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Water table dynamics of dune slacks in an arid zone

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Abstract

In this study, a characterisation is undertaken of the humid dune slacks water table situated in the arid transgressive coastal dune field of the Maspalomas Special Area of Conservation, ES701007 (Gran Canaria, Canary Islands, Spain). Humid dune slacks are listed as a European Union Habitat (EU Habitat 2190 humid dune slacks) in Annex I of the EU Habitats Directive. This water table is relatively stable throughout the year, with a 41 cm maximum oscillation. The annual dynamics of the flow pattern and water table level depend on the climate conditions. At the end of the hydrological dry season the mean water table drops (ca. 11 cm) and water flows to the lagoon. After rains, the mean water table level rises (ca. 4 cm) and flows towards the Maspalomas beach. The distribution of plant communities (associated to EU Habitat 2190) in the Maspalomas humid dune slacks depends on water table depth, pH and salinity. The knowledge acquired in this study of the water table dynamics has enabled a better understanding of the spatial distribution patterns of the vegetation of these slacks, in particular with respect to the relationship between the water table flux toward the coast during the dry season and the distribution of plant communities in the slacks closest to the coast. The study of the dynamics of the water table of the slacks and the associated vegetation has allowed us to better understand the characteristics of the Maspalomas humid dune slacks and potentially improve their management as EU Habitat. This is especially significant considering that the only European arid climate dune field where this habitat can be found is in Maspalomas.

Keywords Canary Islands · Inter-dune areas · Dune slacks vegetation · Coastal management · European Union Habitat · 2190 humid dune slacks

Introduction and objectives

The focus of coastal dune management is the conservation of environmental values and the numerous ecosystem services that they can provide to society (Everard et al. 2010). Conservation and environmental management include both biotic and abiotic aspects (van der Meulen and Salman 1996). Wet inter-dune areas, also known as humid or wet dune slacks (Tansley 1949), are one of the most singular dune field habitats. Inter-dune areas can be considered a morphodynamical component of the dunes, since they represent a base level for dune movement (Kocurek 1981). The

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shallow water table of coastal inter-dune areas favours dune preservation (Crabaug and Kocurek 1993), as well as the accumulation rate of both the dune and inter-dune space (Kocurek and Havholm 1993), and determines the depth of the preserved inter-dune units (Kocurek et al. 2001). In other words, the morphology of the dune field can be regulated by the oscillations of the water table (Luna et al. 2012).

In coastal systems, groundwater, seawater and lagoon water, where present, are interconnected, with dynamic equilibrium in their margins. A reduction of the groundwater volume, due to overexploitation, causes seawater intrusion and water system distortion (Bear et al. 1999; Momii et al. 2005). The shallow water table in a coastal dune system is integrated into the coastal aquifer system and responds to a tidal effect. Due to the impact of tides on the shallow water table, numerous researchers have modelled tide-induced shallow water table fluctuations (Parlange et al. 1984; Sun 1997; Boufadel 2000; Ataie-Ashtiani et al. 2001; Li et al. 2001; Teo et al. 2003; Jeng et al. 2005a, b; Momii et al. 2005).

Wet dune slacks represent one of the most studied dune ecosystems in humid, tropical and temperate climates (Ranwell 1959; Ranwell 1960; Lubke and Avis 1988; Noest 1994; Avis and Lubke 1996; Grootjans et al. 1991; Lammerts et al. 1999; Moreno-Casasola and Vázquez 1999; Muñoz-Reinoso 2001; Grootjans et al. 2002; Muñoz-Reinoso and Castro 2005). However, these systems are less understood in arid coastal dune fields such as the Maspalomas Dunes Special Nature Reserve (Canary Islands, Spain).

Precipitation regulates the plant colonization of dune slacks in transgressive coastal dune fields in dry climates or climates with a marked dry season (Avis and Lubke 1988; Hernández-Cordero et al. 2006). In this context, in arid transgressive coastal dune systems the dune slacks are spaces in which plant colonization of mobile dunes occurs (Hernández-Cordero et al. 2015a). Dune slacks therefore play a vital role in the conservation of these ecosystems, constituting centres of mobile dune biodiversity in transgressive dune fields (Avis and Lubke 1996). Importantly, humid dune slacks have been listed on Annex I of the European Union Habitats Directive as a natural habitat (European Union Habitat 2190 humid dune slacks) whose conservation requires the designation of Special Areas of Conservation.

In the Canary Islands, humid dune slacks are only recorded in the Maspalomas Dunes Special Nature Reserve (Hernández-Cordero et al. 2015b). Although Hernández-Cordero et al. (2015b, c) identified and characterized the types of vegetation and habitat in the Maspalomas humid slacks, an in-depth study of the environmental factors that regulate the distribution of habitats, especially the water table dynamics, could help to better explain the dynamics of this habitat and contribute to the development of conservation strategies.

The aim of this paper is to analyse the relationship between the dynamics of the water table and the vegetation of the humid dune slacks, in order to contribute to a better understanding of this European Union Habitat (EU Habitat) in an arid dune field context and, in consequence, contribute to its efficient conservation.

Study area

The Maspalomas Dunes Special Nature Reserve, which has also been designated a Special Area of Conservation (ES701007) under the EU Habitats Directive, is situated in the south of Gran Canaria (Fig. 1). It is a coastal dune system with an extension of ca. 3.6 km^2. A lagoon, with marked seasonal variations (Almunia et al. 1999), and numerous humid dune slacks (inter-dune areas) are included within this Reserve. The current aeolian sedimentary system overlays an ancient fan delta, fed by the Fataga ravines (Balcells et al. 1992). As a result, the substrate of the sand dunes consists of alluvial pebbles, fine material, and carbonated palaeosol, with marine reworking, and beachrocks in some areas.

Most of the dune slacks are permanently humid, with the shallow water table at < 1 m depth. The sediment of these humid dune slacks is mainly sand, with some outcrops of alluvial and beach pebble bars, aeoleanites, or fine material with carbonate cement. During extreme storm events, associated with strong south-westerly waves, these depressed areas are flooded by seawater, generating ephemeral lagoons. During our study period, such conditions occurred in April 2006.

The average distance between low and high tide marks on the Maspalomas beach is 80 m, with 3–4% of shoreface slope. At El Inglés beach these values are 35 m and 7–10% respectively.

One of the hydrological characteristics of Maspalomas is the existence of a natural lagoon associated to the dune system. This constitutes the remains of a larger lagoon and flood-plain complex, active until the 1960s. In aerial photographs from 1948, this lagoon complex appears as meandering channels that formed isolated lagoons during the dry season. A similar lagoon description of two sinuous channels and a marsh was also given by the British ornithologist David A. Bannerman (1922).

The development of tourism has greatly impacted this wetland system, reducing the lagoon to its present-day extension. The main actions have been: 1) extensive construction of tourist resorts along the western margin of the present-day lagoon with the elimination of the natural adjacent lagoon areas; 2) isolation of the main channel, and the consequent modification of the hydrological dynamics, and 3) its channelling into an artificial tunnel resized by rock slabs.

