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Modelling of estuarine response to sea-level rise during the Holocene: Application to the Guadiana Estuary–SW Iberia

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ABSTRACT

This paper focuses on simulations of the morphological evolution of an estuary during sedimentary infilling that accompanied Holocene sea-level rise. The simulations were conducted using the Estuarine Sedimentation Model, which uses a behaviour-oriented approach, supported by the chronostratigraphy of the estuary's sedimentary sequence. Behaviour curves were computed to represent the relationship between the estuarine channel depth below maximum high tide and the net accretion at a given location relative to the average sedimentation rate of the estuary during the Holocene. The model was validated by comparing the observed present-day bathymetry of the Guadiana River Estuary, southeastern Portugal, with the corresponding simulated bathymetries for nine control sections across the estuary. The best fit between simulated and actual sediment surface elevations was obtained along the cross-sections in the sheltered, low-energy environments of the estuary. The accuracy of the sedimentary stratigraphy of the best-fit model was further established using 16 radiocarbon ages obtained from five boreholes in the estuary. The present approach is particularly suitable for simulating long-term morphological evolution in sheltered estuarine environments where tidally driven vertical aggradation dominates at centennial to millennium timescales. However, the accuracy of simulated sediment surface elevations and consequently the robustness of behaviour-type models based on Geographical Information System platforms can be enhanced by incorporating (i) the impacts of nearshore hydrodynamic processes and episodic flood events in highly energetic channels, and (ii) the impacts of cross-currents in meandering channel sections.

1. Introduction

An estuary is a semi-enclosed water body that is associated with a complex mosaic of ecosystems linking terrestrial and aquatic environments, including the subtidal, intertidal, and surrounding terrestrial habitats. These highly complex and diverse systems are sensitive to natural forcing, as generated by sea-level rise, and to human activities such as the development of harbours, shipping channels and recreational facilities (Lanzoni and Seminara, 2002). Estuaries are ephemeral features that during the eustatic sea-level rise of the last 15,000 yrs progressed along drowned fluvial valleys (Schubel, 1971; Perillo, 1995). Under natural sediment supply conditions, these estuaries have gradually adapted to the prevailing hydrodynamic conditions during the period of sea-level stabilization (Lanzoni and Seminara, 2002). According to Cooper et al. (2012), some evidence suggests that incised valley estuarine systems exhibit an adaptive capacity in response to sea-level rise (e.g. "keep-up" and "catch up" estuaries) while tending towards equilibrium conditions in which the local sea-level rise is balanced by the sediment accumulation (Stevenson et al., 1986; Nichols, 1989).

The morphological evolution of an estuary is the result of non-linear interactions between water, sedimentary processes, and bathymetry during both fluvial and marine flooding, which occur over a wide range of temporal and spatial scales (Hibma et al., 2004). According to Friedrichs et al. (1990), an increase in sea level in an estuarine system where the banks have curved profiles initially results in channel deepening and the expansion of accommodation space, thereby enhancing ebb and flood asymmetry (i.e., the difference between peak ebb and flood tidal currents). Consequently, more sediment from marine and/or fluvial sources enters the estuary, resulting in an increase in sediment deposition rates and a decrease in depth, thereby reducing the marine influence (Pethick, 1994; Anthony et al., 2002). If the sediment supply is unhindered, this feedback process will lead the estuary to achieve a new equilibrium state. Throughout the Holocene, estuarine systems migrated landwards in response to sea-level rise in a two-stage feedback process (Townend and Pethick, 2002): (1) horizontal retreat of the seaward margins of salt marshes and upper mudflats, and (2) vertical accretion on the newly submerged surfaces because of increased accommodation space. If there is a decrease in sediment supply and/or rapid increase in sea-level rise above the adaptive capacity of the

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system, the feedback mechanisms may not be sufficient to maintain stable water depths in an estuary. Thus, according to the classification of Cooper et al. (2012), an estuary can turn into a 'give-up' estuary from its original behaviour of either a 'keep-up' or 'catch-up' estuary.

The coastal zone occupies 18% of the world's land surface and stretches over 842,000 km (Smith, 2005). Coastal plains and lowland river valleys have always been the most populated areas (Wolanski et al., 2004) in which human activities and associated infrastructure have increased steadily over the last several centuries (McGranahan et al., 2007). Dams that control the world's major rivers have reduced sediment supply to the shoreline by up to 90% (Syvitski et al., 2005), and shorelines have been further impacted by the construction of coastal defences and by land reclamation (Townend and Pethick, 2002).

Global vulnerability analyses by Nicholls et al. (2007) and IPCC (2007) have predicted an increased vulnerability of the coastal zone to sea-level rise, increased storminess, and climate change. Indeed, the assembled records of altimetric data from the TOPEX/Poseidon, Jason-1, and Jason-2 satellite missions indicate that the average rate of sea-level rise during the period 1993–2009 was 3.4 ± 0.4 mm/yr (Nerem et al., 2010), which is double the 1.7 mm/yr rate of the twentieth century.

