The development of a Beach Vulnerability Index (BVI) for the assessment of erosion in the case of the North Cretan Coast (Aegean Sea)*

George Alexandrakis*[1], Serafim Poulos[1], Stelios Petrakis[1] & Michael Collins[2]

[1]Department of Geography & Climatology, Faculty of Geology & Geoenvironment, National & Kapodistrian University of Athens, Panepistimioupolis-Zografou, 15784, Greece

**e-mail: g_alex@geol.uoa.gr*

[2]School of Ocean and Earth Science, Southampton Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK

ABSTRACT: The beach vulnerability Index (BVI) that is presented in this study is dedicated to the assessment of vulnerability to erosion in the case of beach zones developed in microtidal environment, experiencing significant nearshore hydrodynamics. This approach combines the coastal system's susceptibility to change, with its natural ability to adapt to changing environmental conditions, including relative sea level change. The index incorporates a quantitative, although relative, measure of the coast's natural vulnerability to the effects of erosion processes. Subsequently, the developed BVI has been applied to two beach zones (i.e. Ammoudara and Almiros) located on the northern coast of Crete. It is revealed that the most important variables that control the beach zone evolution; in general and in particular the areas under investigation are the grain size, beach morphology and incoming wave energy. In the case of the Ammoudara beach zone, the western part is the most vulnerable as it is unprotected by a submerged reef, whose presence reduces, drastically, the incoming wave energy over its central and eastern parts. Along the shore of the Almiros beach zone, it is the western part less vulnerable to erosion processes, as it is 'sheltered" to the dominant NW incoming waves. It has also to be mentioned that the index values could not be used for comparison between different beach zones, as the maximum possible variability (100%) for individual parameters was not common between them.

Key-words: *beach zone, vulnerability, erosion, Crete*.

ΠΕΡΙΛΗΨΗ: Στην εργασία αυτή παρουσιάζεται ένας δείκτης για την εκτίμηση της τρωτότητας των παραλιακών ζωνών στη διάβρωση, οι οποίες έχουν αναπτυχθεί σε μικροπαλιρροιακά περιβάλλοντα και υπόκεινται σε σημαντικές παράκτιες υδροδυναμικές (κυματικές) συνθήκες. Η προσέγγιση αυτή συνδυάζει την τρωτότητα του παράκτιου συστήματος σε περιβαλλοντικές μεταβολές, συμπεριλαμβανομένης της σχετικής ανόδου της στάθμης της θάλασσας, με τη φυσική του ικανότητα να προσαρμόζεται σε αυτές. Ο δείκτης τρωτότητας δίνει τη δυνατότητα ποσοτικοποίησης των διεργασιών που προκαλούν τη διάβρωση. Ακολούθως, ο δείκτης τρωτότητας εφαρμόζεται σε δύο παράκτιες ζώνες (Αμμουδάρας και Αλμυρού), οι οποίες βρίσκονται στη Βόρεια ακτή της Κρήτης. Κατά τη διαμόρφωση του δείκτη προέκυψε ότι οι σημαντικότεροι παράγοντες που ελέγχουν την εξέλιξη μιας παραλίας είναι το μέγεθος των κόκκων, η μορφολογία της παραλίας και η ενέργεια των προσερχόμενων κυμάτων. Στην περίπτωση της παράκτιας ζώνης της Αμμουδάρας, το πιο τρωτό τμήμα είναι το δυτικό, καθώς δεν προστατεύεται από το βυθισμένο ύφαλο, η παρουσία του οποίου μειώνει δραστικά την κυματική ενέργεια στο κεντρικό και ανατολικό της τμήμα. Στη περίπτωση του Αλμυρού, το δυτικό τμήμα είναι το λιγότερο τρωτό καθώς λόγω της παράκτιας μορφολογίας 'προστατεύεται' από τα επικρατούντα ΒΔ κύματα. Θα πρέπει επίσης να σημειωθεί ότι ο δείκτης τρωτότητας δεν δύναται να χρησιμοποιηθεί για σύγκριση μεταξύ διαφορετικών παραλιακών ζωνών, καθώς η μέγιστη μεταβλητότητα(100%) κάθε παραμέτρου του δείκτη δεν είναι κοινή μεταξύ τους.

Λέξεις-κλειδιά: *Παραλιακή ζώνη, τρωτότητα, διάβρωση, Κρήτη.*

INTRODUCTION

Coastal erosion is defined as the long-term loss of shore material (by volume) relative to fixed reference line (baseline) and an initial reference volume to seaward of this line, above some arbitrary vertical datum (Basco, 1999). Coastal erosion is accompanied always by shoreward recession of the shoreline and, whether it refers to natural or anthropogenic causes, results in significant economical losses, social problems, and ecological damage (Weide *et al*., 2001).

In the Mediterranean region, coastal erosion has been a longstanding, large-scale issue around deltaic areas, such as those of the Nile and Po Rivers, together with other smaller deltas such as those of the Albanian rivers (Poulos & Collins, 2002). It has also been a major issue at smaller scales, especially to the resort beaches along the (relatively) more densely developed northern coastline. More than 40% of beaches in France, Italy and Spain have been found to be eroding in the EU project CORINE, completed in 1990. According to the Atlas of Italian Beaches (Fierro & Ivaldi, 2001), 27% of the Italian beaches (that represent the 61% of the overall Italian coastline), are retreating. In Greece, coastal retreat affects also tourist beaches, e.g. the northern coast of Samos Island (Bleta *et al*., 2009), the NW beach zone of Lefkada island (Ghionis *et al*., 2008), Kato Axaia (Poulos & Chronis, 2001), Erresos beach on Lesvos Island (Velegrakis *et al*., 2008) and Gouves beach in Crete (Bouziotopoulou *et al*., 2006).

The purpose of the present contribution is the develop-

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ment of an index for the evaluation of the vulnerability of beach-zones, to erosion; this may be due to natural processes, climatic change and/or to human activities. By definition, the beach zone vulnerability assessment includes both anticipated impacts and available adaptation options. According to IPCC (1992) this is referred primarily to the impacts of the climatic change on coastal zone.

The concept of the development of an index dedicated to the vulnerability assessment of the beachzones has its origins in the Coastal Vulnerability Index; this was used initially by GORNITZ (1990), for the East coast of the United States. The Coastal Vulnerability Index (CVI) was modified by altering the algorithms used for the estimation of the contribution of the variables examined (GORNITZ *et al.*, 1994), as well as to the sensitivity index employed by SHAW *et al.* (1998). It has been used by Hammar-Klose and Thieler for the estimation of the future shoreline response to a possible sea-level rise for the U.S. Atlantic Coast and the Gulf of Mexico (HAMMAR-KLOSE & THIELER, 2001). According to this approach, different classes of vulnerability ranging from low to very high, related to climatic change (i.e. sea level rise), can be attributed to different coastal sections, defining the relative susceptibility of a coast (LOZANO *et al.*, 2004).