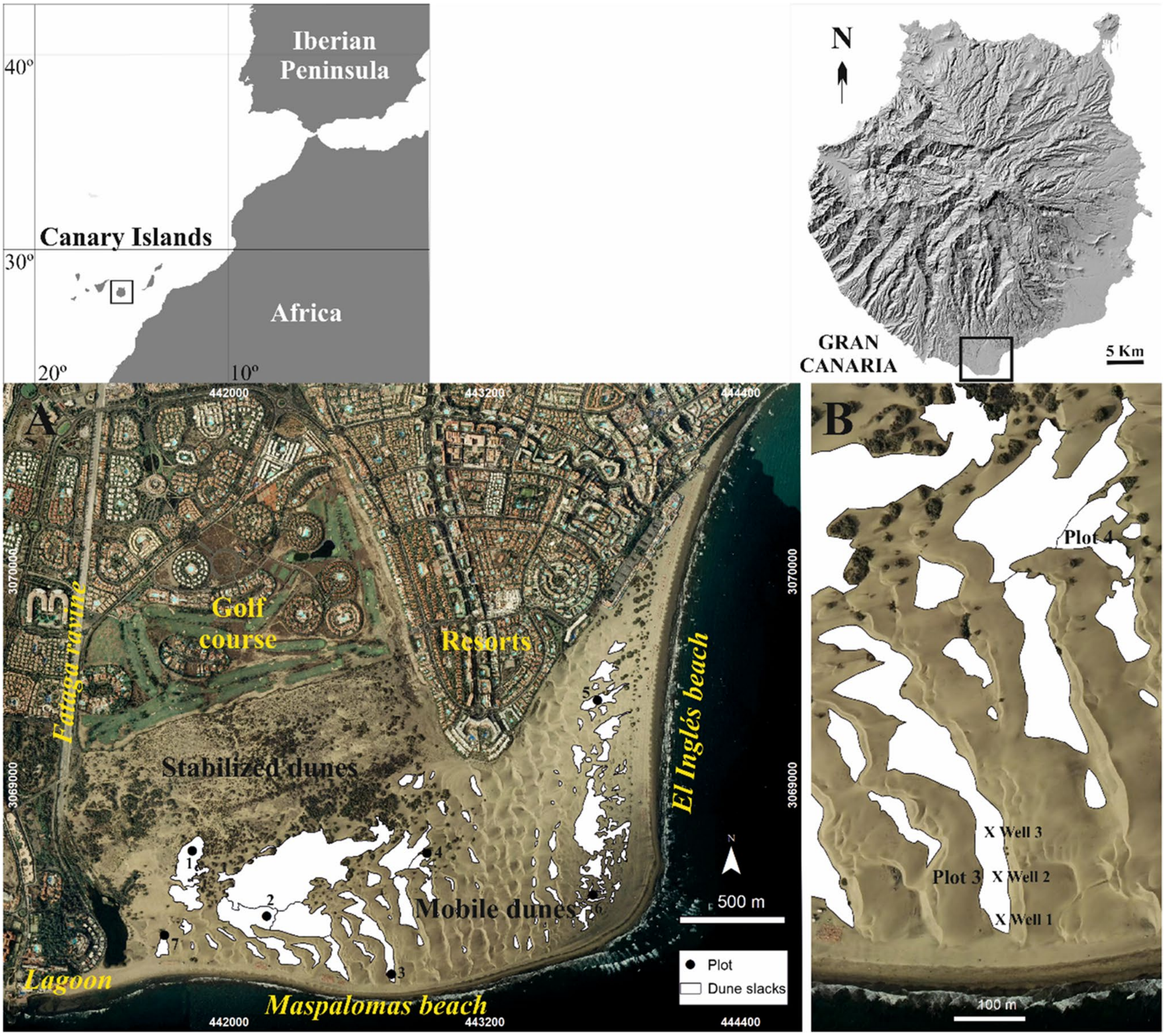

Fig. 1 Location of the study area and sampling plots (**A**). Site of the three wells excavated down to the water table depth in plot 3 to register tidal range oscillation (**B**), at 65, 119 and 181 m from the shoreline (wells 1–3). Source: Orthophoto year 2006. IDECanarias (GRAFCAN, SA)

The Maspalomas dune field, located on the arid coast leeward of Gran Canaria, is partly sheltered from the prevailing northerly trade winds. The mean annual temperature (21ºC) and annual rainfall (81 mm) define the arid Maspalomas climate (Hernández-Cordero et al. 2015c; Fig. 2). This climate favours sediment mobility, generating the transgressive dune system. Based on the aeolian sedimentary activity, three zones can be distinguished (Hernández-Cordero et al. 2015c): an active zone (consisting of foredunes and mobile dunes with associated dune slacks and deflation surfaces); a semi-stabilized zone (consisting of nebkhas, barchan dunes, sand sheets, and deflation surfaces); and a stabilized zone (formed by stabilized dunes and dune slacks). The vegetation of the Maspalomas dune field is comprised of 19 plant communities, associated with different habitats (Hernández-Cordero et al. 2015c, 2017). The nomenclature of the phytosociological associations is based on Del Arco Aguilar and Rodríguez Delgado (2018) and Salas-Pascual et al. (2018): foredune (*Traganum moquinii* plant community: phytosociological association *Traganetum moquinii*), dry or humid slacks (amongst others—*Cyperus laevigatus* plant community: phytosociological association *Cyperetum laevigati*, *Tamarix canariensis* plant community: phytosociological association *Atriplici ifniensis-Tamaricetum canariensis*, *Juncus acutus* plant community: phytosociological association *Scirpo globiferi-Juncetum acuti*, *Tetraena fontanesii* plant community, *Launaea arborescens* plant community:

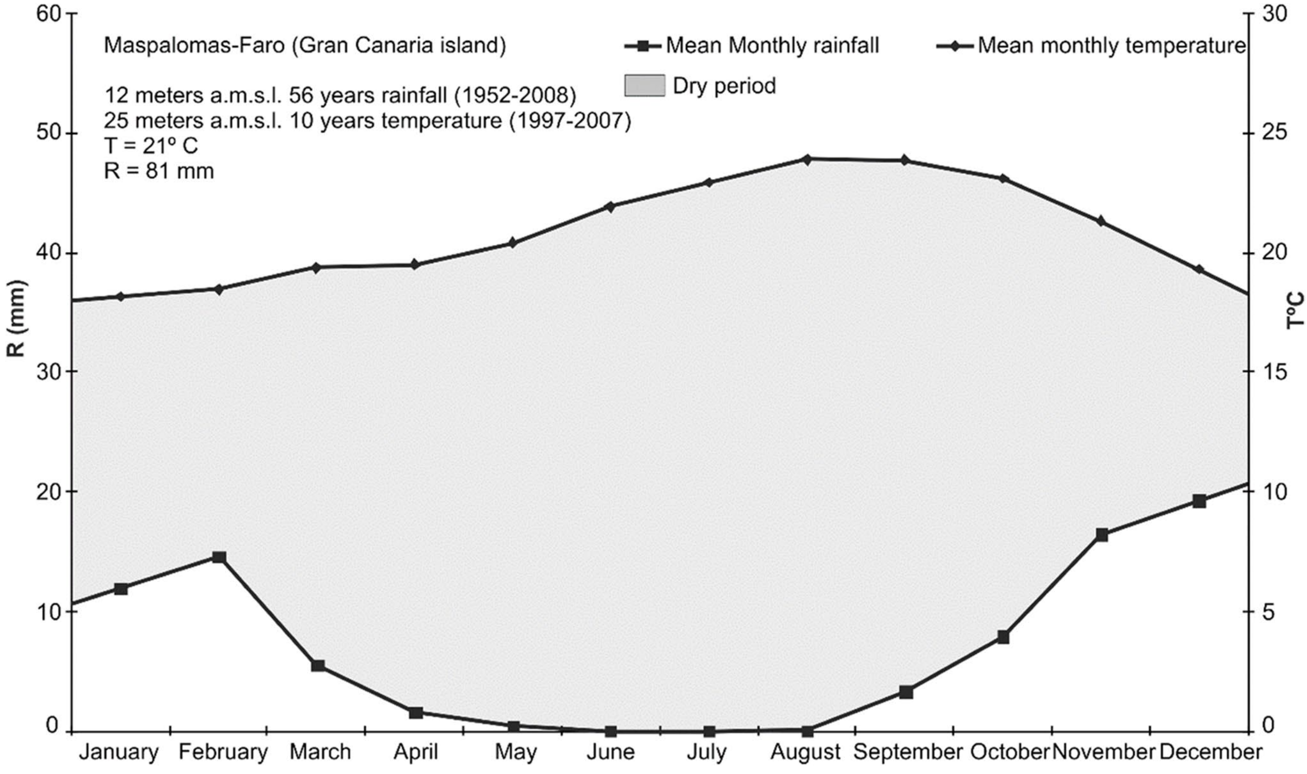

Fig. 2 Ombrothermic diagram of the study area (from Hernández-Cordero et al. 2015c)

phytosociological association *Launaeo arborescentis-Schizogynetum glaberrimae cyperetosum capitati*), mobile dunes (*Tamarix canariensis* plant community: phytosociological association *Atriplici ifniensis-Tamaricetum canariensis cyperetosum capitati*) and stabilized dunes (amongst others—*Cyperus capitatus-Ononis tournefortii* plant community: phytosociological association *Ononido tournefortii-Cyperetum capitati*, *Tamarix canariensis* plant community: phytosociological association *Atriplici ifniensis-Tamaricetum canariensis cyperetosum capitati*, *Launaea arborescens* plant community: phytosociological association *Launaeo arborescentis-Schizogynetum glaberrimae cyperetosum capitati*).

Materials and methods

Topography

A total of 7 humid dune slacks (from a total of 97; Fig. 1A) were selected for this study (Table 1). The selection was based on a spatial criterion that allowed coverage of most of the dune system in their cartographic modelling. The topographic measurements of the slacks were made with two Leica GPS 500 receivers. The mobile receiver was used in cinematic mode, with an observation time of 90 s and a periodicity of 5 s. The altitude data were initially referred to the ellipsoid, with an error value of ± 1 cm. The necessary

Table 1 Surface area, grain size of the sediment and altimetry of the studied dune slacks

Plot	UTM coordinates (28R)	Surface (m^2)	Fine Sand (%)	Silt–Clay (%)	Carbonate (%)	Altitude (m)
1	441828/3068693	22,452	47	1	68	1.4
2	442276/3068387	28,341	60	0	72	0.8
3	442761/3068114	23,436	75	1	55	0.8
4	442928/3068681	5,773	78	1	46	1.1
5	443729/3069399	8,711	66	1	50	1.6
6	443707/3068486	3,254	71	0	60	0.8
7	441697/3068297	4,245	77	1	38	0.9

reference of these values to the geoid was generated by the Spanish Geographic Institute (IGN) with a model of geoid undulations and an error value of ± 5 cm.

