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Morphological response of the saltmarsh habitats of the Guadiana estuary due to flow regulation and sea-level rise

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ABSTRACT

In the context of rapid sea-level rise in the 21st century, the reduction of fluvial sediment supply due to the regulation of river discharge represents a major challenge for the management of estuarine ecosystems. Therefore, the present study aims to assess the cumulative impacts of the reduction of river discharge and projected sea-level rise on the morphological evolution of the Guadiana estuary during the 21st century. The assessment was based on a set of analytical solutions to simplified equations of tidal wave propagation in shallow waters and empirical knowledge of the system. As methods applied to estimate environmental flows do not take into consideration the fluvial discharge required to maintain saltmarsh habitats and the impact of sea-level rise, simulations were carried out for ten cases in terms of base river flow and sea-level rise so as to understand their sensitivity on the deepening of saltmarsh platforms.

Results suggest saltmarsh habitats may not be affected severely in response to lower limit scenarios of sea-level rise and sedimentation. A similar behaviour can be expected even due to the upper limit scenarios until 2050, but with a significant submergence afterwards. In the case of the upper limit scenarios under scrutiny, there was a net erosion of sediment from the estuary. Multiplications of amplitudes of the base flow function by factors 1.5, 2, and 5 result in reduction of the estimated net eroded sediment volume by 25, 40, and 80%, respectively, with respect to the net eroded volume for observed river discharge. The results also indicate that defining the minimum environmental flow as a percentage of dry season flow (as done presently) should be updated to include the full spectrum of natural flows, incorporating temporal variability to better anticipate scenarios of sea-level rise during this century. As permanent submergence of intertidal habitats can be significant after 2050, due to the projected 79 cm rise of sea-level by the year 2100, a multi-dimensional approach should be adopted to mitigate the consequences of sea-level rise and strong flow regulations on the ecosystem of the Guadiana Estuary.

1. Introduction

Estuarine ecosystems—including saltmarshes—provide economic, social, and environmental benefits, including distinctive biodiversity and important ecosystem services such as coastal defence, fishery support, and nutrient cycling (Veiga et al., 2006). Saltmarshes are built on the fine-grained sediment substratum of the intertidal zone and are among the most fragile coastal habitats whose equilibrium depends on a variety of anthropogenic and natural processes (Dijkema, 1987). Saltmarshes are vulnerable to rising sea levels, coastal developments, pollution due to urbanization, farming and aquaculture (Boorman et al., 2002), and any decrease in river discharge forced by damming, and intensive irrigation upstream (Wolanski et al., 2006). Since numerous observations have established climate change driven rapid sea-level rise (SLR) with increased ice sheet melting during the 21st century (Paolo et al., 2015; Seo et al., 2015; IPCC, 2014), saltmarshes can be exposed to increased hydroperiod, erosion, and long-term submergence (French, 2006).

Saltmarshes develop naturally when intertidal mud flats accumulate fine sediments to a level at which pioneer saltmarsh plant species can colonize, if conditions are suitable for their germination and establishment (Boorman et al., 2002). Development of saltmarshes and their long-term survival will therefore depend on the hydroperiod, which is ultimately controlled by the rising sea level (Day et al., 2000) and both allochthonous and autochthonous

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sedimentation (French, 2006). In contrast to the Holocene period of high sediment input, which supported a depositional coastal response to SLR, coastal systems such as saltmarshes retreat under future SLR, with reduced river flow and terrestrial sediment input due to increased damming (Plater and Kirby, 2006). In the case of the Guadiana estuary saltmarshes, fine-grained sediment is mainly derived from fluvial sources; thus river discharge is critical for sustaining saltmarsh habitats. Influence of wind waves is insignificant in saltmarshes as waves are typically attenuated by littoral spits or barrier islands (Morales et al., 2006) and vegetation canopy (Möller and Spencer, 2002).

The environment of an estuarine system can be degraded when the system is poorly flushed due to reduced freshwater inflows during periods of drought or flow regulations by dams (Mateus et al., 2008). The discharge of the Guadiana River is regulated by more than 100 dams, including the Alqueva dam, which was completed in 2002 and now forms the largest fresh-water reservoir in Europe (Dias et al., 2004). Low river discharge (<20 m^3/sec) and pulse-like, unseasonal river flows are characteristic of the post-dam phase of the Guadiana River (Wolanski et al., 2006). These dams effectively trap sediments eroded in the catchment instead of being transported to the coastal system. The present area of the saltmarsh habitat is less than the mid-late Holocene period (Boski et al., 2008) when, following the maximum post-glacial transgression, a progressive infilling of the estuarine embayment occurred.

The most widely used strategy to mitigate the negative consequences of river runoff regulations is based on defining environmental flows (EF), which are the minimum water requirements left in a river system—or released into it—for the specific purpose of managing the conditions and functioning of that ecosystem (King et al., 2003). The objective of EF is to mimic components of the river's natural flow variability, including the magnitude, frequency, timing, duration and rate of change, and predictability of flow events (Arthington et al., 2006). The main types of flow-assessment approaches are: (1) hydrological; (2) hydraulic rating; (3) habitat rating; and (4) holistic (Tharme, 2003). The first approach is based on long-term hydrological time-series data and the utilization of a summary of flow statistics—which may or may not be ecologically relevant—to define suitable flows, often for fish habitats (Gopal, 2013). Probably because of the time-scale of the phenomena concerned, no EF assessment methods focus on the fluvial discharge required to maintain saltmarshes and do not consider impacts of SLR.