In contrast, the proposed Beach(zone) Vulnerability Index (BVI) refers, spatially, to the smaller scale of a single beach-zone; likewise to short periods of time. The BVI takes into account individual extreme events (e.g. storms), which often contribute considerably to the erosion of a particular beach zone. BVI is an indication of which part of a beach is more

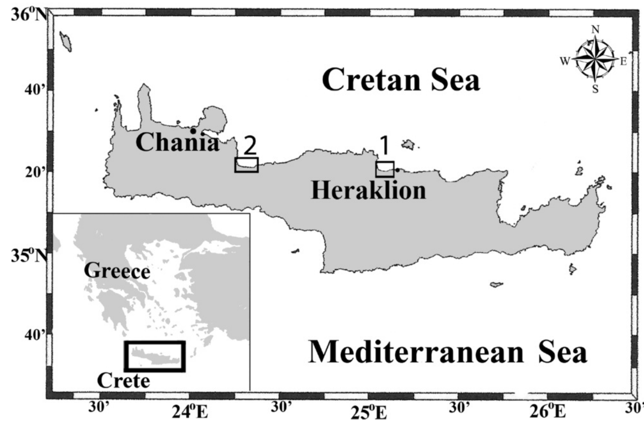

Fig. 1. Locations of the Ammoudara (1) and Almiros (2) beach zones in relation to Crete and Greece.

probable to be eroded, if erosion due to any cause occurs, whilst CVI is a measure of how vulnerable exclusively to sea-level rise is a coastal section. Here, the development and application of such an index concerns microtidal marine environments exposed to wave activity, such as those of the eastern Mediterranean.

STUDY AREAS

For the application of the newly formed BVI, two study areas have been selected on the northern coast of Crete Island: the Ammoudara and the Almiros beach zones (Fig.1).

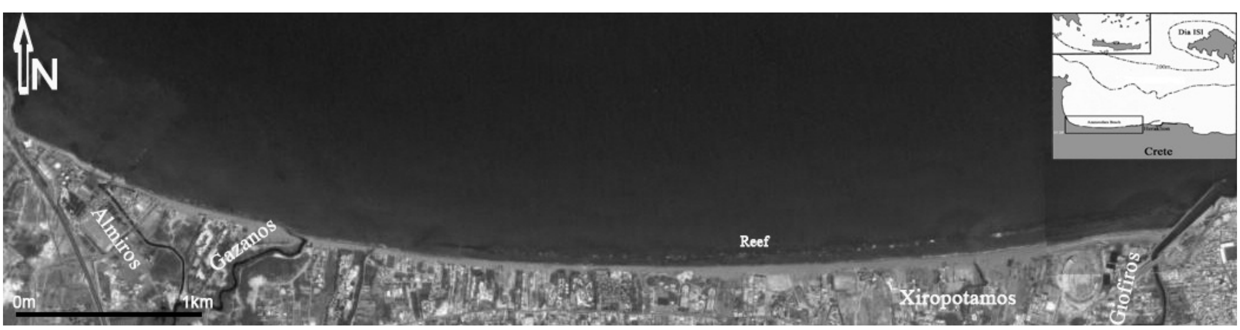

Fig. 2. Map of the Ammoudara beach zone (from Google earth, 2003).

Fig. 3. Map of the Almiros beach zone (from Google Earth, 2003).

Ammoudara beach zone

The beach zone of Ammoudara (Fig. 2) is located on the northern coast of Crete, approximately 2 km to the west of Heraklion. The total coastline length here is 6.1 km, trending from W to E; it is slightly curved and has a subaerial width of up to 60 m. The beach is formed in front of an alluvial plain and is associated with a sand dune field (with heights <3 m). Small rivers, Gazanos (192 km^2), Xiropotamos (35 km^2) and Giofiros (279 km^2) discharge into the shoreline whilst, at its western part, there is the karstic spring of Almiros (Fig. 2). The inland part of the dune field, formed by fluvial illuviation, includes a low-lying region, where elevations lie either very close to present sea level, or even below it. The actual seaward limit of the central and western part of the Ammoudara beach zone (from the mouth of R. Gazanos to that of the R. Giofiros) is established on the basis of the presence of a submerged coastal reef. The reef has a length of approximately 4 km, a mean width of around 35m and is located at a distance of approximately 60 m from the shoreline, (where average water depths are 2.6 m). On its seaward side, water depths exceed 3 m; to landward they are less than 2 m. The height above the seafloor exceeds 0.8 m whilst, in places it is less than 0.5 m from the sea surface. To the west of the mouth of R. Gazanos, this submerged reef continues to be attached to the beach face, as a typical beach-rock formation; it is absent in front of any of the river mouths. On the basis of these observations and considering its internal structure and overall morphology, Alexandrakis *et al*. (2007) concluded that the reef is a submerged beach rock formation; as such, it is indicative of the position of a former, now submerged, coastline, associated with relative sea level rise.

The beach zone under investigation, as part of the northern Cretan coast, undergoes minimal astronomical tidal ranges (<10 cm) (Tsimplis, 1994). The maximum observed elevation of sea level, due to meteorological forcing, can reach the 1 m (Hydrographic Office, 2005). The beach is exposed primarily to northerly (NW, N and NE) wind-induced waves, with NW winds being the most frequent, representing an annual occurrence of 28.9%. Generally, wave heights are less than 2m (88%), with 36% being less than 0.5 m, with only 2% higher than 4 m, on an annual basis (Athanasoulis & Skarsoulis, 1992). Likewise, 77.3% of annual offshore wave periods are less than 5 s, with waves with periods greater than 11s being only 0.74%. The maximum wave conditions are induced by the most frequently occurring NW and N winds, whose significant wave heights and periods occurred in January (annual frequency of occurrence=0.012%) and in March (0.032%). Thus, NW wind-induced waves have height/period values of about 2.3 m / 4.6 s, whilst the N waves have higher values of 6 m / 11 s (Ghionis *et al*., 2004).

Almiros Beach zone

The second study area, Almiros (Fig. 3), is located also on the northern coast Crete, but at its western part (Fig. 1). The length of the beach is approximately 9.5 km, having a W-E direction; it receives waves that are induced predominately by the NW, N and NE winds. The subaqueous part of the beach-zone is sandy, deepening gradually. To landwards, the beach zone is backed by a low relief dune field (<3 m), which, in many places, has been destroyed by human activities (e.g. tourist resorts, hotels, parking lots). Furthermore, the beach zone incorporates the mouths of four small rivers, Almiros (160 km^2), Delfinas (39 km^2), Mousselas (51 km^2) and Petres (140 km^2)

The beach is exposed primarily to northerly winds (NW, N and NE), with NW winds being the most abundant; these represent an annual frequency of occurrence of 25.5%. Generally, and on an annual basis, wave heights are less than 2 m (86%), with 65% being less than 0.5 m and only 0.5% being higher than 4 m (Soukisian, 2007). Likewise, 74.4% of the wave periods are less than 5 s annually, with wave periods higher than 7s occurring as much as 14.2% of the time. Maximum wave conditions, induced by northerly blowing winds, incorporate significant wave heights and corresponding periods are about 4.2 m and 9.1 s, respectively.

METHODOLOGY

The development of the Beach Vulnerability Index (BVI)

The Beach Vulnerability Index (BVI), in essential tideless environments, incorporates the hydrodynamic variables that modify the sediment budget of any beach zone evolution: (i) longshore sediment transport (Q_L); (ii) cross-shore transport (Q_C); (iii) riverine inputs (Q_R); (iv) storm surge (SS); (v) wave run-up (WR); and, (vi) aeolian sediment transport (Q_A). The calculation of the aforementioned variables includes the estimation of other important parameters, such as granulometry, wave conditions (e.g. significant wave height and period), geomorphological characteristics of the beach zone (e.g. beach zone dimensions, slope).

