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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)

Fernando Barrio-Parra [a,*], Inmaculada Rodríguez-Santalla [b]

[a] Department of Energy and fuels, Polytechnic University of Madrid, Superior Technical School of Mines and Energy, 28003 Madrid, Spain
[b] Department of Biology and Geology, Physics and Inorganic Chemistry, Superior School of Experimental Sciences and Technology, Rey Juan Carlos University, 28933 Móstoles, Madrid, 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

* Correspondence to: Polytechnic University of Madrid, Superior Technical School of Mines and Energy, M III Building, Office 431, Alenza St., 4, 28003 Madrid, Spain.
E-mail address: fernando.barrio@upm.es (F. Barrio-Parra).

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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

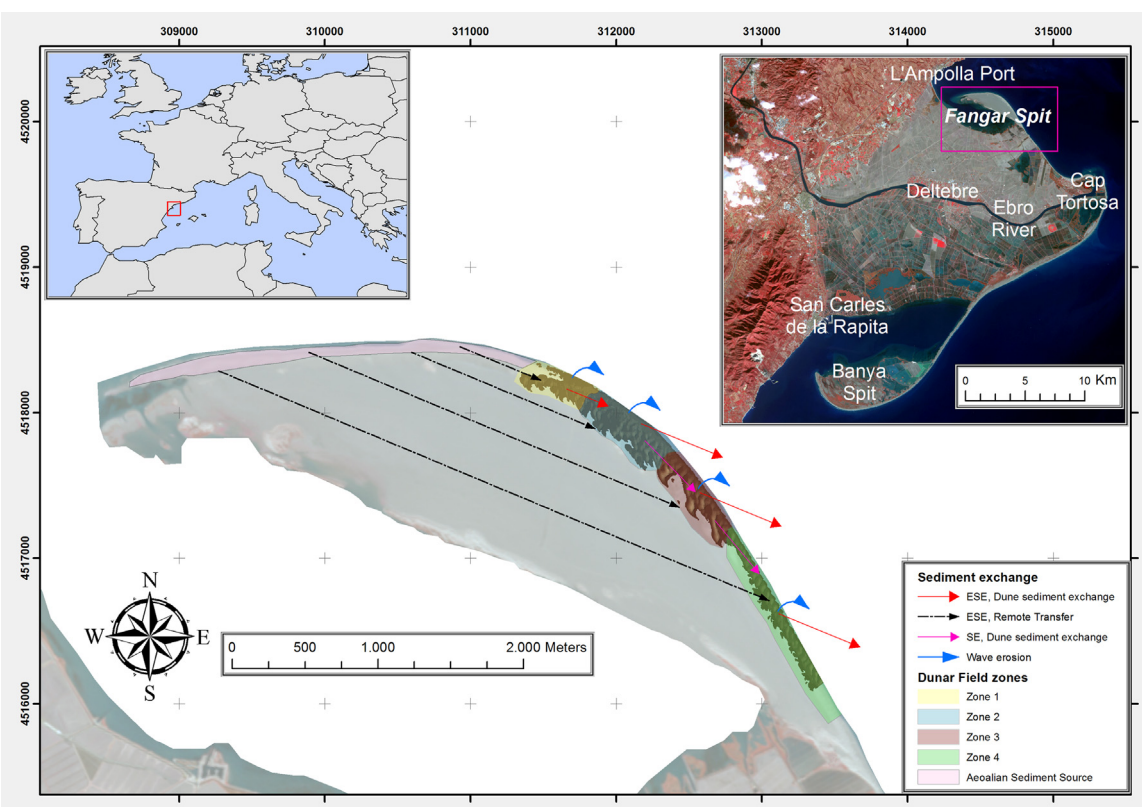

Fig. 1. El Fangar Spit dune system location, zoning and conceptual model of dune-beach sediment interaction.

defence at the start of the Spit (Rodríguez-Santalla et al., 2011).