Hydrological characteristics

The depth of the water table was gauged in triplicate extraction for each of the selected dune slacks over a total of six 3–4 month periods, from November 2004 to July 2006. Data were collected in two different climate conditions: dry or wet (humid). Dry conditions occur between mid-spring and mid-autumn, while wet (rainy) conditions occur between mid-autumn and mid-spring (Fig. 2).

The water table depth was directly measured from small wells made with a soil auger and bucket using tension lysimeters (Soilmoisture 1989; Sival and Strijkstra-Kalk 1999; Menéndez et al. 2003; Clarke et al. 2010). The auger bucket allows undisturbed sediment recovery. Water samples were extracted from the sand located above (unsaturated zone) and below the water table (saturated zone). The parameters analysed in situ were pH (Crison GLP 22 pH meter with temperature probe) and electric conductivity (Crison GLP 32 conductivity meter).

The water table and topographic 3D models were generated using the Surfer 13 program (Kim and Yu 2009; Pye et al. 2014; Jones et al. 2017). A spatial interpolation of the mean depth data of the water table was performed to determine the direction of the water flow.

The tidal range for each location was registered to evaluate its effect on the water table level. Measurements were performed to assess the time-lag between the tidal phase and the distance to the shoreline. This descriptive measurement involved hourly measurements of the water table level and the tide level over a 12-h period. The day chosen for the measurements was in the equinoctial period (20th August 2005) when a maximum tidal range was predicted. Three wells were excavated to the water table depth, at distances of 65, 119 and 181 m from the shoreline (Fig. 1B). The water table depth was measured each hour, from 7 am to 7 pm.

The water content of the sediment from the dune slacks was determined as the difference in sediment weight before and after drying in an oven at 50ºC for 4–5 days. The salinity profile was obtained by measuring the electrical conductivity in a water-saturated slurry (one part of sediment to five parts of deionized water; Corwin and Lesch 2003).

Climatic characteristics

The meteorological data (temperature, wind and humidity) were recorded at the Maspalomas lighthouse observatory from 2004 to 2006. The evaporation rates of the dune slacks were obtained through the potential evapotranspiration (ETp) expression (Penman 1948; Voortman et al. 2015):

$$\mathrm{ETp} = \mathrm{f} \cdot \mathrm{E} \tag{1}$$

where

- f is a coefficient, with 0.75 as a mean annual value (Aguilo et al. 2006).
- E is the evaporation rate from the open water surface, in mm/day, calculated as

$$\mathrm{E} = (\mathrm{D/g} \cdot \mathrm{Rn} + \mathrm{Ea})/(\mathrm{D/g} + 1) \tag{2}$$

where

- D is the slope of the saturation curve of steam pressure, in hPa,

$$\mathrm{D} = 1.99932 \cdot (0.00738\mathrm{T} + 0.8072)7 - 0.000116 \tag{3}$$

- T is the average temperature of the station, in ºC,
- g is the psychrometric constant, in hPa,

$$\mathrm{g} = 0.3831 \cdot (\mathrm{P/c}) \tag{4}$$

where

- P is the atmospheric pressure, depending on altitude, and ***c*** is the latent heat of vaporisation.
- Rn is the net radiation (in the limit of the atmosphere) translated into mm of water evaporated per day. This parameter was extracted from Table 5 cited in Sanchez-Toribio (1992) and elaborated by Doorembos and Pruitt (1977).
- Ea is the evaporation function based on the saturation deficit and wind speed. It is a term that describes the speed of vapour diffusion:

$$\mathrm{Ea} = 0.35 \cdot (0.50 + 0.54 \cdot \mathrm{V}_2) \cdot (\mathrm{e}_\mathrm{s} - \mathrm{e}), \text{ in mm/day} \tag{5}$$

where V_2 is the mean wind speed measured at 2 m above ground level (agl). Since the anemometers measured the wind at 10 m agl (V_{10}) a correction factor has to be introduced.

$$\mathrm{V}_2 = \mathrm{V}_{10}(2/10)^{0,2} \tag{6}$$

The expression (e_s—e) in Eq. (5) is the saturation vapour pressure deficit in which e_s is the saturation vapour pressure at a given temperature, by month, in hPa (Sonntag 1990). The value was obtained from the air temperature, in ºC, expressed in hPa:

$$\ln \mathrm{e}_\mathrm{s} = \ln(6.112) + (17.62 \cdot \mathrm{T}/243 \cdot \mathrm{T}) \tag{7}$$

$$\mathrm{e} = 0.01.\mathrm{e}_\mathrm{s}.\mathrm{rh} \tag{8}$$

where rh is the relative humidity, in %.

The vertical fluxes of the water table were estimated from the wet surface evaporation rate in the inter-dune areas. The evaporation data was calculated from the free water surface using Eqs. (1) and (2). The water content of the sandy surface was calculated from the two results.

Vegetation

The vegetation of each of the seven sampling points (dune slacks; Fig. 1A), was characterized through relevés in areas of between 100 and 200 m^2. The relevés were carried out in the centre of the existing vegetation unit in each sampling point of the dune slacks or at the closest point to it. Seven relevés were performed between June and July 2005 and May 2006. In each relevé, the identity of each plant species was recorded as well as its cover using the cover-abundance scale of Braun-Blanquet. Species richness and diversity (Shannon's diversity index) were determined in each relevé. The semi-quantitative data of the linear cover-abundance scale were converted into a coverage index of quantitative data for their statistical analysis (+ (5%), 1 (10%), 2 (25%), 3 (50%), 4 (75%) and 5 (100%)), following the method of Arozena and Molina (2000).

Identification of plant communities was performed by clustering with the SPSS program, using Ward's method as grouping criterion and the square Euclidean distance measurement.

To determine the environmental variables that correlate to the different plant communities of this habitat, a canonical correspondence analysis (CCA) was carried out with the PC-ORD 5 program using the coverage index of the plant species obtained in the relevés and the environmental variables of mean depth, pH, and electrical conductivity of the water table. The axes resulting from the CCA were correlated to these environmental variables using the SPSS 15 program.

Results

Tidal effect

The tidal oscillation of the water table level and the distance of the measured point from the shore were highly correlated ($R^2 = 0.99$, Fig. 3). The water table oscillation followed a distinct tidal effect. At 65 m from the shore its oscillation was 10 cm with a tidal delay of ca. 3 h (Fig. 4). At 119 m from the shore the water table oscillation was 5 cm, and at 180 m just 2 cm.

The saturated hydraulic conductivity was estimated from tidal movement, yielding a value of about 520 m/day, within the range of well-sorted sand and gravel values (Gallage et al. 2013).

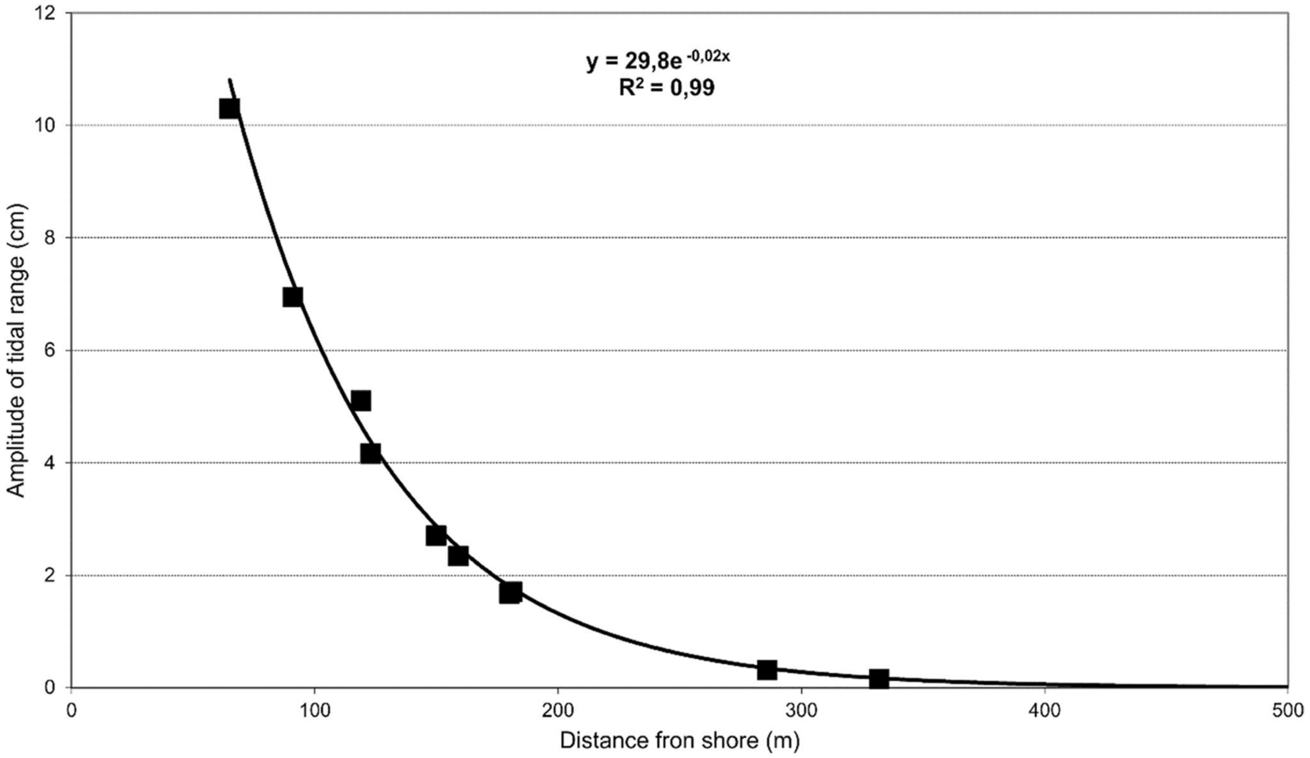

Fig. 3 Exponential relationship between tidal oscillation of the water table (Y) and distance from the shore (X)

