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Coastline changes in relation to longshore sediment transport and human impact, along the shoreline of Kato Achaia (NW Peloponnese, Greece)

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Abstract

Coastal configuration depends upon the equilibrium between available sediment budget and prevailing nearshore wave and current conditions. Human activities often disturb this natural equilibrium by altering the sources of beach material and littoral drift pattern. In the coastal zone of the NW Peloponnese, an essentially tideless environment, the oblique approach of wind-induced waves implies an overall longshore drift from east to west. On an annual basis, the potential longshore sediment transport rates in the different sections of the study area (Kato Achaia) is estimated to vary between 0.02 10^{-3} m^3/s and $5x10^3$ m^3/s and to fluctuate seasonally. The construction of a port and the extraction of aggregates from the R. Peiros have significantly changed the pattern of sediment transport, inducing dramatic changes in coastline configuration; thus, the part of the coastline west of the port has retreated as much as 70 m, eliminating a tourist beach, while the entrance to the port has silted up, inhibiting navigation. Coastal engineering measures, such as modification of port-breakwaters and construction of groins have made an only minimal contribution to beach recovery. Hence, coastal management plans should consider this dynamic equilibrium and protect the natural coastal system from arbitrary human activities.

Keywords: Coastal zone, Sediment transport, Shoreline erosion, Human impact, Greece.

Introduction

A shoreline is a dynamic system with sediment moving continually, being deposited here and eroded there, as the shoreline attempts to establish an equilibrium with respect to available sediment budget and prevailing nearshore marine processes. In the microtidal environment of Greek waters, shoreline morphodynamics are dominated by the existing (locally) wind-induced wave climate. Furthermore, the oblique approach of the waves generates longshore currents that transport sand parallel to the shore, if it is not intercepted and moved offshore by rip currents. Hence, the natural evolution of coastline configuration depends primarily upon the offshore wave conditions, the associated longshore current activity, coastline morphometry, sedimentary material of the sea-bed and the overall sediment budget of any coastal cell under consideration (CARTER, 1988).

Many studies, concerning the coastal zone of the Mediterranean Sea, have shown that until the beginning of the 20th century the general trend has been one of growth (LEWIN *et al.*, 1995); this has been exceptionally pronounced in the case of coastlines near river mouths. In contrast, over the last few decades human activities (e.g. construction of dams) have caused a dramatic reduction in sediment supply from the rivers, while coastal structures often disturb the natural equilibrium between the sources of beach material and the littoral drift pattern, frequently resulting in a general coastal retreat. For example, erosion has been reported not only in the case of the deltaic coasts of major Mediterranean rivers such as that of the R. Nile (Egypt) (FANOS, 1995), the R. Ebro (Spain) (MARINO, 1992), the R. Axios (Greece) (POULOS *et al.,* 1996), but also along other parts of the Mediterranean shoreline in Spain (MARQUES & JULIA, 1986), Tunis (PASKOF, 1992) and Italy (BAVESTELLO *et al.,* 1995; COLANTONI *et al.,* 1997).

The present study concerns the coastal area of Kato Achaia (NW Peloponnese, Greece) where human activities such as abstraction of aggregates from the lower reaches of the R. Peiros and the construction of a small port have caused extended changes in the coastline. The subsequent measures undertaken against changes (i.e. groins) have produced further alterations to the configuration of the coastline. For the purpose of this investigation longshore sediment transport rates are estimated, on a seasonal basis, and related to human-induced coastline changes over the last 20 years, as indicated by aerial photographs.

The Study Area

The coastal cell, under investigation, is that part of the southern coast of the Gulf of Patras (NW Peloponnese) extending from the mouth of the small R. Peiros, in the east, to the region of the coastal cliff (named "Liritzi cliffs"), in the west (Fig. 1). The Gulf of Patras is a Plio-Quaternary graben (PIPER *et al.,* 1990) with maximum water depth of 130 m. To the west, it opens into the Ionian Sea and to the east, it is linked