For the calculation of each variable, a number of equations have been selected from the bibliography, taking under consideration the incorporation of the most important parameters that modulate sediment budget, their applicability to different (microtidal) environments, and the feasibility of the estimation of the individual parameters involved, with respect to fieldwork measurements. The selected relationships are summarized below:

(I) Longshore sediment transport is given by Komar's (1998) equation:

$$Q_L = 1{,}1\ \rho\, g^{3/2}\, H_b^{5/2}\ \eta\mu(\alpha_b)\sigma\upsilon\nu(\alpha_b) \quad (1)$$

where, Q_L is potential volumetric longshore transport rate (m^3/day), ρ is water density; g is the acceleration of gravity, H_b is breaking wave height and a_b is wave crest angle at breaking.

(II) Cross-shore sediment transport (Qc) is provided by the Bailard & Inman's (1981) equation:

$$Q_L = \rho C_D u_b^3 \left\{ \frac{\varepsilon_B}{\tan\phi} \left(\psi_1 + \frac{2}{3}\delta_u - \frac{\tan\beta}{\tan\phi} u_3^* \right) + \frac{u_b}{w_s} \varepsilon_s \left[\psi_2 + \delta_u u_3^* - \frac{u_o}{w_s} \varepsilon_5 u_3^* \tan\beta \right] \right\} \quad (2)$$

where, $\varepsilon_B = 0.2$; $\varepsilon_S = 0.025$; C_D is the drag coefficient, w_s is sediment fall settling velocity, φ is the angle of repose, β is beach slope, u_b is near bed water velocity, ρ is water density, and, ρ_s is the density of the sediment. Variables δ_u, ψ_1, ψ_2, ψ_1, u_3^* and u_5^* refer to cross-shore velocities and depending upon the significant wave height are provided by Bailard (1982).

(III) The riverine sediment input (Q_R) is provided by the Hovious' (1998) equation:

$$\ln E = -0.416 \ln A + 4.26 \cdot 10^{-4} H + 0.15T + 0.095T_R + 0.0015R + 3.58 \quad (3)$$

where, A is drainage area, E is sediment weight (gr/m^2), H is the maximum elevation of the drainage basin, T is mean temperature, T_R is temperature range; and R is river run off.

In the following application of the BVI, this parameter omitted, due to the small size of their drainage basin and the human intervention along their routes, that has minimised (if not stopped) their sediment fluxes.

(IV) The effect of storm surge (SS), incorporating also a relative sea level rise, variable (S) is calculated from Dean's (1991) semi-empirical relationship, which combines the storm effect and the Bruun's rule (Bruun, 1962):

$$R_{SS} = (S + 0.0068 H_b) \cdot \left(\frac{Ws}{B + h_b} \right) \quad (4)$$

where, S is relative mean sea level rise (in m), W_s is the surf zone length, B is berm height, H_b is the wave breaking height and h_b is the breaking depth.

(V) The wave run-up (WR) is given from Mase's (1989) equations for:
breaking waves:

$$\frac{R_W}{H_0} = 2.32 \xi_0^{0.17} \quad (5a),$$

and non-breaking waves:

$$\frac{R_w}{H_0} = \sqrt{2\pi} \cdot \left(\frac{\pi}{2B} \right)^{1/4} \quad (5b)$$

where, Ho is the offshore significant wave height; B is the berm height, and ξ: the Irribaren number (from Irribaren & Nogales, 1949)

$$\xi_o = \tan\beta \sqrt{\frac{L_0}{H_0}},$$

where β is the beach slope and Lo and Ho are the wave length and the offshore significant wave height, respectively.

(VI) The aeolian transport (Q_A=q) variable is provided by the Hsu (1986) equation:

$$q = V_a P_a (e^{-0.63+0.91D}) \left[\sqrt{\frac{U_x}{g d_{50}}} \right] \quad (6)$$

where, *q* is the sand transport rate (in gm/cm/s), U_x is the shear velocity, *g* is the acceleration due to gravity, d_{50} is the mean grain diameter; *Va* is the air kinematic viscosity and *Pa* is the air mass density.

Subsequently, numerical values of the variables involved in the BVI, are transformed into percentages, ranging between 0.00 (0%) and 1.00 (100%); this is based on the assumption that 0% represents zero value of variability, whilst 100% corresponds to the highest possible (potential) variability for each individual variable. In addition, variables associated with the addition and/or removal of sediment from the beach zone (e.g. cross-shore sediment transport), will be assigned as either negative or positive. The maximum values of each variable are calculated using the highest values of the parameters involved. Finally, the BVI values are derived using equation 7:

$$BVI = \frac{Q_L + Q_C + WR + SS + Q_A}{5} \quad (7)$$

For the application of the BVI, each beach zone is divided alongshore, into sections of appropriate length according to the anticipated variability. The data required were obtained either from numerical model outputs (e.g. wave heights, breaking height and angle) and/or from field measurements.

Data collection and methodology related to the BVI application in the case of Ammoudara and Almiros beach zones.

For the morphological mapping of the study areas, topographic maps (1:5000, published by the Hellenic Army Geographical Service (H.A.G.S.)) and geological maps for the study areas (scale 1:50.000, published, in 1989, by the Institute of Geological and Mineral Exploration (IGME)), were used. The morphodynamic measurements included representative shore-normal profiles along the beach zone (Fig. 3), which extended from the sand dunes to the depth of 5m. Beach elevations and slopes were measured with the use of topographic rods and GPS, whilst depth soundings (at distances of every 5 m) were taken with the use of a portable echo-sounder (ZODEX), up to a water depth of 5 m. Furthermore, surficial sediment samples were collected along the profiles (6-7 samples, per section) and analysed according to the Folk (1974) procedure. 14 profiles have been investigated along the Ammoudara beach zone and 8 profiles at Almiros (for locations, see Fig. 4). In addition, the slope of beach face has been measured between the profile positions. The surficial sediment samples analyzed granulometrically were 60 from Ammoudara and 51 from Almiros. For each sediment sample, the d_{50} parameter and the angle of internal

