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Case study

Cellular automata to understand the behaviour of beach-dune systems: Application to El Fangar Spit active dune system (Ebro delta, Spain)

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ABSTRACT

Coastal dunes are sedimentary environments characterized by their high dynamism. Their evolution is determined by sedimentary exchanges between the beach-dune subsystems and the dune dynamics itself. Knowledge about these exchanges is important to prioritize management and conservation strategies of these environments. The aim of this work is the inclusion of the aeolian transport rates obtained using a calibrated cellular automaton to estimate the beach-dune sediment exchange rates in a real active dune field at El Fangar Spit (Ebro Delta, Spain). The dune dynamics model is able to estimate average aeolian sediment fluxes. These are used in combination with the observed net sediment budget to obtain a quantitative characterization of the sediment exchange interactions. The methods produce a substantial improvement in the understanding of coastal sedimentary systems that could have major implications in areas where the management and conservation of dune fields are of concern.

1. Introduction

The evolution of a coastal dune system can be characterized by the changes in its sand volume and these are determined in turn by the sediment exchanges between the beach-dune and dune-dune sub-systems. All these sand inputs and outputs generate a net sediment budget in a time interval. A good methodology for assessing the net sediment budget is dune field surveying (Andrews et al., 2002; Anthony et al., 2006; Barrio-Parra and Rodríguez-Santalla, 2014; Sánchez-García, 2008; Saye et al., 2005) This method is sufficient to characterize the beach dune interaction in the case of foredunes that act as aeolian sediment sinks (Anthony et al., 2006; Bauer and Davidson-Arnott, 2002; Delgado-Fernandez and Davidson-Arnott, 2011; Delgado-Fernandez, 2011; Richter et al., 2013; Saye et al., 2005; Vespremeanu-Stroe and Preoteasa, 2007). In dune systems with more complex sediment transfers (i.e. active dune fields with remote sediment sources and curvilinear shorelines) the surveying frequency necessary to characterize the beach-dune interactions can be very high and should be combined with estimates of aeolian sediment inputs and outputs and erosion rates (where erosion rates represent a significant sediment output), making field data collection more demanding, or even unfeasible, and therefore insufficient to obtain the sediment transferences rates. Under these circumstances the application of modelling techniques is required to characterize the sediment inputs and outputs that generate the observed net sediment budget (Barrio-Parra and Rodríguez-Santalla, 2014; Barrio-Parra et al., 2013).

Cellular automata models are the most representative of the behaviour oriented dune dynamic models (Baas and Nield, 2010; de Castro, 1995; Katsuki and Kikuchi, 2011; Katsuki et al., 2011; Nishimori and Tanaka, 2003; Werner, 1995). They represent dune morphology at a given time by a mesh of cells with local surface elevation values given by a Digital Elevation Model (DEM, h(x,y,t)). The dune dynamics is represented by the saltation and avalanche algorithms at each time step. The saltation algorithm represents how a volume of sand (a height of a cell) is eroded in a cell and reallocated at a downwind distance. The avalanche algorithm represents the gravitational sand displacement that occurs when the repose angle is exceeded. As suggested by Barrio-Parra et al. (2013), cellular models should introduce wind data as an input parameter into the saltation process to reproduce real dune systems dynamics. The model of Barrio-Parra and Rodríguez-Santalla (2014) incorporates algorithms to introduce a variable wind regime and field specific transport equations to reproduce real dune field dynamics. They also present a calibration methodology based on the analysis of the geomorphology resulting of the application of several combinations of phenomenological variables to the model. The combination of phenomenological variables which

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better reproduces the observed dune final state is considered as calibrated parameters. The simulation results obtained with calibrated parameters can be used to estimate aeolian sediment input and output rates. The aim of this paper is to propose and implement a methodology that integrates the dune dynamics modelling using cellular automata to estimate the sediment exchange rates in complex beach-dune systems.

2. Material and methods

2.1. Study area

El Fangar Spit is located in the North of the Ebro River Delta on the Spanish Mediterranean coast, approximately 170 km southwest of Barcelona (Fig. 1). El Fangar spit shoreline evolution has shown a dichotomous reshaping trend. The longshore sediment transport gradient increases along the middle-south shoreline, eroding the coast. The energy dissipation due to the change in the shore orientation facilitates the deposition of the eroded sediment on the north coast, which has shown a considerable accretion (Rodríguez-Santalla, 1999, 2000). Fig. 1 shows a conceptual model of the beach-dune sediment exchange. The coast recoil produces the erosion of an active dune system, while the accretion on the north coast of El Fangar Spit could increase the aeolian sediment supply to the dunes in agreement with the fetch effect model for sand supply to foredunes (Delgado-Fernandez and Davidson-Arnott, 2011; Delgado-Fernandez, 2010, 2011).