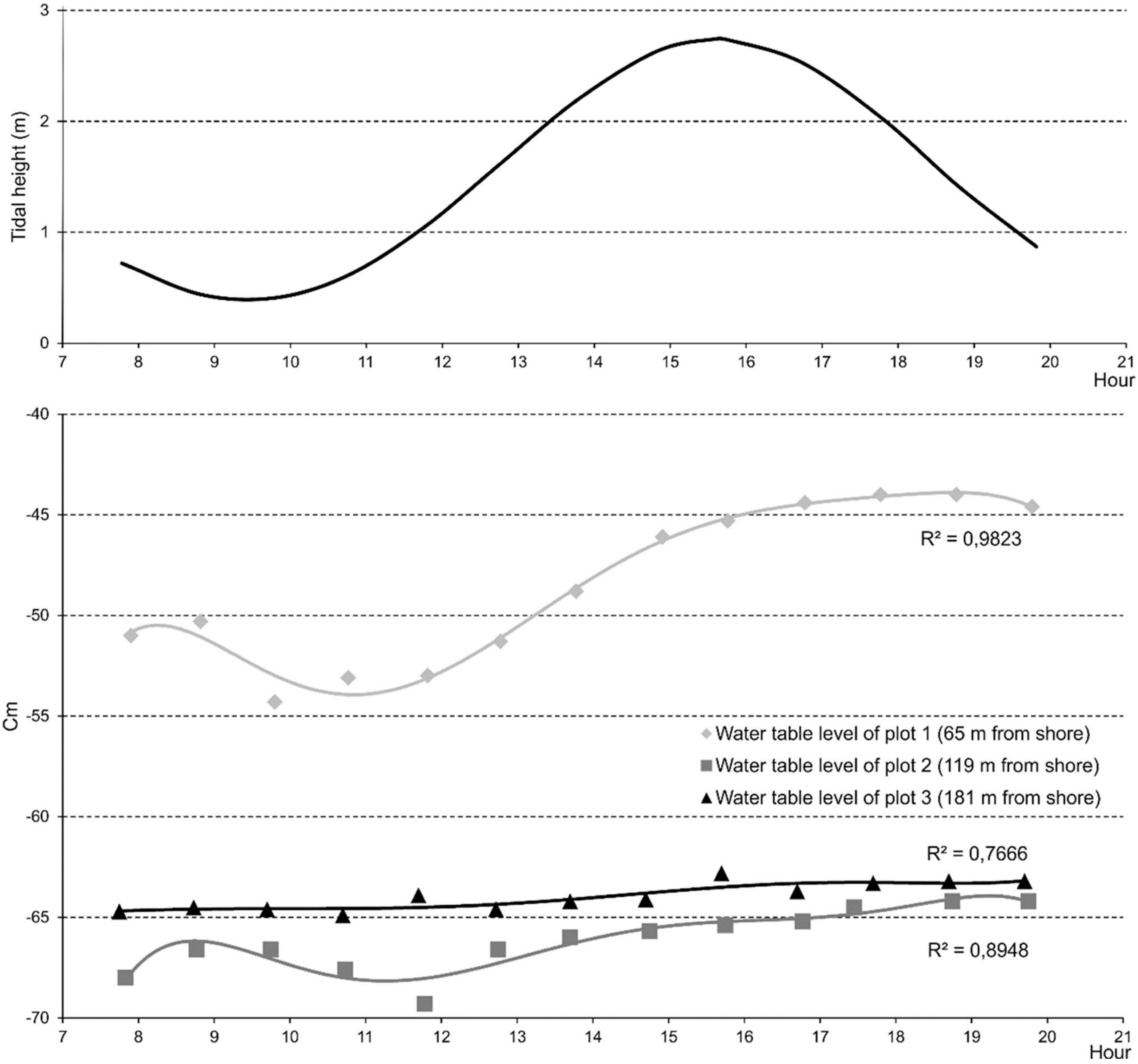

Fig. 4 Tidal height above low tide and the water table level at different distances from the shoreline

Shallow water table seasonality

Although the dune slacks are essentially flat, some locations have elevation differences of up to 0.9 m. In general, the gradient decreases towards Maspalomas beach, with two depressed areas around locations 2 and 6 (Fig. 5).

The mean water table level in the hydrological dry periods was -53 cm; and in the wet periods -50 cm, with oscillations of 35 cm (± 11) and 12 cm (± 4), respectively (Table 2). This process was not consistent throughout the study area. Field sites 1 and 7 showed a clear drop in the water table level during the hydrological dry periods compared to the wet periods, while field site 6 showed the opposite trend (Fig. 5).

The differences in the shallow water table level during hydrological dry and wet periods were significant, but with a time delay (Figs. 5 and 6). The maximum water table depth was record prior to the period of abundant rainfall on the island. However, in hydrological wet periods, the drop of the water table (ca. 3 cm) produced a change in the direction of the water flow. This flow is seaward during high water table levels, but reverses direction, to the lagoon, during low water table levels. Regarding water table depth, during the hydrological dry period, the water flows into the lagoon, and, during the hydrological wet period, the water flow is seaward.