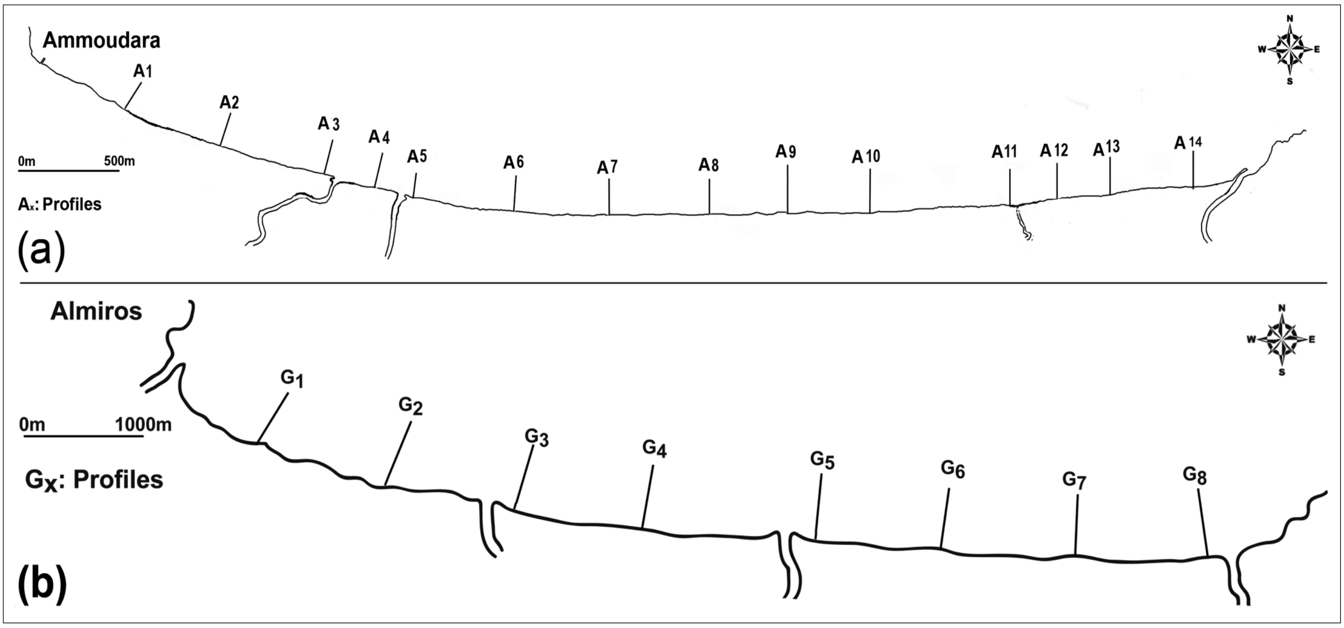

Fig. 4. Profile positions in Ammoudara (a) and Almiros (b) beach zone.

friction (Φ) were calculated, using the aforementioned equations. In addition, the width of the beach zone in each section was determined (Ws), using the measured profile length (L), berm height (B) and beach slope (tanβ).

The wave regime has been calculated with the use of the CERC (1984) equations and utilising the local wind data (mean annual frequency of wind speed and direction) provided by the Wind and Wave Atlas of the Eastern Mediterranean Sea (Athanasoulis & Skarsoulis, 1992). Thus, for any particular wind speed and direction, the significant wave height, wave period and wave length were calculated. Also, the breaking height (h_b) and depth (d_b) were calculated for each beach zone and for each wind direction. These parameters were calculated using the RCPWAVE routine of the Coastal Engineering Design and Analysis System (CEDAS) v4.0. Finally, for the relative Sea Level Rise, the estimate provided by IPCC (2007) is adopted, i.e. an average rise of 0.38 m is expected for the year 2100.

RESULTS AND DISCUSSION

Hydrodynamic, morphometric and granulometric parameters of the study areas.

In order to estimate the BVI along the sections of the beach zones of Ammoudara and Almiros, initially, the nearshore hydrodynamic parameters have been calculated. Secondly, the parameters referred to beach zone morphometry and granulometry have been derived; for the former, as the tidal signal is rather low (<10 cm) (Tsimplis, 1994), the nearshore wave characteristics have been considered and calculated, whilst for the latter the results of the *in-situ* morphological measurements and the granulometric results have been utilised.

In terms of wave climate, both the Ammoudara and the

TABLE 1

The Ammoudara beach zone: The maximum, weighted by frequency average (W.A.); the weighted by frequency average of the 4 higher values of the significant offshore wave (W.H.A.); wave period (Tp); significant height (Hs); length (Lo); breaking height (Hb) and depth (db). Data presented for the different frequency of occurrence (f), wind speed (Ua) and direction (N, NE and NW).

Direction	Value	f (%)	Ua (m/s)	Tp (s)	Hs (m)	hc (m)	Lo (m)	H_b (m)	d_b (m)
N	Max	0.01	33.91	10.39	6.91	12.67	168.45	7.40	8.86
N	W.A	0.12	8.99	6.70	1.83	3.66	70.12	2.15	2.35
	W.H.A		21.27	8.91	4.34	8.23	123.80	4.79	5.56
NE	W.A	0.04	5.87	3.62	0.58	1.15	20.49	0.67	0.75
	W.H.A		10.79	4.43	1.07	2.04	30.61	1.18	1.37
NW	W.A	0.24	8.38	2.45	0.38	0.70	9.35	0.41	0.49
	W.H.A		12.06	2.76	0.55	0.98	11.89	0.58	0.71

Note: the maximum values are shaded

TABLE 2

The Almiros beach zone: The maximum, weighted by frequency average (W.A.); the weighted by frequency average of the 4 higher values of the significant offshore wave (W.H.A.); wave period (Tp); significant height (Hs); length (Lo); breaking height (Hb) and depth (db). Data presented for the different frequency of occurrence (f), wind speed (Ua) and direction (N, NE and NW).

Direction	Value	f (%)	Ua (m/s)	Tp (s)	Hs (m)	hc (m)	Lo (m)	H_b (m)	d_b (m)
N	Max	0.01	9.48	4.98	9.43	14.79	5.48	6.38	23.18
N	W.A	16.14	6.56	1.63	3.28	10.23	1.94	2.09	7.58
	W.H.A		8.41	3.47	6.72	13.13	3.91	4.44	16.14
NE	W.A	5.87	4.87	0.85	1.73	7.60	1.03	1.10	5.87
	W.H.A		3.76	0.51	1.04	5.87	0.61	0.65	4.54
NW	W.A	6.31	2.20	0.28	0.53	3.43	0.31	0.36	6.31
	W.H.A		2.54	0.44	0.80	3.97	0.47	0.57	9.82

Note: the maximum values are shaded

TABLE 3
The geomorphological and sedimentological parameters for the 13 sections of the Ammoudara beach zone (for section's location see Figure 4a).

Geomorphological parameters															
Sections:			1	2	3	4	5	6	7	8	9	10	11	12	13
B (m)			0.6	1	1.16	2.30	1.96	1.50	0.99	1.88	3.70	3.3	2.01	2.72	3.25
W_b (m)			22	39	50	28	30	38	28	31	50	61	50	43	35
Ws (m)	Max		260	330	320	330	310	320	325	310	315	320	300	290	290
	N	WA	50	51	120	147	126	140	180	150	115	115	115	180	130
		WHA	180	280	270	240	260	270	270	260	200	210	230	230	225
	NE	WA	15	25	25	5	20	54	64	65	58	76	15	40	75
		WHA	30	60	60	70	40	70	90	85	90	85	95	137	102
	NW	WA	10	18	10	12	15	50	10	55	58	55	7	42	9
		WHA	14	15	24	14	18	52	65	68	60	70	8	43	80
Sedimentological parameters															
Sections:			1	2	3	4	5	6	7	8	9	10	11	12	13
L	d_{50} (mm)		1.86	2.20	2.36	2.77	2.71	1.76	1.95	2.78	2.16	2.38	2.69	1.78	2.75
S	d_{50} (mm)		0.30	0.25	0.24	1.52	0.80	0.57	0.84	0.55	0.59	0.86	2.50	2.28	2.75

Key: B= Berm height in m, Wb= width of the subaerial part of the beach zone in m, Ws= the width of the surf zone (in m), W.A = weighted average by frequency of occurrence, WHA = weighted average by frequency of occurrence, corresponding to the 4 highest values of the significant offshore wave height; L= subaerial samples, S= sub-aqueous samples