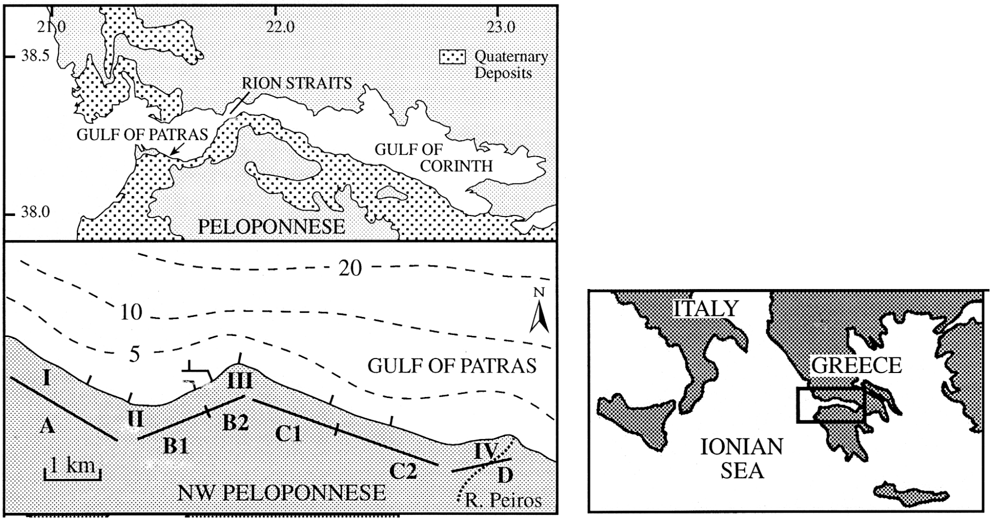

Fig. 1: The study area (I: Raxi Liritzi; II: White Castle Hotel; III: promontory; IV: river mouth).

with the Gulf of Corinth via the narrow (<2 km) and shallow (~ 62 m) Rion strait.

The coastal cell consists of recent marine and fluvial deposits of, mostly, fine-grained and loose sediments. The nearby inland zone is formed by Plio-pleistocene lagoonal deposits (i.e. Liritzi cliffs; after DOUTSOS *et al.,* 1988) and Holocene alluvial formations represented by sandy, silty and conglomerate formations (Fig. 1). In particular, the backshore area is characterised by the presence of sandy formations whice locally exceed 400 m in width and reach elevations of up to 10 m. Seaward the littoral zone deepens gently (1.5^o-4^o) reaching water depths of 10 and 20 m at distances of 1.2 and 2 km, respectively. Bed material of the nearshore zone consists mostly of sandy deposits with mean grain-diameter between 0.1 and 0.5 mm (THALASSINOS, 1988).

The coastal area under investigation, at its eastern limit, receives water and sediment fluxes from the small River Peiros; it drains a mountainous area of 437.5 km^2 with elevations exceeding 1000 m. A gross estimate of water and suspended sediment discharge of 9.7 m^3/s and $120x10^3$ tonnes/yr, respectively, have been attributed to the R. Peiros (after POULOS & CHRONIS, 1997).

The study area, as part of the Gulf of Patras, is characterised only by minimal tidal ranges (<10 cm; after TSIMPLIS, 1994). Thus, the locally wind-induced waves and associated longshore currents are expected to play the dominant role in littoral sediment transport.

Wind data (of hourly measurements for the period 1965-1985) comes from the Araxos airport, located some 30 km WNW of the study area. Wind climate is characterised by long calm periods varying from 34% (March) up to 41.3% (July) and maximum values of wind speed rarely exceeding 20 m/s. On a seasonal basis (Fig. 2), the wind climate during winter and autumn is similar, characterised by the dominance of NE and E winds. In spring, the winds are more evenly distributed, although the NE component is the principal one for winds ≥4B. Summer winds are generally weaker (<4B) and blow mostly from westerly directions (SW, W, NW).

Methodology

In the absence of wave records, wave characteristics required for the calculation of the rate of wave-induced longshore sediment transport have been estimated using wind data. Thus, the significant wave height (H_s) and the peak period (T_m) of the wave spectrum, are calculated for the dominant fetch directions (NW, N, NE and E), using deep-water (d/L<0.25; d: water depth and L: wave length in deep waters), wave forecasting equations for the fetch-limited case (CERC, 1984):

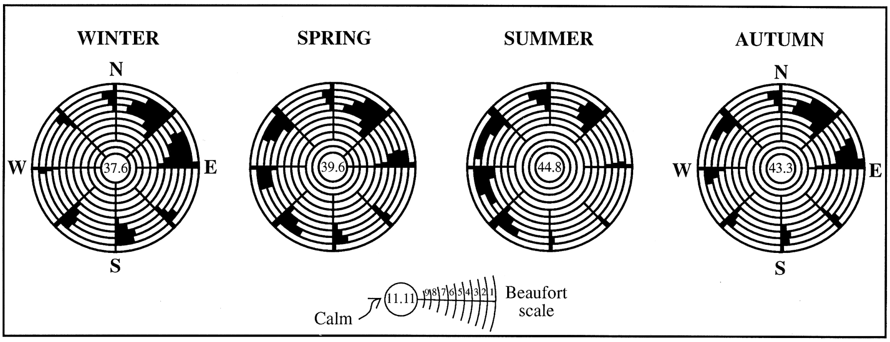

Fig. 2: Schematic presentation of seasonal distribution of wind velocity and direction.

$$H_s = 5.112 \times 10^{-4} \times W \times F^{0.5} \quad (1)$$

$$T_m = 6.238 \times 10^{-2} \times (W \times F)^{0.33} \quad (2)$$

where, W is wind stress (m/s) related to measured wind speed (U) through the equation $W=0.71\ U^{1.23}$, F is the fetch in m, while the prediction of both H_s and T_m is based upon the assumption that wind blows over the sea surface for a sufficient time for the generated waves to obtain their maximum height under the given fetch limited conditions. Following, the significant period (T_s) is given as 0.95 T_m.

