2009). Bottom sediments are predominantly sands, with mean diameters of about 600 μm, except near the channel margins, where significant amounts of mud are present (Fortunato and Oliveira, 2004). Morales et al. (2014) distinguished four types of beds in the lower estuary: (1) close to the mouth, the sediment is characterized by a mean grain size of coarse sand, but with an important population of medium sand with a moderate sorting, a mesokurtic shape and slightly positive skewness; (2) further upstream above region 1, the sediment is characterized by a mean grain size of medium sand, but with abundant populations of coarse and fine sands, moderate sorting and a positively skewed distribution (leptokurtic shape); (3) another 0.5 km upstream of the previous area and near shallow regions, the abundance of fine sediment increases; and (4) further upstream sediment types exhibit extremely poor sorting, negative skewness (coarse-skewed) and a platykurtic shape.

2.2. Hydrologic and hydrodynamic setting

Prior to damming, the hydrographic regime of the Guadiana River was highly variable, characterized by low flows in summer and discharges three orders of magnitude higher (i.e. episodic floods) in winter (Garel et al., 2009). The maximum historical peak discharges were estimated to be around 11,000 m^3/s in the winter of 1876 (Rocha and Correia, 1994; Ortega and Garzón, 2009). According to Garel et al. (2009), monthly river discharge ranged from <10 m^3/s to 4660 m^3/s for the period from 1947 to 2001 (Fig. 2a, b). During the Alqueva Dam construction and filling from 1999 to 2003, fluvial discharge was below 10 m^3/s, while the summer river flow increased to 10–15 m^3/s during 2004 and 2005, then reached 20–25 m^3/s during 2007 and 2008 before decreasing again to below 10 m^3/s during 2008 and 2009 (Galvão et al., 2012). In 2002, the total dammed area in the watershed reached 89% (Gonzalez et al., 2007).

Flow at the mouth is forced mainly by tides and river discharge (Fortunato and Oliveira, 2004) and the system is strongly flood-dominated because it has limited tidal flats (Fortunato et al., 2002).