TABLE 4
The geomorphological and sedimentological parameters for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

Geomorphological parameters										
Sections:			1	2	3	4	5	6	7	8
B (m)			2.70	2.05	0.99	1.71	1.66	3.21	3.22	3.13
W_b (m)			80	70	45	33	22	49	36	53
Ws (m)	Max		310	320	310	315	300	310	315	320
	N	WA	180	190	134	113	76	129	117	104
		WHA	270	280	280	270	260	255	255	260
	NE	WA	120	140	104	78	28	84	71	63
		WHA	86	80	85	58	24	53	61	58
	NW	WA	81	75	47	38	22	51	58	55
		WHA	82	79	66	53	24	52	60	56
Sedimentological parameters										
Sections:			1	2	3	4	5	6	7	8
L	d_{50} (mm)		1.37	0.26	4.38	0.30	0.47	1.63	0.38	2.44
S	d_{50} (mm)		0.29	0.23	3.90	0.65	0.46	0.52	0.29	0.53

Key: B= Berm height in m, Wb= width of the subaerial part of the beach zone in m, Ws= the width of the surf zone (in m), W.A = weighted average by frequency of occurrence, WHA = weighted average by frequency of occurrence, corresponding to the 4 highest values of the significant offshore wave height; L= subaerial samples, S= sub-aqueous samples

TABLE 5
Maximum and annual longshore transport values (Q_L in 10^3 m^3/year) for the 13 sections of Ammoudara beach zone (for section's locationsee Figure 4a).

	Sections												
Q_L	1	2	3	4	5	6	7	8	9	10	11	12	13
Max	-2.76	-3.82	-1.31	-1.17	-1.20	0.95	1.08	0.29	-1.35	0.59	4.46	4.98	3.07
Q_L	-0.59	-0.76	-3.31	-3.76	-0.86	0.40	0.58	-0.09	-0.33	-0.15	0.71	1.27	1.47

(Note: + indicate that direction is from E to W).

Almiros beach zones are exposed (mainly) to N, NE and NW wind-generated waves. Hence, the corresponding wave characteristics for these wind directions have been calculated and are presented in Tables 1 and 2, respectively, for: (a) the weighted average value with respect to the frequency of occurrence of all wind speeds and (b) the weighted average value of the highest four wind speeds. For the calculation of the maximum value of the index, in both cases the N wind speed value of 33.9 m/s was used to produce the highest wave event (annual frequency of occurrence =0.01%).

The various morphometric and granulometric parameters are listed in Table 3 (Ammoudara) and Table 4 (Almiros). As can be seen, the Ammoudara beach zone has a maximum berm height of 3.25 m at Section 13, with a minimum of 0.6 m at Section 1. The width of the sub-aerial part of the beach zone (W_b) varies from 22 m (Section 1) up to 61m (Section 10). Also, the width of the surf zone (Ws) varies from 330 m at Section 2 for the maximum wave event, to 5 m at Section 4 for the weighted average value for the northeasterly direction wind events. The length of the beach profile (L) is equal to the distance between the highest point of the berm crest and the coastline, together with the distance from the coastline to the offshore end of the beach zone as it is defined by the closure depth (h_c) (L=Wb + Ws). The values of dD_{50} range from 1.76 mm (fine sand) to 2.78 mm (gravely sand), for the sub-aerial surficial sediment samples; this becomes finer in the case of the sub-aqueous samples, as they range between 0.25 mm and 2.75 mm.

For the Almiros beach zone the maximum berm height of 3.2 m appears at Section 7, with the minimum value of 0.99 m at Section 3 (Table 4). The width of the sub-aerial part of the beach zone (W_b) varies from 22 m, at Section 1, to 80 m, at Section 10. Also, the width of the surf zone (Ws) varies from 543 m at Section 8 for the maximum wave event, to 22 m at Section 5 for the weighted average value for the northwesterly direction wind events. The length of beach profile (L) has been estimated as in the case of the Ammoudara beach zone. The values of d_{50} range from 0.30 mm (fine sand) to 4.38 mm (sandy gravels) for the subaerial surficial sediment samples; this becomes finer in the case of the subaquous samples, as they range between 0.23 mm and 3.90 mm (medium to find sand).

TABLE 6
Maximum and annual cross-shore transport values (Q_C in 10^3 m^3/year) for the 13 sections of the Ammoudara beach zone (for section's location see Figure 4a).

	Sections												
Q_C	1	2	3	4	5	6	7	8	9	10	11	12	13
Max	35.49	35.98	36.01	35.17	35.30	35.54	35.46	35.43	35.32	35.33	35.09	34.93	34.80
N	9.51	7.86	8.13	8.17	8.57	8.12	7.86	8.68	8.94	8.32	8.11	8.96	9.34
NE	9.34	6.72	6.85	7.42	7.18	6.85	6.62	7.45	9.81	8.78	7.25	7.95	8.74
NW	10.81	7.13	6.85	8.62	11.40	7.15	5.52	7.32	8.62	7.68	5.65	5.43	7.35
Tot.	29.67	21.70	21.83	24.19	27.16	22.11	20.01	23.46	27.36	24.80	21.01	22.33	25.42

BVI variables for the Ammoudara Beach zone

Longshore Transport variable (Q_L)

The calculated values for the longshore sediment transport in the Ammoudara beach zone (Table 5) has shown that the dominant direction is towards the east, whilst the higher transported values refer to its western part (e.g. 13.1 10^3 m^3/year at Section 3). The annual maximum value is attributed to Section 4 (3.8 10^3 m^3/year), with the lowest (0.15 10^3 m^3/year) to Section 10. The decrease in values along the eastern part (Sections 9 to 12) is related to the pronounced presence of the submerged reef.

Cross-shore Transport variable (Q_C)

The calculated values for the cross-shore sediment transport variable (Q_s) (Table 6) reveal that the offshore sediment movement induced by the maximum wave conditions present similar values for each section, this varies from 34.8 10^3 m^3/year (Section 13) to 36 10^3 m^3/year (Section 2). Further, the lowest annual values appear to be associated with waves coming from the North (7.9 10^3 m^3/year at Sections 2 and 7 and 5.3 10^3 m^3/year at Section 1). The highest values are caused by waves approaching from the NW (from 5.4 10^3 m^3/year at Section 12, to 11.8 10^3 m^3/year at Section 1). Once again, the eastern part (Sections 11 to 13) presents the lowest values, related to the submerged coastal reef.

Wave Run-up variable (WR)

The calculated wave run-up values for each sector are presented in Table 7. Here it can be seen that all of the values refer to the maximum wave conditions exceeding the 2.2 m., with its highest value (3.1 m) in the western Section 1. Furthermore, N waves present higher WR values (0.9-2 m), the NE waves relatively lower values (0.6-0.9 m). The lowest values are given by the NW waves (<0.6 m).

Aeolian variable (Q_A)

The aeolian transport at the Ammoudara Beach zone was calculated for the weighted average value of each wind direction, considered as the most representative. As shown in Table 8, the highest transport value occurs at Section 8 for the NW winds, whilst the NE winds are not capable of setting the beach sediment in motion. Furthermore, the direction of the aeolian transport, with respect to coastline direction (westwards or eastwards) and perpendicular to it (onshore/offshore), is deduced from the direction of each wind for each of the sections. As can be seen in Table 8, the longshore aeolian transport is towards the west, whilst transport perpendicular to the shoreline is directed to seawards; this contributes, therefore, in erosion of the beach zone.