The adequacy of the approach that determines EF for rivers in Portugal has been challenged (e.g., Galvão et al., 2012; Chícharo et al., 2009). For the Guadiana River, EF is 2 m^3/sec, during the dry season (Wolanski et al., 2006). Thus, the Guadiana estuarine system is likely to be affected by an increased rate of sea level and starved fluvial sediment due to the construction of large dams (Sampath et al., 2015). Therefore, this study is focused on a model-based assessment of the role of river discharge in maintaining the depth of the intertidal zone where the saltmarshes can thrive. The main objectives of this study are twofold: (1) to simulate the morphological evolution of the Guadiana estuary under the updated (Hunter, 2010) 5% and 95% limit time-series of the A1FI SLR scenario (IPCC, 2007) and reduced river discharge due to dams; and (2) to assess the sensitivity of the base flow of the river discharge to morphological evolution, as a preliminary estimation method of the EF within the holistic approach (King et al., 2003).

2. Study area

2.1. Hydrological and hydrodynamic setting

The Guadiana estuary (Fig. 1) is located along the southwestern border of Portugal and Spain, in a semi-arid region with a Mediterranean climate (Faria et al., 2006). According to Garel et al. (2009), the river inputs that flow into the Guadiana estuary are highly variable; at a seasonal and inter-annual scale, they produce severe droughts and episodic floods in the river basin (Fig. 2a). The monthly river discharge ranged from <10 m^3/sec to 4660 m^3/sec for the period of 1947–2001, with 50% of the recorded values were less than 110 m^3/sec (Garel et al., 2009). The mean river flow measured at Pulo do Lobo (ca. 85 km upstream from the river mouth) during the summer reached 20–25 m^3/s during 1997 and 1998, before closing of the Alqueva Dam, and decreased to below 10 m^3/sec from 1999 to 2003, during the Alqueva Dam's construction and filling Galvão et al. (2012). Following the dam's completion, summer river flow increased to 10–15 m^3/s during 2004 and 2005, reached 20–25 m^3/s during 2007 and 2008 and declined back below 10 m^3/sec during 2008 and 2009 (Fig. 2b). Currents observed in the estuary result from tides and river flow (Fortunato and Oliveira, 2004) and, because the system has few tidal flats (Fortunato et al., 2002), it is notably flood-dominated. 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 3.5 m (Fortunato and Oliveira, 2004). Tidal waves in the estuary generates currents with velocities exceeding 0.5 m/s (Morales, 1997).

2.2. Sediment transportation

On the Portuguese margin, saltmarshes are sheltered by an ebb-tidal delta that drains into the estuarine channel, while the eastern margin is a mosaic of barrier islands and spits separated by extensive saltmarshes that mainly drain to the sea through the Carreras tidal inlet (Morales et al., 2006). According to the overall sediment budget of the Guadiana estuary, estimated bed load and suspended load are about 43.96 and 57.9×10^4 m^3/yr, respectively (Morales, 1997). The estuary may have trapped approximately 10% of the total fluvial sediment contribution ($0.5–1.5 \times 10^6$ t/yr) to the littoral zone from 1980 to 2000 (Portela, 2006). Sediments transported during an exceptional flood contained higher inorganic fraction and the construction of the Alqueva dam will attenuate these flood events, decreasing the amount of sediment supplied by the river to the coastal zone in the future (Caetano et al., 2006). Under low flow conditions ($Q_R < 50$ m^3/sec), the Guadiana Estuary can be considered well-mixed in salinity (Fortunato et al., 2002) and the suspended sediment concentration (SSC) is 10 mg/L at the mouth and about 100 mg/L in the middle estuary; where maximum turbidity is observed (Garel et al., 2009). Suspended sediment is predominantly composed of phyllosilicates, represented principally by illite (>50%), kaolinite, and chlorite (Machado et al., 2007). The fluvial sediments exported from the estuary mix in the proximity of the river mouth with sediments transported by longshore drift (Gonzalez et al., 2004). Tidal currents carry this sediment back into the estuarine system (Boski et al., 2008).

2.3. Bed sediment types

Well sorted medium sand (quartz, feldspar, bioclasts, plus lithic components of diverse origin) lies at the lower estuary (Lobo et al., 2004). Only about 7 km of the channel from the mouth is composed of soft sediment (Garel et al., 2009). Channel bottom sediments are predominantly sands, except in the intertidal zone flanks, which are covered by muds (Fortunato and Oliveira, 2004). Morales et al. (2014) distinguished four types of beds in the lower estuary (Table 1). The distribution of sediment grain size (Fig. 3) within the study area is based on data provided by Boski et al. (2002, 2008)