2.2. Data set

In order to estimate the aeolian sediment inputs and outputs at each zone of the dune field, the model of Barrio-Parra and Rodríguez-Santalla (2014) is applied. This model requires topographic information of the dune field at the start and end of the simulation period and data on wind intensity and direction. The active dune system of El Fangar spit was monitored by topographic surveys during the period 2005-2006 with a Differential Global Positioning System (DGPS). Data was acquired on foot, taking first topographic data of the dune perimeter and then making transversal and longitudinal profiles along the dune crest during periods of calm wind. The data was processed in order to delete points with height estimation errors higher than 20 cm. The points were employed to create Triangulated Irregular Network (TIN) Digital Elevation Models (DEMs) (Rodríguez-Santalla et al., 2009; Sánchez-García, 2008). The topographic data base employed in this study was built by Sánchez-García (2008) and consists of seven DEMs that cover the period from April 2005 to October 2006. A total of six simulations per dune field zone are set. The start and end dates for each simulation is summarized in Table 1. The start date of each simulation coincides with the date of the obtainment of the topographic data. The simulation ends at the acquisition date of the next DEM. The input and output aeolian rates obtained with the model are averaged for each zone and expressed in yearly rates.

TINs were transformed into an ASCII raster format in order to be introduced as initial and final DEMs in the model. A 0.7 m cell size was set to apply the values of the phenomenological variables obtained by the calibration of Barrio-Parra and Rodríguez-Santalla (2014). The ASCII DEMs were divided in agreement with the four zones in the dune field defined with geomorphological criteria. With the aim of reducing the area without dune field information (plain surface), the DEMs in zones 1 to 3 were rotated 45°, and 55° in zone 4 counterclockwise (wind data was consequently corrected). For each zone, all the DEMs cells were aligned to be comparable between surveys. A base height layer was created via sampling the interdune spaces in the DEMs and interpolating the punctual data with the inverse weighting method. To obtain the volume of sand available at each cell, all DEMs were corrected by the base surface layer.

Wind data (intensity and direction) was obtained from a meteorological station located in the Port of L'Ampolla, situated about 6 km north of the dune field (Fig. 1). Wind data is available with a frequency of one record each ten minutes. To reduce the number of time steps and set the same data frequency as was used in the calibration procedure, the wind data records were averaged to obtain a frequency of ten daily data. The mean wind conditions and the number of time steps for each simulation are summarized in Table 1.

2.3. Dune model description

The model has the adaptations needed to be implemented in dune fields with wind regimes of variable direction (Barrio-Parra et al., 2013): (1) introduces the eroded volume as a function of the wind intensity and cell height, (2) evaluates if a cell is exposed to a wind or not due to its relative aspect to the incident wind and (3) estimates the location of the eroded sand in the X and Y axes in function of the wind intensity, direction and eroded cell height. Both temporal and spatial scales of the model make it capable of reproducing the morphological evolution of a dune field. The model represents the migration of the pre-existing sand in a dune field, taking as a boundary condition that sand does not enter into the system at each time step. The main assumption of the model is that the volume differences between the initial, final modelled, and final measured dune field DEMs allows a reasonable estimation of the sediment input and output that generate the observed sediment budget (Fig. 2). In order to increase the velocity of the model, the algorithms have been programmed into an object oriented framework in a Matlab® environment. The equations that relate wind records with aeolian transport were derived empirically for the study area by Sánchez-García (2008).The repose angle is assumed to be 35°, the wind data frequency is 144 daily records and the DEM cell size applied is 0,7 m. These conditions are the same as those used in the model calibration performed for the same area (Barrio-Parra and Rodríguez-Santalla, 2014) and therefore, the values of the phenomenological variables (involved in the rules that prescribe the erosion and motion of the sand (Diniega et al., 2010)) obtained during this calibration ($a=0.5$, $b=1$, $d=2$ and $e=2$) are applicable in this study.