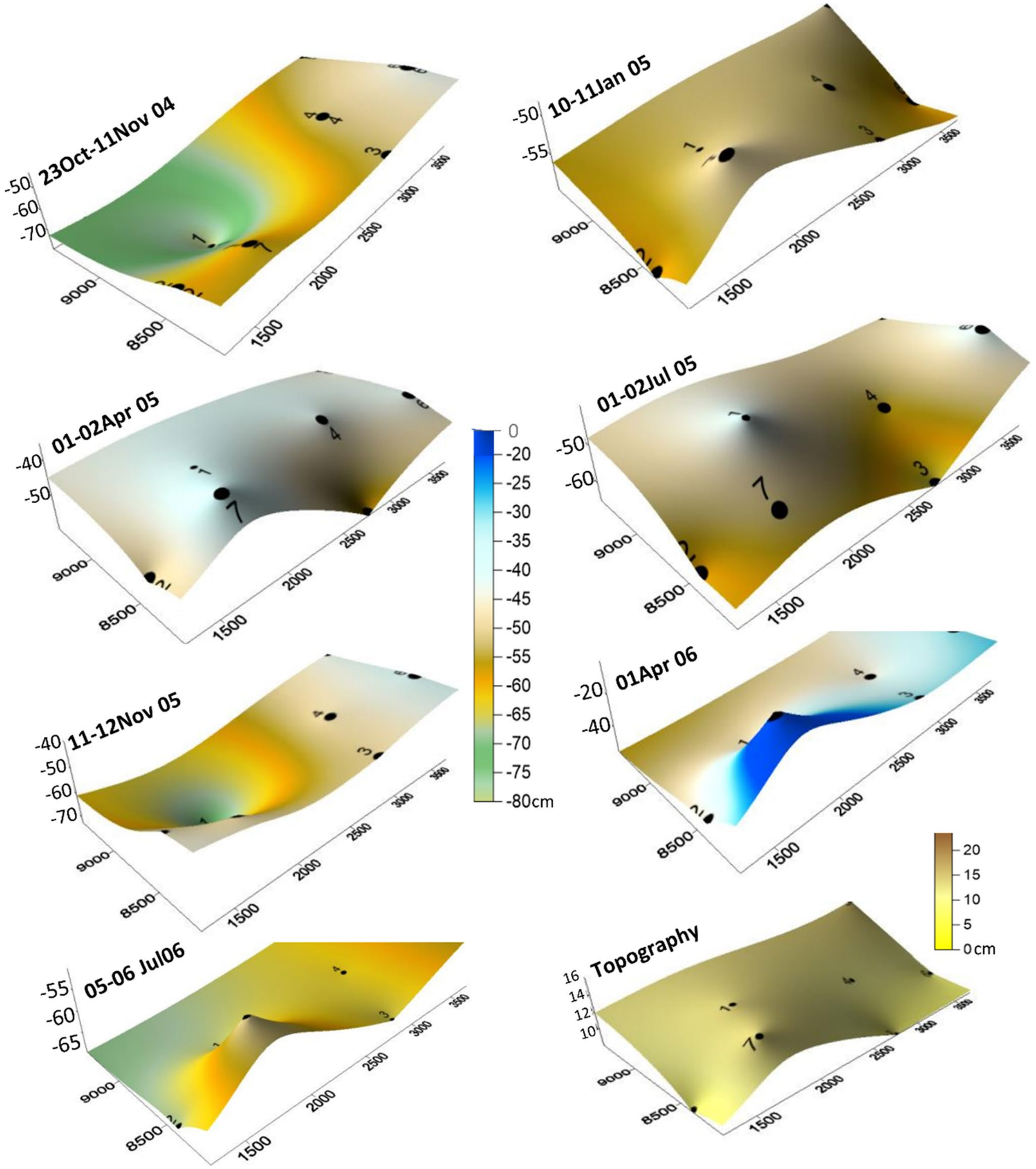

Fig. 5 Inferred topography of the humid slacks in the Maspalomas dune field and water table shape in the different hydrological wet and dry periods, measured in the selected humid slack locations

Water content, evaporation rates and salinity profile

An increase in water content in the saturated zone, from 1–10% to 17–22% (Fig. 7a), was observed during rainy periods. Free water evaporation calculated using Penman's method (1948) is shown in Table 3. The maximum value (175 mm/day) was in February and the minimum (101–94 mm/day) between June and September. In

Table 2 Tidal range (in m) at each location, sampling date, and depth of the water table and tide oscillation (in cm), regarding to the shore distance (in m)

Sampling Date	Dry/Wet	Slack plots	1	2	3	4	5	6	7	$\overline{X}$	sd
		Shore distance	286	150	180	332	159	123	91		
23 Oct.—1 Nov. 04	Dry	Tidal range	1.3	1.3	1.3	1.6	1.6	1.6	1.6		
		Oscillation	0	1	1	0	2	3	5		
		Water table depth	-80	-60	-53	-52	-53	-43	-57	-57	11
10–11 Jan. 05	Wet	Tidal range	2.0	2.0	2.0	2.3	2.3	2.3	2.3		
		Oscillation	0	2	1	0	2	4	6		
		Water table depth	-53	-60	-55	-53	-49	-60	-48	-54	5
1–2 Apr. 05	Wet	Tidal range	1.0	1.0	1.0	1.2	1.2	1.2	1.0		
		Oscillation	0	1	1	0	1	2	3		
		Water table depth	-39	-51	-60	-42	-45	-42	-35	-45	8
1–2 Jul. 05	Wet	Tidal range	1.3	1.3	1.3	1.3	1.4	1.4	1.3		
		Oscillation	0	1	1	0	1	2	4		
		Water table depth	-40	-60	-65	-56	-48	-40	-52	-52	10
11–12 Nov. 05	Dry	Tidal range	1.3	1.3	1.3	1.3	1.4	1.4	1.3		
		Oscillation	0	1	1	0	1	2	4		
		Water table depth	-73	-46	-50	-48	-43	-40	-50	-50	11
1 Apr. 06	Wet	Tidal range	2.0	2.0	2.0	2.0	2.0	2.0	2.0		
		Oscillation	0	2	1	0	2	3	6		
		Water table depth	-45	-45	-30	-45	-40	-30	*	-39	7
5–6 Jul. 06	Wet	Tidal range	1.9	1.9	1.9	2.0	2.0	2.0	2.0		
		Oscillation	0	3	2	0	2	4	7		
		Water table depth	-66	-68	-65	-63	-57	-53	-50	-60	7
Oct. 04 Jul. 06		Range	-41	-23	-35	-21	-17	-30	-22	-27	
		dry periods	-76	-53	-51	-50	-48	-42	-53	-53	
		sd	5	10	2	3	8	2	5	11	
		wet periods	-49	-57	-55	-52	-48	-45	-46	-50	
		sd	11	9	15	8	6	12	8	4	
		Level difference	28	-4	-4	-2	0	-3	7	3	

* Flooded

Dry/wet: when the water flows into the lagoon it is considered a hydrological dry period, when the water flows into the sea it is considered a hydrological wet period

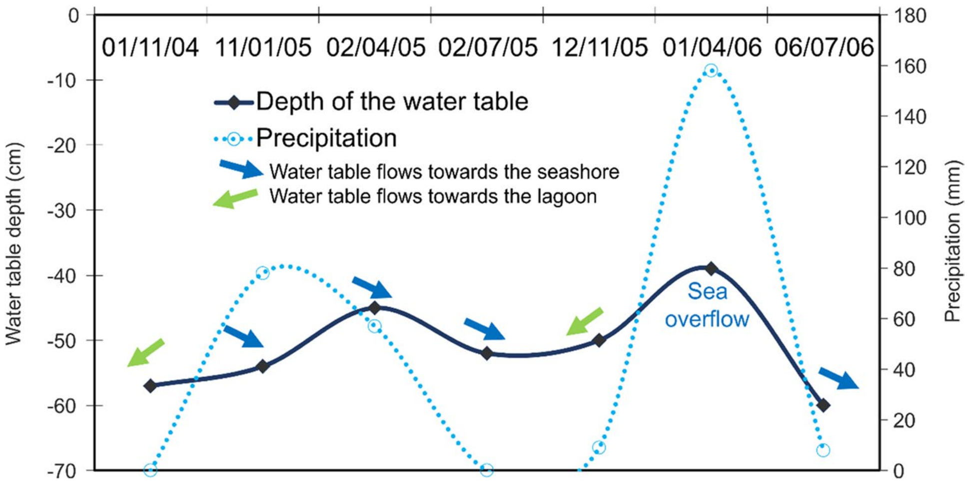

Fig. 6 Mean water table values and preferential fluxes in each sampling period related to local rainfall. Modifications of the fluxes occurs after the water table reaches its lowest level