The active dune field has an extension of about 6 km and is located on the external coast of the Spit. The migration of the dunes is related to the predominant wind direction of 315° (Rodríguez-Santalla et al., 2009). The inner coast of the spit is flooded episodically during meteorological tides. This phenomenon is the cause of the existence of a salt crust in the spit plain that acts as a non-erodible base through which the active dune field can migrate to the south east. Part of the dune field is usually eroded by wave action during storms. This interaction between the dune and beach systems involves the incorporation of eroded material to the alongshore transport system. Part of the aeolian input from the north accretive coast is retained by the sand dunes, allowing the persistence of the dune system. The dune migration process and the erosion of the dunes by waves are sediment outputs of the system that complicate the conceptual model of beach dune sediment exchange in El Fangar Spit. Until now, there have been no estimates of the beach-dune aeolian exchange that consider the sediment exchange between zones of the dune field and the sediment output due to wave action.

Considering the shape and height of the dunes, the dune field is divided into four different areas (Rodríguez-Santalla et al., 2009; Sánchez-García et al., 2007) (Fig. 1). The North zone (Zone 1, 10 ha) has the southern limit at the coast point where the erosive trend changes into accretive. This zone has small isolated barchans (1–2 m height) and configures the feeding region of the dune field. The adjacent zone (Zone 2, 18 ha) has larger barchanoids ridges, 2–3 m high, with lower migration rates. The third zone (16 ha) has higher dunes with heights up to 5 m and morphologies that vary between barchanoid and seif dunes. Zone 4 (26 ha) has barchan dunes of 2.5 m average height, with less activity than the dunes in Zone 1. The morphological differences are due to differences in the sediment budgets (Pye and Tsoar, 1990). The sediment exchanges between these zones and between the sediment sources and sinks have not been characterized as yet. At this point, the cellular model and the calibration results of Barrio-Parra and Rodríguez-Santalla (2014) are useful tools in order to obtain reasonable estimates of these transport rates. The interest of this dune system lies in that it represent the only mobile dune field along the Ebro Delta coast, and is at risk of being eroded by waves after the modification of the shoreline due to the installation of a coastal

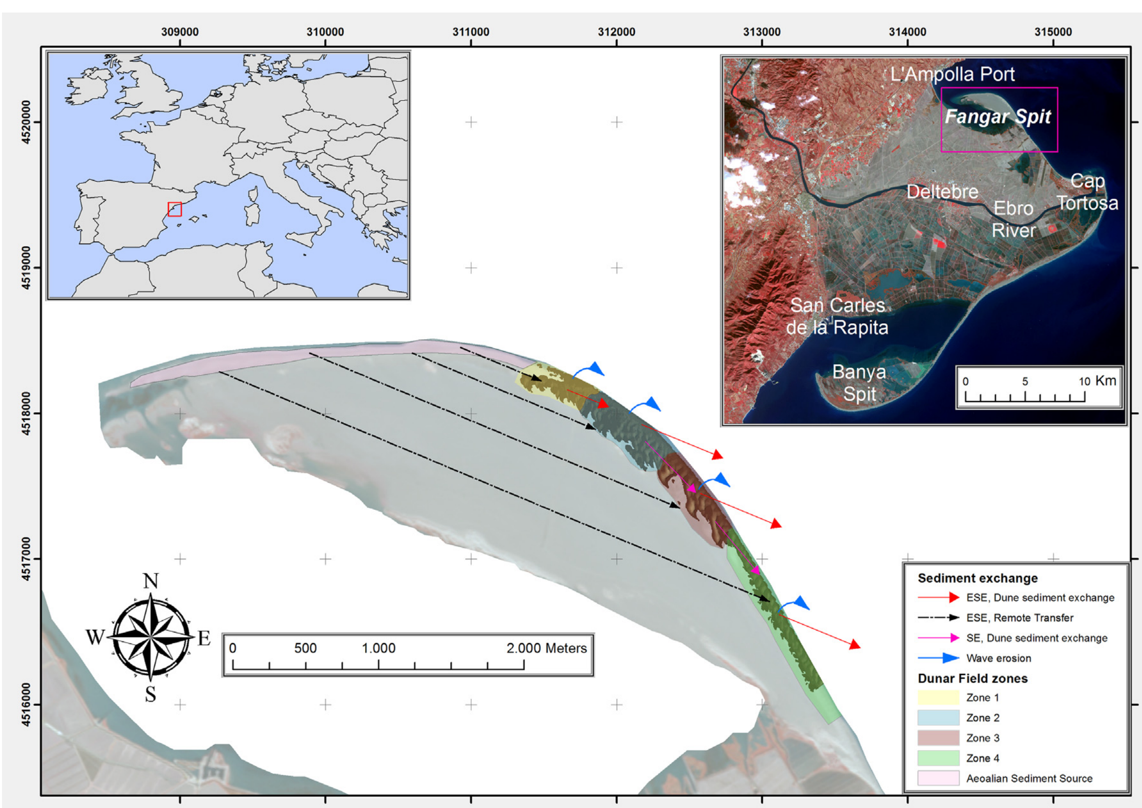

Fig. 1. El Fangar Spit dune system location, zoning and conceptual model of dune-beach sediment interaction.