2.4. Sediment exchange rates estimation

To estimate the sediment exchange rates between the different subsystems (Fig. 1) a box diagram is considered (Fig. 3). The sediment exchanges are obtained from the adjustment of the different input and output sediment rates from each zone, setting the sediment balance under the following assumptions:

1. The aeolian flux has a SW direction, in agreement with the higher intensity and frequency winds from 315° (Rodríguez-Santalla et al., 2009)
2. The average aeolian sand fluxes obtained as the result of the simulations are representative of the study period at each zone.
3. The principal sediment source for a Zone of the dune field (Z_n) is its precedent Zone (Z_{n-1}).
4. The rate at which the waves remove sand from the dune system is estimated as the mismatch of the observed sediment budget with the sediment budget obtained as the average aeolian in and out rates.
5. If the sediment output from Z_{n-1} is less than the sediment input in Z_n, then Z_n receives sediment from a remote sediment source (Fig. 1) equal to the difference between the aeolian sediment input in Z_n and the sediment output in Z_{n-1}.
6. The aeolian sediment output in Z_4 is transported to the sea.

Table 1
Initial and final simulation dates, mean wind conditions and number of time steps.

Simulation	Initial date	Final date	Mean wind intensity (m/s)	Mean wind direction (°)	Number of time steps
1	April 18, 2005	September 30, 2005	3.66	230.31	3422
2	September 30, 2005	November 01, 2005	3.53	235.42	4085
3	November 01, 2005	December 11, 2005	4.24	293.28	830
4	December 11, 2005	March 04, 2006	3.61	283.89	1722
5	March 04, 2006	April 09, 2006	5.68	249.67	507
6	April 09, 2006	October 10, 2006	2.59	196.34	3774

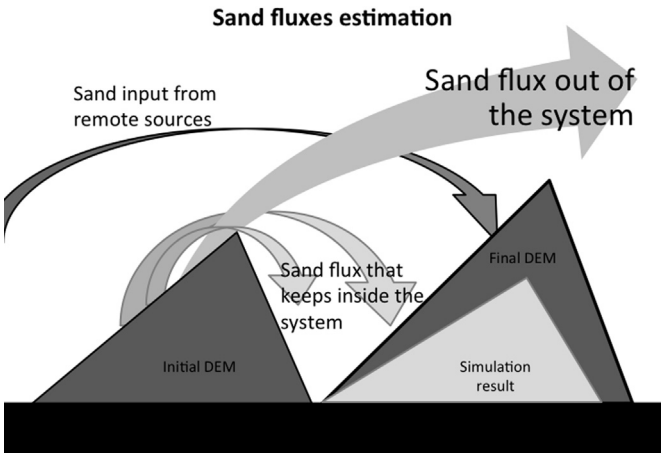

Fig. 2. Scheme of how the volume differences between the initial DEM of the dune system, the volume obtained with the simulation and the measured final DEM are employed to estimate the aeolian sediment input and output rates.

7. The aeolian transport to the sea is estimated as the difference between the average aeolian output in Z_n and the sediment exchange to Z_{n+1}.
8. The sediment input at Z_1 comes from the sediment source situated at the north beach of the spit.

3. Results

Fig. 4 shows examples of the DEMs obtained at each Zone of El Fangar dune system. These figures also show the differences between the simulation results and the observed final dune state. The *X* and *Y* axis are in cell units, *Z* scale is in metres. The observed initial and final volumes, the aeolian sediment input and output rates and their respective lower and upper limits are summarized in Table 2. The limits are based on the sensitivity of the volume input estimation to the phenomenological variables values shown in Barrio-Parra and Rodríguez-Santalla (2014). For the phenomenological variables employed, the lower limit of the influx estimation is 50% lower than the model estimation and the upper limit 60% higher. The model estimates at each simulation are employed to obtain average sediment input and output rates. These average rates are used to estimate the sediment exchange rates. Table 2 shows several negative values, that are supposedly due to a sediment exit in the system not related with aeolian transport (wave erosion in the study site) and, therefore, they are not considered in the average aeolian sediment input and output rates. The resulting average aeolian rates are shown in Fig. 5. The aeolian exchanges and the wave erosion rates are graphically represented in Fig. 6.

Fig. 3. Flow diagram employed to estimate the sediment exchange between Zones in the dune field (Z_n), aeolian catchment from remote sediment sources, and the loss by aeolian transport toward the sea and wave erosion.