Storm Surge variable (SS)

The storm surge variable (SS) was found to be significant for the northerly winds, having values similar to those referred to the maximum wave conditions (0.35-0.45 m) (Table 9). Moreover, the weighted average (mean) values of the

TABLE 7
Wave run-up values, (WR in meters), for the 13 sections of the Ammoudara beach zone (for section's location see Figure 4a).

	Sections												
WR	1	2	3	4	5	6	7	8	9	10	11	12	13
Max	3.1	2.2	2.5	2.9	2.8	2.4	2.4	2.5	2.8	2.8	2.5	2.5	2.5
N	2.0	1.7	1.1	1.2	1.3	1.1	0.9	1.2	1.5	1.4	1.2	1.1	1.5
NE	0.9	0.6	0.5	0.8	0.9	0.6	0.5	0.6	0.7	0.7	0.5	0.5	0.7
NW	0.4	0.3	0.2	0.5	0.4	0.2	0.2	0.3	0.3	0.3	0.4	0.3	0.3
W.A.	1.1	0.8	0.8	1.0	1.1	0.8	0.8	0.9	1.0	1.0	1.0	0.9	1.0

TABLE 8
The Aeolian sediment transport parameter (Q_A in m^3/year) for the 13 sections of the Ammoudara beach zone (for section's location seeFigure 4a).

	Sections												
Q_A	1	2	3	4	5	6	7	8	9	10	11	12	13
N	0.22	1.42	2.76	16.17	12.51	0.15	0.48	17.01	1.17	3.06	11.30	0.16	14.97
NE	-	-	-	-	-	-	-	-	-	-	-	-	-
E	0.12	0.76	1.48	8.68	6.72	0.08	0.26	9.13	0.63	1.64	6.07	0.09	8.04
SE	0.14	0.58	1.13	6.64		0.09	0.20	6.98	0.48	1.26	4.64	0.10	6.14
S	0.15	0.61	1.19	6.99	5.40	0.10	0.21	7.35	0.51	1.32	4.88	0.11	6.47
SW	0.13	0.54	1.05	6.12	4.74	0.08	0.18	6.44	0.44	1.16	4.28	0.09	5.67
W	0.72	3.02	5.89	34.47	26.66	0.48	1.03	36.25	2.49	6.52	24.09	0.53	31.90
NW	0.46	2.97	5.79	33.93	26.24	0.31	1.01	35.68	2.45	6.42	23.71	0.34	31.40
Cross-	-0.06	-0.51	-0.99	-5.78	-4.47	-0.04	-0.17	-6.08	-0.42	-1.09	-4.04	-0.05	-5.35
Long-	0.14	1.31	2.56	14.96	11.57	0.09	0.45	15.74	1.08	2.83	10.46	0.10	13.85

TABLE 9
The storm surge parameter (SS in meters), for the 13 sections of the Ammoudara beach zone (for section's location see Figure 4a).

		Sections												
SS (m)		1	2	3	4	5	6	7	8	9	10	11	12	13
Max		1.65	2.00	1.90	1.73	1.68	1.83	1.97	1.70	1.44	1.52	1.62	1.46	1.38
N	WA	0.30	0.26	0.59	0.54	0.50	0.62	0.93	0.61	0.32	0.34	0.45	0.60	0.39
	WHA	1.11	1.61	1.51	1.13	1.28	1.43	1.56	1.30	0.78	0.86	1.13	1.02	0.93
NE	WA	0.09	0.12	0.11	0.01	0.06	0.19	0.30	0.20	0.10	0.15	0.04	0.09	0.15
	WHA	0.19	0.30	0.28	0.22	0.14	0.29	0.46	0.31	0.20	0.21	0.33	0.39	0.26
NW	WA	0.06	0.08	0.04	0.03	0.04	0.17	0.05	0.15	0.09	0.10	0.02	0.09	0.02
	WHA	0.09	0.07	0.10	0.04	0.05	0.19	0.31	0.21	0.11	0.14	0.02	0.10	0.16

Key W.A = weighted average by frequency of occurrence, WHA = weighted average by frequency of occurrence, corresponding to the 4 highest values of the significant offshore wave height.

TABLE 10
The values of the BVI and its variables, for the 13 sections of the Ammoudara beach zone (see also Figure 5).

	Sections													
	1	2	3	4	5	6	7	8	9	10	11	12	13	Average
Q_L	21.28	19.94	25.32	32.09	71.51	42.53	54.35	30.97	24.51	24.71	15.93	25.55	47.79	33.57
Q_C	82.42	60.28	60.63	67.18	75.42	61.41	55.57	65.17	76.00	68.88	58.32	62.03	70.60	66.46
WR	31.68	23.12	22.75	30.71	29.52	24.05	22.66	25.57	32.25	29.27	26.78	27.69	30.32	27.41
Q_A	0.63	5.06	9.87	57.78	44.69	0.42	1.72	60.77	4.18	10.93	40.38	0.46	53.47	22.33
SS	14.83	13.20	29.56	26.93	24.99	31.27	46.74	30.34	16.02	17.20	22.53	30.12	19.62	24.87
BVI	30.17	24.32	29.62	42.94	49.23	31.93	36.21	42.56	30.59	30.20	32.79	29.17	44.36	34.93

TABLE 11
Maximum and annual longshore transport values (Q_L in 10^3 m^3/year) for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

	Sections							
Q_L	1	2	3	4	5	6	7	8
Max	4.49	-2.50	-1.08	-2.30	2.02	-0.99	-1.62	2.26
Ann	1.81	0.58	0.21	0.27	0.75	0.46	0.72	0.57

(Note: + indicates that direction is from E to W).

TABLE 12
Maximum and annual Crosshore transport values (Q_C in 10^3 m^3/year), for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

	Sections							
Qc	1	2	3	4	5	6	7	8
Max	37.52	38.05	37.13	37.47	37.22	37.52	37.78	37.59
N	6.82	5.32	4.62	5.17	6.86	5.34	5.57	4.92
NE	5.74	5.88	5.35	6.25	9.60	10.72	13.53	6.66
NW	9.46	8.74	4.89	9.67	21.19	15.72	14.20	14.25
Ann. total	22.03	19.95	14.87	21.09	37.66	31.79	33.31	25.84

TABLE 13
Wave run-up values (WR in meters), for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

	Sections							
WR	1	2	3	4	5	6	7	8
Max	2.89	2.22	2.32	2.40	3.06	2.45	2.44	2.30
N	1.77	1.74	1.87	2.03	3.07	3.21	3.85	2.18
NE	0.45	0.41	0.28	0.48	0.94	0.72	0.65	0.66
NW	0.30	0.26	0.21	0.33	0.59	0.47	0.43	0.44
WHA	0.84	0.81	0.79	0.95	1.53	1.47	1.64	1.09

TABLE 14
Aeolian sediment transport parameter (Q_A in m^3/year), for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

	Sections							
Q_A	1	2	3	4	5	6	7	8
N	0.04	<0.01	-	<0.01	<0.01	0.12	<0.01	1.40
NE	0.21	<0.01	-	<0.01	<0.01	0.59	<0.01	7.11
E	0.02	<0.01	-	<0.01	<0.01	0.06	<0.01	0.56
SE	0.01	<0.01	-	<0.01	<0.01	0.08	<0.01	2.85
S	0.02	<0.01	-	<0.01	<0.01	0.09	<0.01	3.04
SW	0.02	<0.01	-	<0.01	<0.01	0.10	<0.01	3.36
W	0.09	<0.01	-	<0.01	<0.01	0.45	<0.01	14.67
NW	0.03	<0.01	-	<0.01	<0.01	0.09	<0.01	0.92
Cross	-0.12	<0.01	-	<0.01	<0.01	-0.33	<0.01	- 2.92
Long	0.14	<0.01	-	<0.01	<0.01	0.36	<0.01	1.28

northerly waves are highest at Section 7 (0.93 m) and lowest at Section 2 (0.26 m). For the NE and NW incoming waves, the maximum values (0.17-0.19 m) occur over the central part (Section 6), while the lowest values are found at Section 4 for the NE wave events (0.01 m) and at Section 13 (0.07 m) for the NW wave events.