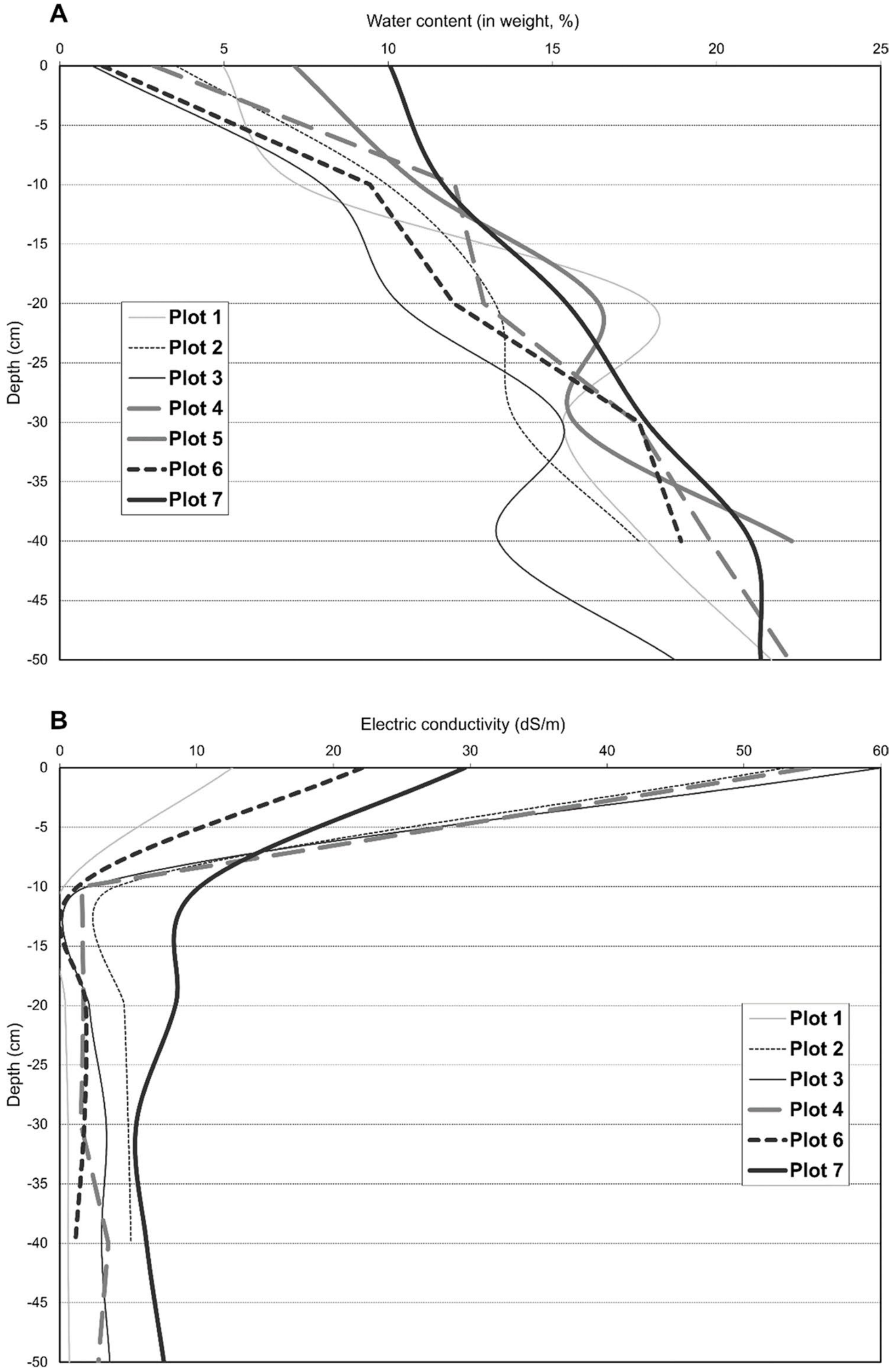

Fig. 7 (**a**) Sediment water content profile, and (**b**) salinity profile for the humid dune slacks locations. Both parameters were measured each 10 cm from the sand surface down to the top of the water table

general, water content increases from about 5% just below the sand surface to nearly 20% just above the water table surface (Fig. 7a).

There is a noticeable salinity gradient, from high values at the sand surface to markedly lower values in deeper

Table 3 Calculation of the potential evapotranspiration (PET), in mm/day, using the Penman formula (1 and 2). Further details in the Materials and Methods section

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Temperature (ºC)	18	19	19	19	20	22	24	25	24	23	21	19
H (%)	66	58	60	67	68	74	74	74	73	69	61	62
V (km/h)	280	432	337	299	261	244	252	250	242	336	344	371
f	1	1	1	1	1	1	1	1	1	1	1	1
D	1	1	1	1	1	2	2	2	2	2	2	1
c	587	586	587	586	586	585	584	583	584	584	585	587
P	1010	1010	1010	1010	1010	1010	1010	1010	1010	1010	1010	1010
g	1	1	1	1	1	1	1	1	1	1	1	1
Rn	9	11	13	15	17	17	17	16	14	12	10	9
V2	169	261	204	180	158	147	152	151	146	203	208	224
es	21	23	22	23	23	26	27	29	28	27	25	22
e	14	13	14	15	16	19	20	21	20	19	15	13
D/g	2	2	2	2	2	2	3	3	3	3	2	2
D/g + 1	3	3	3	3	3	3	4	4	4	4	3	3
Ea (mm/day)	236	470	344	259	221	187	207	214	208	317	380	357
E (mm/day)	97	175	139	115	106	95	101	100	94	119	137	135
PET (mm/day)	58	105	97	81	84	76	81	80	66	83	82	81

Table 4 Water table and vegetation characteristics of each plot

Plot	Species (coverage index)	Depth (cm)		pH		Salinity (mScm^{-1})	
		$\overline{X}$	Range	$\overline{X}$	Range	$\overline{X}$	Range
1	*Juncus acutus* (100%), *Schizogyne glaberrima* (5%), *Launaea arborescens* (5%), *Typha domingensis* (5%)	-56.5	-40.7	7.4	0.4	5.7	2.7
2	*Tamarix canariensis* (5%), *Suaeda mollis* (10%), *Tetraena fontanesii* (25%), *Frankenia boissieri* (10%)	-55.7	-23.3	7.5	0.5	24.3	26.6
3	*Cyperus laevigatus* (100%)	-54.0	-35.3	8.1	0.6	15.6	11.8
4	*Tamarix canariensis* (100%)	-51.1	-20.4	7.6	0.9	8.5	9.9
5	*Tragaum moquinii* (100%)	-48.0	-17.5	8.9	1.4	7.3	6.4
6	*Tragaum moquinii* (50%)	-44.1	-30.0	8.4	0.5	7.2	7.6
7	*Juncus acutus* (50%), *Tamarix caanriensis* (10%), *Cyperus laevigatus* (100%)	-48.6	-21.7	7.9	0.4	12.8	7.1

zones (Fig. 7b). Salinity increases and the water table becomes shallower in hydrological wet periods.

Vegetation associated to the humid dune slacks

Ten plant species were recorded (Table 4), comprising 3 herbaceous species (hemicryptophytes and geophytes): *Juncus acutus*, *Typha domingensis* and *Cyperus laevigatus*; 6 scrub species (nanophanerophytes and chamaephytes): *Traganum moquinii*, *Tetraena fontanesii*, *Launaea arborescens*, *Schizogyne glaberrima*, *Suaeda mollis* and *Frankenia boissieri*; and a small tree: *Tamarix canariensis*.

Five plant communities (groups) were identified in the cluster analyses (Fig. 8; Table 5):

Group A: formed by plot 1. Herbaceous plant community dominated by the hemicryptophyte *Juncus acutus* with a total richness of 4 species (*Juncus acutus*, *Schizogyne glaberrima*, *Launaea arborescens* and *Typha domingensis*). It is the second highest plant community in terms of floristic diversity (Table 5).

Group B: formed by plot 2. Shrubby plant community dominated by the nanophanerophyte *Tetraena fontanesii* with a total richness of 4 species (*Tetraena fontanesii*, *Tamarix canariensis*, *Suaeda mollis* and *Frankenia boissieri*. It is the plant community with the highest floristic diversity.

Group C: formed by plots 3 and 7. Herbaceous plant community dominated by the geophyte *Cyperus laevigatus* with a total richness of 3 species and average richness of

Fig. 8 Plant community groups obtained through the relevés

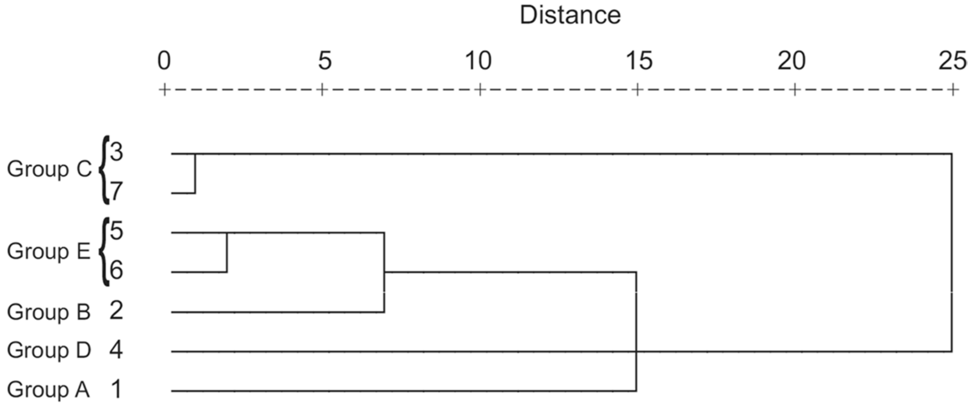

Table 5 Characteristics of dune slack plant communities

Group	Plot	Plant community	Average richness	Shannon's diversity index
A	1	*Juncus acutus*	4.0	0.531
B	2	*Tetraena fontanesii*	4.0	1.220
C	3, 7	*Cyperus laevigatus*	2.0	0.364
D	4	*Tamarix caanriensis*	1.0	0.000
E	5, 6	*Tragaum moquinii*	1.0	0.000
Average	-	-	2.4	0.423

2 species. It is the third highest plant community in terms of floristic diversity.

Group D: formed by plot 4. Arboreal plant community dominated by the macrophanerophyte *Tamarix canariensis*. It is a monospecific plant community.

Group E: formed by plots 5 and 6. Shrubby plant community dominated by the nanophanerophyte *Traganum moquinii*. It is a monospecific plant community located closest to the shore.