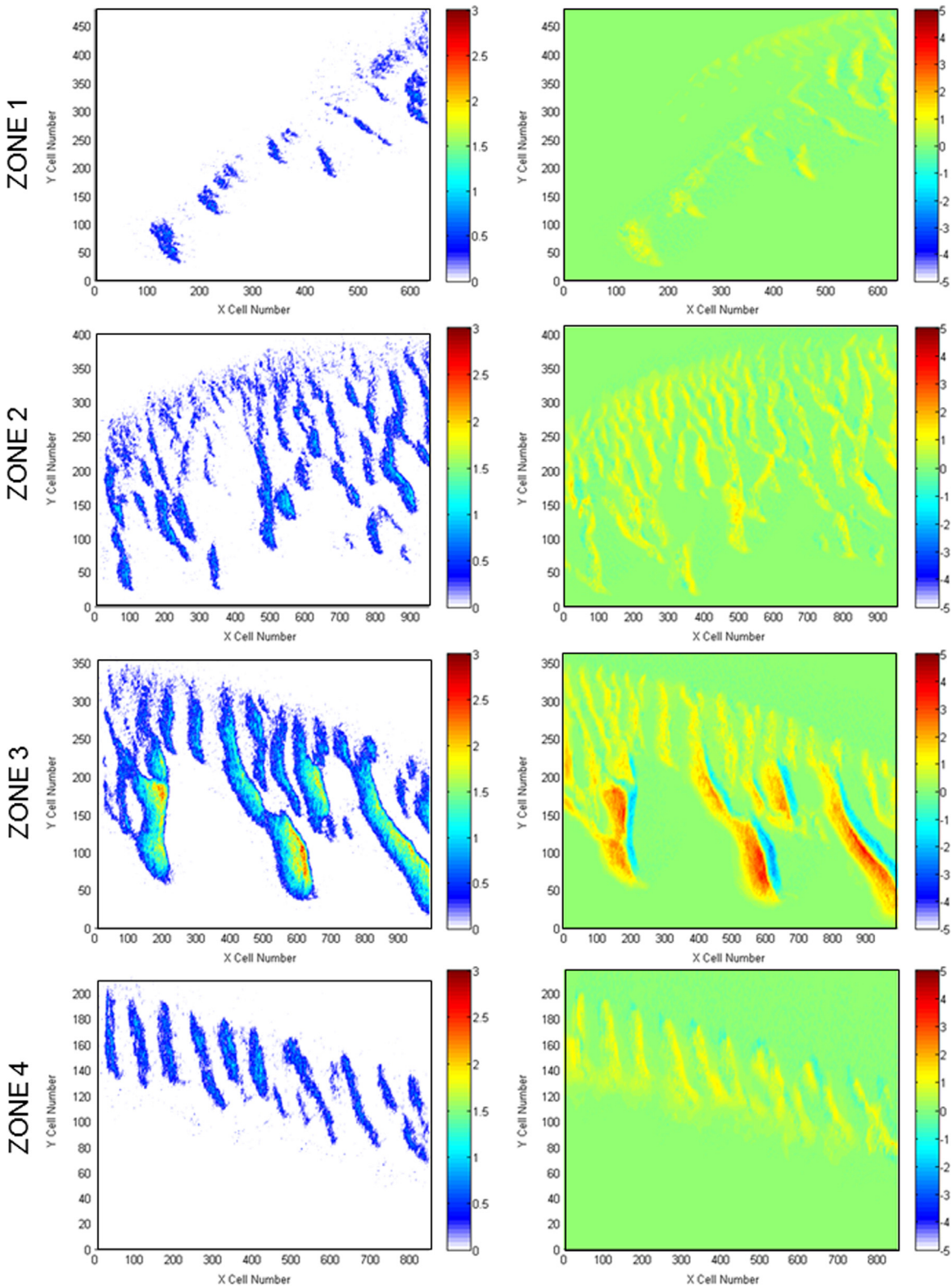

Fig. 4. Final DEMs obtained in Simulation 5 and the deviations with respect to measured final states (right column) at each zone of the dune field. Scale bars are both in metres.