BVI for the Ammoudara beach zone

The values of the BVI variables for each section of the beach zone are presented in Table 10. As can be seen, different variables present their maximum and minimum values at different beach zone sections; this indicates the variability of the processes operating along the different sections of the beach zone. Thus, the highest (71.51%) and the lowest value of the longshore sediment transport appear at Section 5, while the lowest values (<25%) occur at Sections 9 to 12. For the cross-shore variable, the highest value is found at Section 1 (82.42%), whilst the lowest is at Section 7 (55.57%). For the wave run-up the highest value is of the order of 32.25% at Section 9, whilst lowest (22.66%) is at Section 7. For the aeolian transport variable, the highest value is found at Section 8 (60.77%) and the lowest at Section 6 (0.42%). The BVI value for the storm surge variable was found to be lowest at Section 2 (13.20%) and highest at Section 7 (46.74%). Furthermore, the lowest SS values at Sections 9 to 13 are attributed to the submerged coastal reef, which is at a minimum distance from the sea surface in those sections.

All the calculated BVI values are presented in Table 10 and in Fig. 5. The overall BVI values range from 49.23% (Section 5) to 24.32% (Section 12), showing relatively low variability (~11%), from the average value deduced for all the Sections (34.9%). These values show that Ammoudara beach zone is moderately vulnerable to erosion.

BVI variables for the Almiros Beach zone

Longshore Transport variable (Q_L)

The derived values for longshore sediment transport for the Almiros beach zone (Table 11) has shown that the dominant direction is to the east, whilst the high values are related to the western section of the beach (e.g. 2504.16 m^3/year at Section 2). For all the calculated annual values, the direction is towards the west with the highest value at Section 8 (0.57 10^3 m^3/year). The lowest value of 1.81 10^3 m^3/year is at Section 1.

Cross-shore transport Variable (Q_c)

The maximum calculated values (Table 12) for the cross-shore sediment transport are similar along the 8 sections, ranging from 37.13 10^3 m^3/year to 38.05 10^3 m^3/year. Furthermore, the relatively lower values (4.62 -6.86 10^3 m^3/year) appear to be associated with northerly waves, whilst the highest values have been derived for the northwesterly direction (4.9-21.2 10^3 m^3/year,). On an annual basis, the values vary from 14.9 10^3 at Section 3, to 37.7 10^3 m^3/year at Section 5. In general, higher values are associated with the eastern sections (5-7).

Wave run-up variable (WR)

The values of the wave run-up variable for the 8 beach zone sections, presented in Table 13, are referred to the maximum wave conditions (regardless of direction) and to the mean values obtained from the weighted average value of the 4 highest waves (WHA), with respect to their annual frequency of occurrence.

The highest wave run-up exceeds the 2 m, being maximum at Section 5 (3.06 m). For comparison, the weighted average (HA) values range from 0.8m to 1.64 m. The highest value is associated with Section 7 for N waves, whilst the lowest (0.2 m) is at Section 3 for both, N and NW waves.

Aeolian variable (Q_A)

The aeolian transport at the Almiros Beach zone was calculated for the mean value of each wind direction (Table 14). As can be seen, the cross-shore movement presents, on an annual basis, a seaward direction for all sections; this may cause erosion of the subaerial part of the beach zone. In comparison, the longshore aeolian transport is on a westerly direction, enhancing, therefore, erosion over its eastern part and favouring accumulation to the west (Table14).

Storm Surge variable (SS)

The storm surge (SS) variable was found to have higher values in the case of the northern incoming waves. For the maximum wave conditions, the calculated values vary from 1.34 m (Section 6) to 1.8 m (Section 3). Further, the mean values of the northerly waves have their maxima at Section 3 (1.56m), being at a minimum at Section 7 (0.98 m). The NE and NW incoming waves present significantly lower values; as such, their maxima are 0.44m (Section 2) and 0.31m (Section 3), respectively, whilst their minima for both wave directions are 0.8m (Section 5).

TABLE 15
The Storm Surge parameter (SS in meters), for the 8 sections of the Almiros beach zone (for section's location see Figure 4b).

		Sections							
SS (m)		1	2	3	4	5	6	7	8
Max		1.43	1.60	1.80	1.65	1.58	1.34	1.36	1.40
N	W.A	0.58	0.71	0.68	0.46	0.31	0.37	0.34	0.31
	W.H.A	1.12	1.28	1.56	1.31	1.28	0.98	0.98	1.01
NE	W.A	0.31	0.44	0.50	0.27	0.10	0.19	0.16	0.15
	W.H.A	0.19	0.22	0.39	0.18	0.08	0.10	0.12	0.11
NW	W.A	0.15	0.18	0.21	0.11	0.06	0.08	0.09	0.09
	W.H.A	0.18	0.21	0.31	0.17	0.08	0.10	0.11	0.11

TABLE 16
The BVI values for the 8 sections of the Almiros beach zone (see also Figure 6).

	Sections								
	1	2	3	4	5	6	7	8	Average
Q_L	40.29	23.39	19.58	11.94	3.72	46.13	43.30	25.40	26.72
Q_C	57.91	52.44	39.10	55.44	98.97	83.56	87.55	67.92	67.86
WR	33.51	32.18	31.40	37.70	61.16	58.53	65.48	43.64	45.45
Q_A	1.23	0.01	0.00	0.01	0.01	3.25	0.01	29.18	4.21
SS	61.97	71.27	86.68	72.83	70.82	54.34	54.26	56.07	66.03
BVI	38.98	35.86	35.35	35.58	46.93	49.16	50.12	44.44	42.05