The cumulative result of human activities and natural pressures is enhanced erosion, habitat loss, and increased flood risk to the coastal environment (Valiela, 2006). A substantial reduction in the amount of sediment supplied to estuaries reduces vertical accretion and decreases their capacity to keep pace with sea-level rise (Ganju and Schoellhamer, 2010). Such constraints on the adaptive capacity of estuaries to sea-level rise will likely provoke a decrease in the area of wetlands and will affect their habitats in the near future. Many estuarine ecosystems have already lost part of their ability to adapt horizontally (Townend and Pethick, 2002) and vertically (Ganju and Schoellhamer, 2010) in response to sea-level rise. To accommodate these trends in coastal planning and territorial management, a better understanding of the long-term behaviour of an estuarine system is required. Adaptation strategies depend on the ability to integrate information about the geomorphology of the system, knowledge of Holocene estuarine evolution, and information about the forcing conditions such as sea-level rise and tidal conditions across a range of spatial and temporal scales (Townend, 2010). In particular, the early to mid-Holocene may be useful to understanding future sea-level change (PALSEA, 2010) because rates of eustatic sea-level rise during this period were in the order of 6 mm/yr or more (Stanford et al., 2011; Delgado et al., 2012). Such an acceleration in sea-level rise falls well within the range of recent predictions for the latter part of the twenty-first century (Pfeffer et al., 2008). However in contrast to the Holocene, impacts of rapid sea-level rise in the coming decades require consideration of substantial and widespread human intervention in coastal systems.

To complement field investigations that have described geomorphological history and sea-level change over the last 13,000 yrs in the Guadiana Estuary of southwestern Iberia (Boski et al., 2002, 2008; Delgado et al., 2012), in the present study we take a formalised yet simple and idealized model approach based on the behaviour (i.e., the morphological evolutionary trends) of that system. The specific objectives of this study are: (*i*) to simulate the sedimentary infilling of the Guadiana Estuary palaeovalley due to eustatic sea-level rise during the Holocene, and (*ii*) to evaluate model outputs against previous geomorphological and post-glacial palaeoenvironmental reconstructions based on facies interpretation and ^{14}C dating. The simulations were performed using the Estuarine Sedimentation Model (ESM), which follows a behaviour-oriented numerical modelling approach (Bruce et al., 2003) that complements process-based modelling (Townend, 2010).

2. Study area

The Guadiana River 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. It is a narrow, deeply incised (ca. 80 m below present MSL), bedrock-controlled estuary experiencing the final stages of sediment infilling, which has led to an incipient coastal progradation (Boski et al., 2008). The estuary, which is ca. 50 km long, has a maximum channel width of 550 m and depths ranging between 5 and 17 m (Wolanski et al., 2006). In 2001, the total dammed area in the watershed increased to 89% with the construction of the Alqueva dam (Gonzalez et al., 2007). Because of the consequent shortage of silt supplied by the river, there has been a rapid decrease in the area of estuarine salt marshes (Sampath et al., 2011). In addition, the construction of jetties at the mouth of the Guadiana River in the 1970s has interrupted the dominant eastward-directed longshore drift. This has resulted in a reduction in the amount of marine sediment supplied to the estuary over the last 35 yrs. The disruptive effects of the jetties are clearly manifested on the Spanish margin of the estuary, where rapid shoreline retreat at an average rate of 3 m/yr occurred between 1996 and 2005, with a recorded maximum retreat of 4.8 m/yr (Sampath, 2008).

Before the construction of the Alqueva dam, the hydrographic regime of the Guadiana River was characterized by low flows in summer and episodic flooding events in winter. The estuary exhibits a semi-diurnal, meso-tidal regime with a mean range of approximately 2.5 m. The mean neap tidal range is 1.22 m and the mean spring tidal range is 2.82 m (Garel et al., 2009), with a maximum spring tidal range of 3.88 m (Sampath et al., 2011). Tidal wave propagation in the estuary generates currents with velocities exceeding 0.5 m/s (Morales, 1997). The waves in this coastal region can be classified as medium- to low-energy waves, and in terms of frequency of occurrence, 49% of the waves represent Atlantic swells and 51% local sea waves. The mean annual offshore significant wave height is about 1 m with an average period of 4.7 s (Costa et al., 2001).

3. Methodology

3.1. Estuarine Sedimentation Model (ESM)

Hindcasting the morphological evolution of the Guadiana Estuary during the Holocene was performed using ESM. This GIS raster-based model was initially developed by Stolper (1996) and takes into account three factors: (1) changes in the rate of sea-level rise, (2) elevation-dependent accommodation space available for the deposition of sediment, and (3) the inundation-dependent vertical accretion rate of sediment (Bruce et al., 2003). In the context of large-scale coastal behaviour modelling (decades to millennia), estuarine evolution was simulated using the dominant driving factors, which are relative sea-level change, the rate of sediment supply, and tidal inundation. Although wave and river dynamics may influence sediment dynamics in the outer and inner portions of the estuary, respectively, tidal currents play a dominant role in controlling sediment transport in tidal regimes where the tidal range is greater than 2 m (Lanzoni and Seminara, 2002). Tidal inundation is strongly dependent on palaeovalley morphology, which determines the accommodation space for fluvial and marine sediments.

ESM does not explicitly take into account estuarine physical processes, such as tidal hydrodynamics, channel-shoal sediment exchange, and gravitational circulation. This implies that it is not possible to represent dynamic interactions and feedbacks that promote morphological change, because of the limited understanding/record of such processes over a centennial timescale. To partially overcome such limitations, we opted to represent estuarine sediment deposition processes using the net long-term representative sedimentation rates derived from borehole data analysis. In addition, we incorporated semi-empirical formulations given by Prandle (2009) to derive the relationships between the long-term net accretion rate coefficients and water depth below maximum high tide for defined time intervals of several centuries (see Section 3.2). The long-term net accretion rate coefficients represent