4. Discussion

The zone of the dune system with the highest volume of sand is Zone 3, followed by Zone 2. On average, both Zones 1 and 3 had a positive sediment budget, while in Zones 2 and 4 it was negative. The whole system has shown a positive sediment budget trend due to the sediment gain in Zone 3.

Fig. 4 shows the differences between measured and the final state obtained in the simulation 5. In most cases, there is a predominance of positive values. This can be interpreted as that initial sand has reached the final observed position with a volume deficit. This is because the model does not consider sand trapping in the

Table 2
DEM volumes and input and output aeolian sediment rates obtained with the model for each zone and simulation period. Shaded cells indicate values not considered in the calculation of aeolian transport rates.

				Input rate ($10^3 m^3$/yr)			Output rate ($10^3 m^3$/yr)		
Zone	Simulation	Initial Volume (10^3 m^3)	Final Volume (10^3 m^3)	Lower estimation limit	Model estimation	Upper estimation limit	Lower estimation limit	Model estimation	Upper estimation limit
1	1	17.17	7.44	0.16	0.32	0.51	21.34	21.84	22.00
	2	7.44	10.75	18.92	37.84	60.55	0.00	0.17	19.09
	3	10.75	9.70	2.05	4.10	6.57	7.12	13.69	15.74
	4	9.70	11.15	5.01	10.03	16.04	0.00	3.61	8.63
	5	11.15	9.62	38.66	77.32	123.72	0.00	92.88	131.54
	6	9.62	13.62	4.12	8.24	13.18	0.00	0.29	4.41
2	1	65.75	40.48	-2.82	-5.65	-9.03	59.28	50.25	47.42
	2	40.48	46.78	8.17	16.34	26.14	0.00	12.43	20.60
	3	46.78	37.43	-6.89	-13.77	-22.04	50.49	28.46	21.57
	4	37.43	54.13	20.58	41.16	65.85	0.00	8.41	28.98
	5	54.13	50.73	40.23	80.45	128.72	274.48	403.20	443.43
	6	50.73	52.72	3.06	6.12	9.79	0.00	1.54	4.60
3	1	80.31	68.98	-3.42	-6.83	-10.93	29.16	18.23	14.81
	2	68.98	75.07	36.12	72.23	115.57	0.00	2.76	38.88
	3	75.07	99.61	119.49	238.98	382.37	0.00	15.06	134.55
	4	99.61	84.45	-27.14	-54.28	-86.85	99.24	12.40	-14.74
	5	84.45	84.05	263.83	527.67	844.27	0.00	531.74	795.58
	6	84.05	78.42	-5.18	-10.37	-16.59	17.39	0.80	-4.39
4	1	16.95	12.05	1.13	2.27	3.63	9.48	13.11	14.24
	2	12.04	14.62	21.43	42.85	68.56	0.00	13.45	34.88
	3	17.37	14.65	1.13	2.27	3.63	23.45	27.08	28.21
	4	14.65	14.19	4.28	8.55	13.68	0.00	10.60	14.87
	5	14.19	13.11	48.07	96.14	153.83	0.00	107.13	155.20
	6	13.11	14.62	1.91	3.81	6.10	0.00	0.81	2.71

windward side. Zone 3 has negative areas on the leeward side. This is due dunes are high enough to present significant sediment capture in the shadow zone. These processes are not considered in the model, which could be the subject of further research.

Zone 1 has shown an aeolian input (23.000 m^3/yr) from the beach with north orientation. At the end of simulations periods 1 and 5, it is observed the generation of protodunes due to the sediment deposition produced by the accretion of the beach. At the north coast of El Fangar Spit the wave conditions are less energetic because of its orientation relative the wave main direction (Jimenez, 1996; Jimenez et al., 1997). These conditions cause a reduction of the longshore sediment transport (LST), easing the reduction of the LST gradients and the beach accretion and consequently the increment of the beach surface where the wind can act and transfer sediments through aeolian transport.