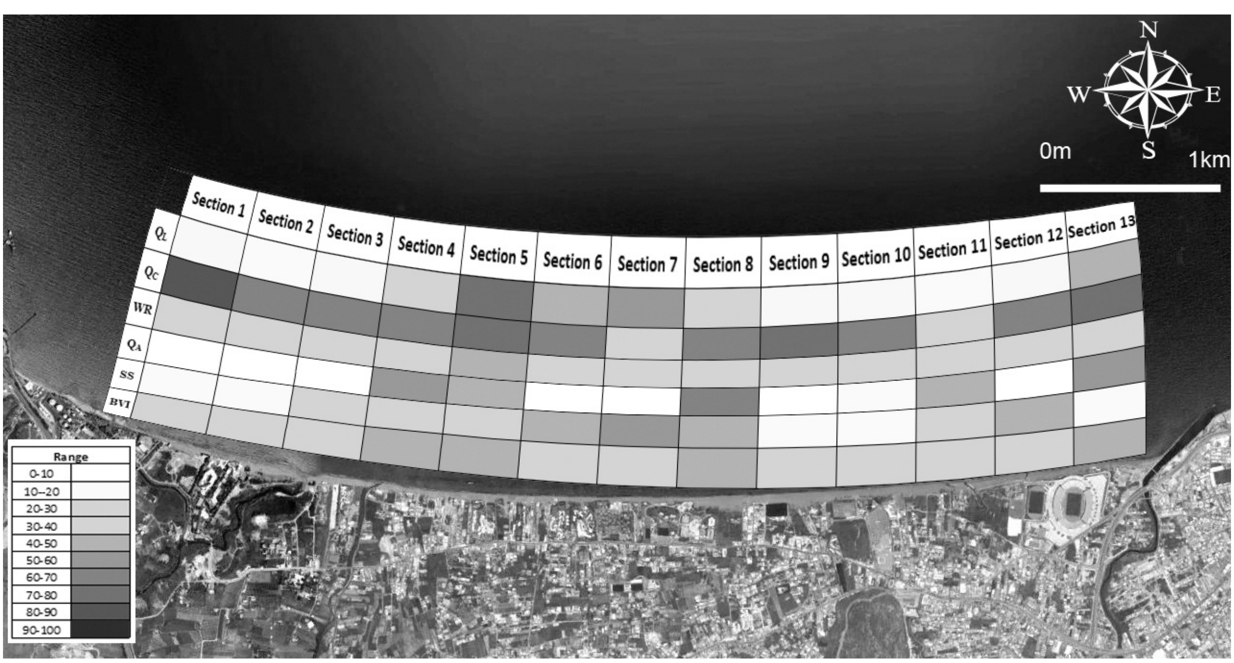

Fig. 5. Graphic presentation of the BVI variable values and the total BVI value for the 13 sections of the Ammoudara beach zone.

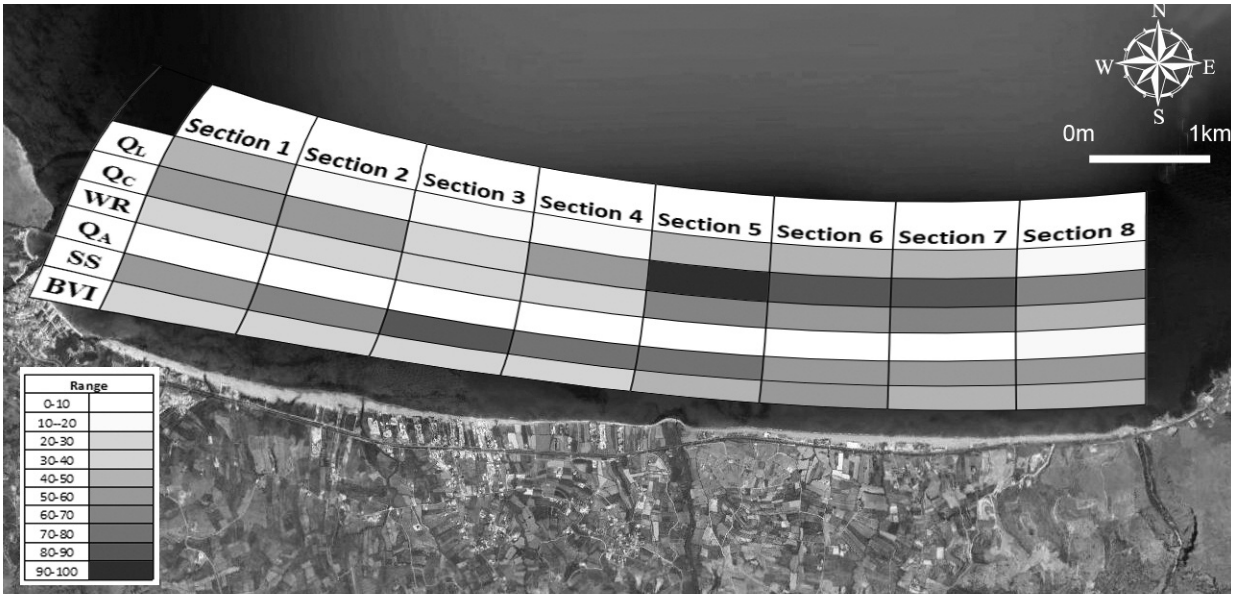

Fig. 6. Graphic presentation of the BVI variable values and the total BVI value for the 8 sections of the Almiros beach zone.

BVI for the Almiros beach zone

The BVI value for the longshore sediment transport value ranges from 11.94% at Section 4, to 43.30% at Section 7. For the cross-shore variable, the highest value is found at Section 5 (98.97%), with the lowest at Section 3 (39.10%). For the wave run-up (WR), the highest value is 65.48% (section 7) and the lowest (31.40%) at Section 3. The variable of aeolian transport (Q_A) is minimal (almost 0%) at Sections 2, 3, 4, 5 and 7, presenting its highest value at Section 8 (29.18%). The storm surge (SS) variable is associated with the highest values (>60%) over the western part (Sections 1-3) with its lowest (<55%) towards the eastern end (Sections 6 and 7).

The overall values of the BVI (Table 16, Fig. 6) show a relatively limited range, between 50.12% (Section 7) and 35.35% (Section 3), whilst the mean value for all of the 8 sections is 42.05%. These values, being below the 50%, indicate a moderate vulnerability to beach zone erosion.

CONCLUSIONS

The application of the BVI has shown that the index is capable to identify areas with different levels of vulnerability to erosion, within the same beach; this is the case of the Ammoudara beach zone, where the coastal geomorphology of the beach zone varies significantly. The vulnerability is related to the presence of a submerged coastal reef over its central and eastern part, which modifies dramatically the incoming wave energy. It is also possible to identify the dominant variable that controls vulnerability over erosion at different sectors of the coastline. For example, for the Ammoudara beach zone, the dominate parameter is longshore sediment transport; for the Almiros beach zone, the most important variable is cross-shore sediment transport. However, the index values could not be used for comparison between different beach zones, if the maximum possible variability (100%) is not common for all the beach zones incorporated into the analysis.

The application of the BVI in the case of Ammoudara and Almiros beach zones has shown that the most important variables that control vulnerability, therefore beach zone evolution, are granulometry, beach morphology and incoming wave energy. Furthermore, it has been shown that the maximum value of one variable does not coincide, necessarily, with the maximum BVI value. It has been found also that, even if a variable appears to have a maximum value over a specific section of the beach, the BVI value of this variable may not be at maximum.

On the basis of the derived BVI values, the western part of the Ammoudara beach zone is relatively more vulnerable to erosion, than its eastern part; as its central and eastern part are protected (low cross-shore sediment transport) by the presence of a reef. The opposite situation applies in the case of Almiros beach zone, where the BVI is relatively higher over its eastern part; this is on comparison to its western part, which is sheltered from the incoming NW wave energy.

A further development of the BVI should include a large number of beach zones, with a wider range of variability, such that an adequate data set can be established. Subsequently, a statistical analysis would provide the appropriate 'common' vulnerability boundaries which, in turn, could be related to different beach zones.

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