Characteristics of the water table and humid dune slacks vegetation

The CCA analyses generated three canonical axes (Fig. 9), whose eigenvalues are 0.955, 0.783 and 0.157 (Table 6). These three axes explain 54% of the variance (axis 1: 27.2%, axis 2: 22.3% and axis 3: 4.5%). Axis 1 correlates more significantly with water table depth (-0.814) and pH (0.863), whilst axis 2 correlates more significantly with salinity (-0.806). Thus, this analysis confirms that the humid dune slacks vegetation of the Maspalomas dune field partially

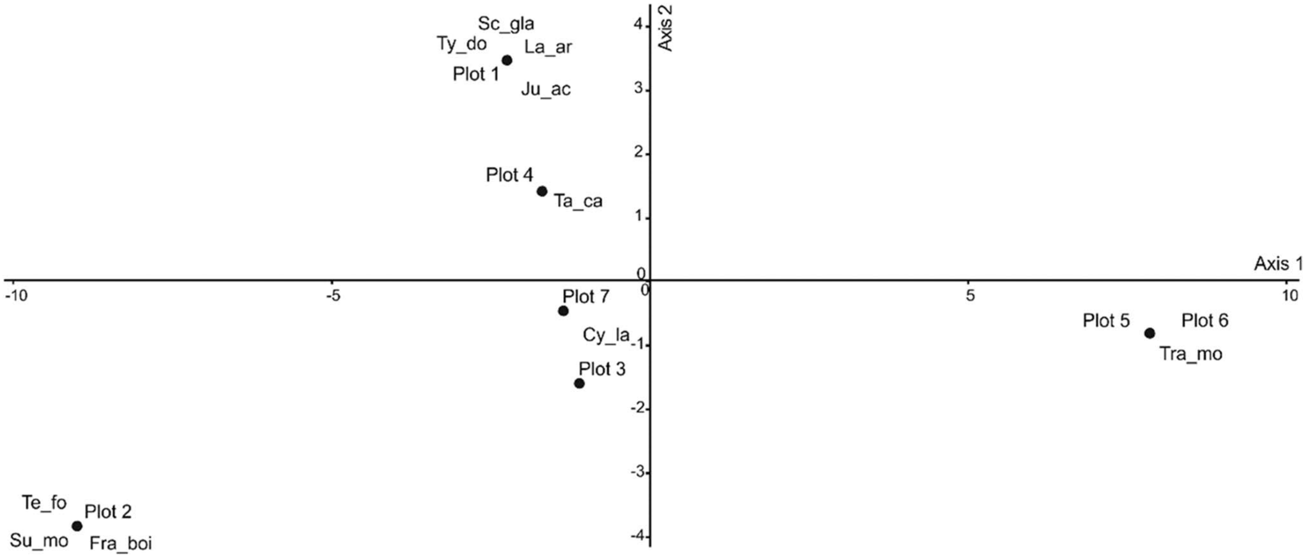

Fig. 9 CCA ordination of relevés according to salinity, depth of the water table and pH on the first two axes. The main plant species are represented (taxon abbreviations are the 2 first letters of genus and species names)

varies according to the salinity, pH, and depth of the water table.

In dune slacks with high salinity values (24.3 mScm^{-1}), the predominant plant community is *Tetraena fontanesii* (Table 4). Areas of medium salinity (values from 7.2 to 15.6 mScm^{-1}) are characterized by *Cyperus laevigatus*, *Tamarix canariensis* and *Traganum moquinii* plant communities, while the *Juncus acutus* plant community predominates in areas with lower salinity (5.7 mScm^{-1}; Table 4).

In dune slacks with lower mean pH values, plant communities of *Juncus acutus* (pH = 7.4), *Tetraena fontanesii* (pH = 7.5) and *Tamarix canariensis* (pH = 7.6) develop. When pH is about 8, plant community of *Cyperus laevigatus* develop, and for higher pH (> 8.1) *Traganum moquinii* plant community (pH = 8.4–8.9).

In dune slacks with lower mean water depths (44.1 and 48.0 cm) *Traganum moquinii* plant community develop. *Tamarix canariensis* community develop on dune slacks with a greater water depth (51.1 cm), followed by *Cyperus laevigatus* (48.6 and 54.0 cm) and *Tetraena fontanesii* (55.7 cm) plant communities. *Juncus acutus* plant community develop on dune slacks with the greatest water depth (56.5 cm).

Discussion

Tidal effect

An exponential equation ($Y = 29.8e^{-0.02X}$) accurately describes the relationship between tidal oscillations (Y) and distance (X) from the ocean shoreline ($R^2 = 0.99$, Fig. 3), enabling modelling of the tidal effect on the shallow water table (Parlange et al. 1984; Li et al. 1997). This function is in accordance with the behaviour of unconfined aquifers and allows prediction of the slight influence of tidal oscillations up to 350 m from the shoreline (Lanyon et al. 1982; Li et al. 2000).

In unconfined aquifers, the concepts of storage coefficients near the water table are important parameters to understand the response of tidal waves. Attenuation and time lag are determined by hydraulic conductivity (horizontal and vertical) and the specific elastic storage of the sediments (Vandenbohede and Lebbe 2007). In a shallow well at the same location, tidal fluctuations were found to be substantially low, as in our study. In addition, fluctuations of water table depth were small at this site because of the generally relatively small difference between low and high tides (A. Vandenbohede personal communication).

The highest estimated value of saturated hydraulic conductivity for the Maspalomas water table (520 m/day: ~ 0.7 cm s^{-1}) is in the same order of magnitude as estimated by Boufadel (2000), applying Hazens's formula (~ 0.3 cm s^{-1}) and measured with the falling head test (~ 1.0 cm s^{-1}; Cedegren 1967; Boufadel 2000) for unconfined sandy coastal aquifers.

Topography and capillarity effect

Topography seems to control the shape of the water table only in hydrological wet situations, when the preferential flows are towards the shoreline (Figs. 5 c, d, e, and g). The capillarity effect on the shallow water table of coastal aquifers was evaluated in the work of Jeng et al. (2005a). They established a capillarity correction at around 2% of the water table fluctuations due to tidal oscillation (H). In our work, H ranged from 0 to 7 cm (Table 4) and 2% of this value is less than 0.14 cm. This value was much lower than the calculated margin of error (standard deviation, sd) of the shallow water table level (Table 2) and may therefore not describe the shape of this water table.

Shallow water table seasonality

Mean shallow water table levels in hydrological dry and wet periods did not significantly differ, as shown by the standard deviation values of Table 2, and only indicated a trend towards an increase in the water table level in wet periods. Nonetheless, an oscillation trend between hydrological dry and wet periods can be observed from the time series in Fig. 6. Both dry periods were characterised by a drop in the shallow water table level. In contrast, water table levels were higher during the wet periods. Moreover, with a delay (Fig. 6), the maximum rainfall periodicity defined the morphology of the shallow water table in hydrological damp periods, with a water flow trend towards the Maspalomas shoreline. In contrast, hydrological dry periods may be characterized by preferential fluxes towards the lagoon. This change in the morphology could be due to the drop in the water level of the lagoon in hydrological dry periods, increasing the water flow towards the lagoon, as has been suggested by other authors (Almunia et al. 1999; Hernández 2002). In addition, the highest lagoon levels produced a sloping water table from the lagoon towards the dunes, as shown in Fig. 5a, d, e, and g. In the same way, in a hyper-arid system, river fluxes create an elevation of the surrounding water table level, sloping to outside the channel (Hou et al. 2007).

There are three major water inputs to the dune system, the marine aquifer, the natural fluvial aquifer, and the water from the surrounding developed areas (stormwater pipelines and irrigation). Occasionally and over a few days per year, fluvial water runs along the canal of the ravine mouth, flooding the lagoon. The oscillation of the marine aquifer affects the shallow water table in the proximity of the shoreline (about

350 m). The contribution of this oscillation was factored into the margin of error with respect to the mean values. The influence of the fluvial aquifer on the shallow water table is lower in dry and higher in wet periods, with the lagoon level known to oscillate more than 1 m between these conditions (data provided by the *Servicio de Medio Ambiente, Cabildo de Gran Canaria;* Environmental Service of the Gran Canaria Island Government). Generally, urban run-off provides a consistent input of water to the aquifer due to the steady year-round tourism.

Water content, evaporation rates and salinity profile

The mean rainfall in Maspalomas area (81 mm/year) is insufficient to recharge the subsurface aquifer, with presumably the lateral inputs of the ravine and urban areas being the main sources of water to the shallow water table.

The evaporation front in the dune slacks rises to the surface and hence may be classified as the first stage of evaporation (Gowing et al. 2006). In this situation, the water bulk of the sediment is enough to keep the surface damp. During daytime periods of maximum evaporation, the surface of the dune slacks area becomes extremely dry and the evaporation front recedes to a few centimetres below the surface. This condition may be classified as the second stage of evaporation (Gowing et al. 2006).

The evaporation values are overestimated as matrix stresses were not included in the calculations. What was being explored here (even when these are overestimated) was the effect of vertical fluxes on the water table. If the lateral fluxes of this sandy substrate are estimated at 520 m/day, the vertical fluxes due to the evaporation effect (even when overestimated to the extent of 114–129 mm/day, Table 5) are three orders of magnitude less than the lateral fluxes. As a result, they may be irrelevant to the shape of the Maspalomas water table.

Evaporation seems to be high in the upper few centimetres of the surface sediment, as has been seen from saline accumulation at the top and close to the surface (Rose et al. 2005; Gowing et al. 2006).

Finally, the dune slacks are flooded by ocean waters during extreme storm events, as occurred twice over the study period (April of 2006). These events increase the shallow water table salinity, and the ground water content. It is also possible that surface evaporation concentrates salt in the top few centimetres of the surface .