For Zones 2 and 3, the model predicted negative sediment input rates, which is interpreted as a sediment output produced by wave erosion. These zones present the biggest dunes and are the most exposed to the most energetic waves coming from the East (Jimenez et al., 1997). These zones have an important sediment input by means of remote transfer from the north beach. The greater height in Zone 3 dunes makes them more efficient in

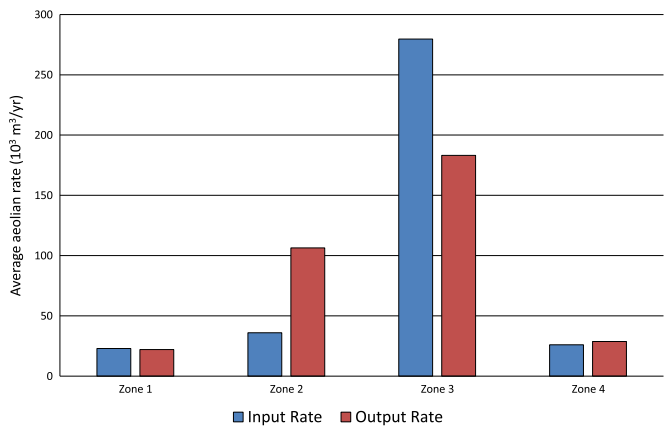

Fig. 5. Average aeolian sediment input and output rates.

capturing sand, explaining the difference in entry rates to Zone 2.

At zone 4, the sediment budget model predicts a null entry of sediment from remote sources, suggesting that the sole source of sediments is Zone 3. During the study period, this sediment input was lower than the sediment output to the sea.

The aeolian raw sediment flux estimated by Sánchez-García (2008) is 232 m^3/m yr for a mean transport direction of 149°. The length of the perpendicular section of the Spit in that direction is about 1500 m. So, the raw aeolian transport is about 350 10^3 m^3 yr^{-1}. Adding up the sediment entries from the north oriented beach in Zones 1–3 obtained with the model, a total input flow of $309 \cdot 10^3$ m^3 yr^{-1} is reached, which is consistent with the estimation of Sánchez-García (2008). Transport rates obtained are very high, indicating an annual sediment mobilization volume greater than the sand volume stored in the system. Thus the current sediment retention capacity is very low in agreement with the low Sand Trapping Efficiency between the 2% and 4% obtained by Sánchez-García (2008).

As far as our knowledge, there are no applications of similar methods in other regions, so that our results cannot be compared. While transport rates obtained with the model are consistent with experimental measurements in the study area, the results should be compared with other experimental measurements to validate the quantitative estimates. The acquisition of field data for model validation is also conditioned by the limitations exposed in Section 1. Despite this, transfer rates obtained allow us to analyse the semiquantitative functioning of the system. It has been found that despite the large amount of sand moving in the transport system by wind from the north, a very small quantity is retained. Sand losses are due to the low uptake of the wind flow through the dunes and the high rates of wave erosion. Therefore, conservation measures should be aimed at capturing the aeolian flow inside the spit, so that the dune inward surface is increased, and at reducing the coastal retreat. With this the losses caused by wave erosion could be compensated and the aeolian transport catchment efficiency increased.

5. Conclusions

The application of the dune dynamic model allows obtaining an estimate of the annual average aeolian sediment input and output in each area of a real active dune system. These flows are useful to describe the sediment exchange interactions that determine the evolution of a complex system, improving the knowledge of its behaviour.

The methods used in this work are helpful to detect the most important mechanisms for maintaining the system, as well as the main threats to it, giving information which facilitates the prioritization of management and conservation strategies. At El Fangar dune system, methods have allowed to characterize the importance of aeolian remote sediment transferences. Therefore, a conservation measure could be the installation of aeolian sediment trapping systems within El Fangar spit.