Table 6 Pearson correlations between the CCA axes and the environmental variables

Axes	Water table depth	pH	Salinity
1	-0.814*	0.863*	-0.718
2	0.930	-0.263	-0.806*
3	-0.210	-0.077	-0.109

*$p < 0.05$

Relationship between water table and dune slacks vegetation

The plant communities associated to the dune slacks in the Maspalomas dune field were the same habitats as found in a previous study (Hernández-Cordero et al. 2015b). Group A (*Juncus acutus* community) with dune slack of stabilized dunes; group B (*Tetraena fontanesii* community) with high salinity of the dune slack water table, and groups C, D and E (*Cyperus laevigatus*, *Tamarix canariensis* and *Traganum moquinii* communities) with dune slack of mobile dunes. The slacks of mobile dunes have the particularity that they move progressively together with the advance of barchanoid ridges, which generates space–time changes in short periods of time (Hernández-Cordero et al. 2015a).

The analysed parameters of the water table (depth, salinity, and pH) explain 54% of the vegetation distribution variance from the dune slacks habitats. In consequence, other non-controlled factors are influencing these habitats. Other dune field studies in temperate climate regions have concluded that plant burial by sand is the main factor in the distribution of dune slack habitats (Ranwell 1959; Willis et al. 1959; McLachlan et al. 1996; Elliott et al. 2000). In Maspalomas, dune mobility constitutes an environmental factor of habitat distribution in humid slacks (Hernández-Cordero et al. 2015c). Thus, the plant communities of *Traganum moquinii*, *Tamarix canariensis* and *Cyperus laevigatus* developed in the humid dune slacks located between the ridges of mobile dunes (sampling points 3, 4, 5, 6 and 7). These plant communities present specific spatial distribution patterns in response to the advance of the dunes over the slacks (Hernández-Cordero et al. 2015a). *Juncus acutus* and *Tetraena fontanesii* communities (plots 1 and 2) are located in the humid slacks of stabilized and semi-stabilized dunes, respectively, because they do not present adaptive responses to burial by sand.

Water table depth and floods are the second most important parameters in the distribution of vegetation in humid slacks because they condition species composition and abundance (Willis et al. 1959; Ranwell 1960; Jones and Etherington 1971; Van der Laan 1979; Studer-Ehrensberger et al. 1993; Muñoz-Reinoso and De Castro 2005). Interannual variations of these parameters also determine vegetation development, as there is mass plant mortality during drought periods in dune slack plants, especially in seedlings, as is the case of *Pinus pinea* (Muñoz-Reinoso and De Castro 2005). During floods, plant survival depends on its ability to redistribute the low amounts of oxygen that are available from its roots to its aerial parts (Studer-Ehrensberger et al. 1993). However, when aerial parts are also submerged, oxygen redistribution is not possible and only those species that are endowed with rhizomes can survive the prolonged deprivation of oxygen (Studer-Ehrensberger et al. 1993). Therefore, in temperate dune fields plant distribution is related to interspecific competition which depends on species tolerance to winter flooding (Studer-Ehrensberger et al. 1993). In the case of Maspalomas, the dune slacks have experienced episodes of seawater flooding on several occasions. Only two (*Juncus acutus* and *Cyperus laevigatus*) of the ten plant species identified have rhizomes. Likewise, the phanerophytes *Traganum moquinii, Tamarix canariensis* and, above all, *Tetraena fontanesii* are resistant to salt water.

The water table depth on which humid slacks depend may experience seasonal variations ranging between 40 and 100 cm (Ranwell 1959; Roxburgh et al. 1994; Grootjans et al. 2002; Van der Hagen et al. 2008; Jones et al. 2017), reaching in some places up to 200 cm (Jones et al. 2006). In Maspalomas, the water table experiences relatively low seasonal depth variations, from 41 cm (plot 1) to 17 cm (plot 5). The location of the Maspalomas dune system over an alluvial fan, formed at the mouth of the hydrographic basin of the Fataga ravine, has favoured the accumulation of groundwater. However, arid climatic conditions, with a water deficit throughout the year, irregular interannual rainfall and a very marked dry season during the summer cannot explain the stability of the water table. This could be due to the presence of a unique, island-wide aquifer, which produces a flow towards the coast from the central rainy recharge area which is positioned at 1000–1500 m altitude and where there is an estimated maximum annual recharge of 1400 mm and an annual flow to the south coast of 0.90 hm^3 (MOP–PNUD 1975). This is favoured by the high permeability of the sedimentary materials of the dune field compared to volcanic materials (MOP–PNUD 1975). Locally, water contributions could also be generated from the tourist developments and the nearby golf course.

In the Maspalomas dune field the fact that the water table flux towards the shore occurs during the climate dry season (May–September; Fig. 5) could be favouring the survival of the plants of the humid slacks located closer to the coast. This would explain the observed concentration of hygrophilous and halophilous vegetation (*Juncus acutus*, *Cyperus laevigatus*, *Tetraena fontanesii* and *Traganum moquinii* communities) associated to the EU Habitat 2190 humid dune slacks at distances of 100–700 m from the shore (Hernández-Cordero et al. 2015c).

The development of these habitats also depends on the formation of new humid slacks. In this regard, the environmental changes generated by the development of tourism in Maspalomas have produced an increase in deflation surfaces, leading in turn to an increase in most of the vegetation associated with the dune slacks (Hernández-Cordero et al. 2017). However, if the effects of tourist buildings continue in the future, there could be the possibility of a more pronounced decrease in the volume of sand, with a probable increase in marine erosion and coastline erosion negatively affecting to the EU habitat 2190 Humid dune slacks.

Another important factor that determines the distribution of vegetation in the Maspalomas humid slacks is water table salinity. More saline waters favour the development of plant communities dominated by halophilous species, such as *Tetraena fontanesii*. This species is resistant to marine spray and is always found near the coast. As salinity decreases, suitable conditions are established for the development of other plant communities according to this gradient: *Cyperus laevigatus*, *Tamarix canariensis*, *Traganum moquinii* and *Juncus acutus*. In the case of *Cyperus laevigatus*, it is also located in slacks with significant salinity in other geographical areas such as Egypt (Ali 2014). The resistance of *Tamarix canariensis* to salinity is associated to its ability to excrete it at night in the form of dew (Barry and Luque 1998). In Maspalomas, *Traganum moquinii* is located near the shore and in areas with active aeolian sedimentary processes, making it a halo-psammophilous species (Hernández-Cordero et al. 2015c, 2017). Therefore, it is likely that its spatial distribution would be more related to the two environmental factors indicated above than to salinity. The distribution of *Juncus acutus* in slacks with lower water salinity may be related to the fact that the germination capacity of its seeds is optimal in low salinity conditions (Boscaiu et al. 2011).

Humid dune slacks are considered a threatened habitat in Europe due to loss, physical damage, eutrophication, overgrowth through lack of grazing, interference with natural hydrological processes and climate change (Houston 2008; Jansen et al. 2016; https://forum.eionet.europa.eu/european-red-list-habitats/library/terrestrial-habitats/b.-coastal/b1.8a-atlantic-and-baltic-moist-and-wet-dune-slack). Therefore, their conservation requires an adequate knowledge of the ecological and dynamic characteristics of this type of habitat, as well as the environmental impacts that may affect them in each specific geographic space. In the case of Maspalomas, tourism development has produced significant ecological and geomorphological changes (Hernández-Cordero et al. 2017, 2018). These changes, as well as a reduction and worsening of the quality of the island's groundwater and an increase in coastal erosion, which are a consequence of improper land use and global climate change, are challenges that need to be tackled to allow the proper management and conservation of the EU habitat 2190 humid dune slacks.

Conclusions

The study of the dynamics of the water table of the Maspalomas humid dune slacks and their associated vegetation has enabled a better understanding of the characteristics of the EU Habitat 2190 humid dune slacks. Such knowledge can potentially be used to improve the management of these slacks. This is especially significant considering that in the Canary Islands humid dune slacks are only present in Maspalomas (Hernández-Cordero et al. 2015b), and that this is the only arid climate dune field in all of Europe where this habitat can be found. Their conservation is therefore essential for the maintenance of the biodiversity of the Canary Islands and indeed Europe.

The knowledge acquired in this study of the characteristics (depth, pH and salinity) and dynamics of the Maspalomas water table has enabled a better understanding of the spatial distribution patterns of the vegetation of these slacks, in particular with respect to the relationship between the water table flux toward the coast during the dry season and the distribution of plant communities in the slacks closest to the coast.

Conservation of the EU habitat 2190 humid dune slacks will depend on preservation of the water table. In turn, this will depend on future weather conditions (at local and regional scale), the impact of tourist use and climate change (which could increase marine erosion), and groundwater management throughout the island given that the existing aquifer in Maspalomas is probably fed by an island-wide aquifer which relies on the contributions of water collected in areas located at higher altitudes.

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