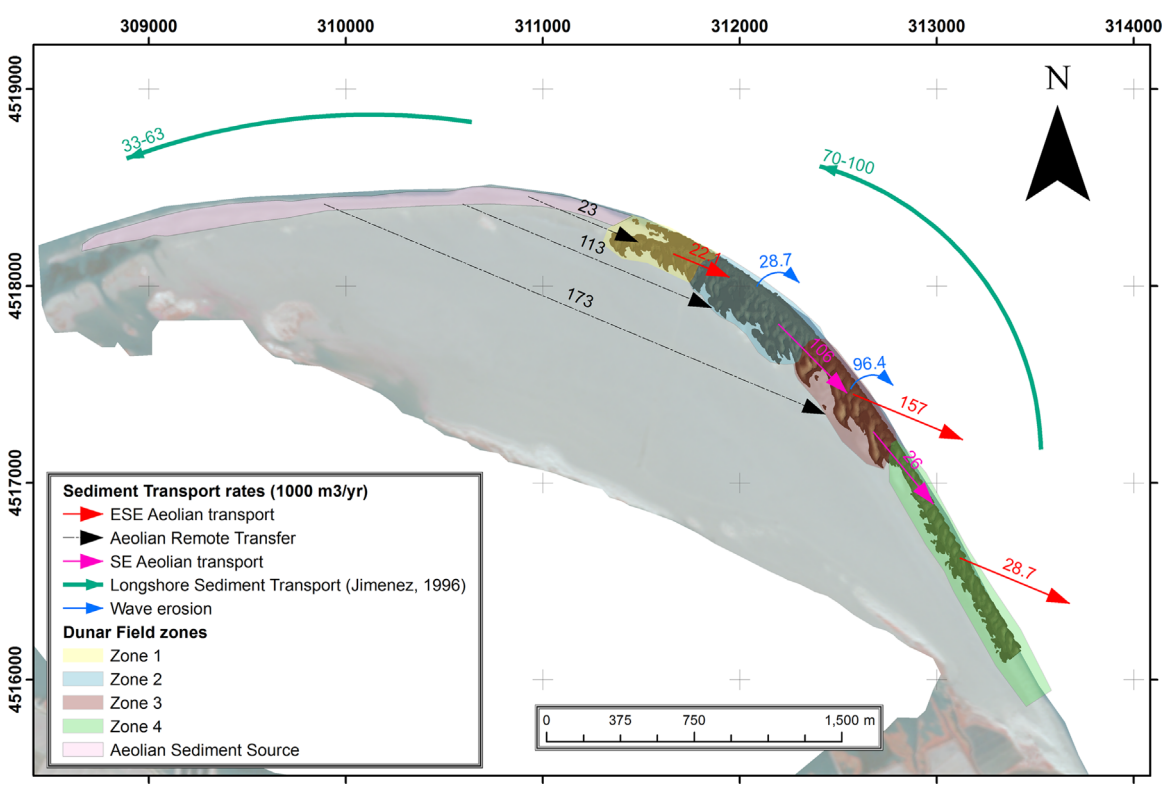

Fig. 6. Sediment exchange rates at El Fangar Spit.

These methods can be used to estimate the sediment exchanges and the dune migration at the meso-scale, which has important applications for the management of areas where active dunes are the object of concern. The main contribution of the present paper is that this is a first approximation to calculate the volumes of sediment that enter and exit an active dune system with open boundary conditions. Therefore, the model is useful in guiding the preservation efforts of dune systems as in the example presented in this paper. It also gives a reasonable prediction of the dune migration which is useful, for analysing the effects of active dune on infrastructures like roads or railways. Therefore, the model has a great applicability in the understanding of the aeolian transport and in the definition of sedimentary budgets in beach-dune systems (especially in the more complex ones), and so it can have engineering and management usefulness.

Further research should focus on how to improve the modelling process, including phenomena that have not been considered and as that can have significant effects on the reproduction of the geomorphological evolution of the dunes, like the effects of the wave erosion. The model needs to incorporate a sand input model witch consider the soil moisture and the fetch effect, in order to be widely applicable to other dune systems. A future research line would be the conduction of field experiments that increase the level of confidence in quantitative estimates of aeolian flow.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2016.05.001.

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