The potential longshore transport rate Q_l (in volume per unit time) is given by the equation (CERC, 1984):

$$Q_l = \frac{0.39 \times P_{ls}}{g \times (\sigma - \rho) \times a'} \quad (3)$$

where, Q_l is measured in m^3/s, σ and ϱ (kg/m^3) are the densities of sediment (2650 kg/m^3) and saltwater (1050 kgr/m^3) respectively, $\alpha'=0.6$ (representing the sand porosity) and P_{ls} is the longshore energy flux factor (entering the surf zone) given by the relation (CERC, 1984):

$$P_{ls} = 0.05 \times \rho \times g^{3/2} \times H_o^{5/2} \times \sin 2a_0 \times (\cos a_0)^{1/4} \quad (4)$$

where H_o is the significant wave height at deep water conditions and a_o is the angle between the wave crest and the coastline, assuming that the nearshore bathymetric contours are parallel to the shoreline.

The coastal area under investigation is divided further into 4 units (A-D) according to their compass orientation (see Fig. 1); this satisfies also the restrictions for the use of equation 4. All the units are exposed to NW, N, NE and E winds with the exception of the units B and D that are not exposed to the winds from the east. The fetch lengths for the different directions and the corresponding angles between the wave crests and the shoreline of the units (A-D) are summarised in Table 1.

For the calculation of the longshore transport rate (Q_l), for each of the four units (A-D), the winds blowing from different directions are grouped into four categories, according to their force on the Beaufort scale (B): (I) 1-2 B; (II) 3-5 B; (III) 6-7 B and (IV) ≥8 B. Using the average wind speed for each of these categories (I-IV), the significant wave height H_s and period T_s are calculated (Table 2). Subsequently, the longshore energy flux factor P_{ls} and the potential rate of longshore transport Q_l are estimated, after taking into consideration the annual frequency (in percentage) of occurrence for each group (I-IV) of wind speeds presented in Table 3. Furthermore, as the point direction of each wind (wave) direction represents a 45-degree sector (e.g. the NE (45^0) represents the sector from 22.5^0 to 67.5^0) the trigonometric quantities ($\cos a$ and $\sin 2a$ in equation 4) are averaged by integrating over the sector of each direction involved.

Finally the study of the evolution of the shoreline is based also on a series (1965, 1973, 1987, 1994) of aerial photographs of approximate scale 1:15,000, obtained from the Hellenic Geographical Service, Athens.

Table 1

Wave fetch (F), shoreline angle (α) relative to the predominant wind directions, for each sub-unit of the study area (positive (+) direction is regarded to be from east to west).

	Unit A		Unit B		Unit C		Unit D	
	F (km)	α (O)	F (km)	α (O)	F(km)	α (O)	F (km)	α (O)
NW	22	-80	22	-30	22	-70	22	-45
N	15	-35	15	+12	15	-30	15	-05
NE	27	+10	27	+60	27	+20	27	+50
E	7	+35			5	+50		

Table 2
Estimated values of significant wave period T_S (sec) and height H_S (m) for deep waters, for different fetch directions and the mean speed of the four (I-IV) wind groups.

Wind groups		NW		N		NE		E	
	m/s	T	H	T	H	T	H	T	H
I	1.75	1.9	0.1	1.6	0.1	2.0	0.1	1.3	0.1
II	7	3.3	0.6	2.9	0.5	3.5	0.6	2.2	0.3
III	13.75	4.3	1.3	3.8	1.1	4.6	1.5	3.0	0.8
IV	22	5.3	2.4	4.6	2.0	5.6	2.7	3.6	1.4

Table 3
Seasonal distribution of the frequency (%) of occurrence for NW, N, NE and E winds, grouped in four categories according to their wind stresses (expressed in Beaufort (B) scale).

Wind	Winter				Spring				Summer				Autumn			
B	NW	N	NE	E	NW	N	NE	E	NW	N	NE	E	NW	N	NE	E
1-2	0.54	0.46	1.00	1.55	1.19	0.48	0.84	0.75	1.71	0.88	0.74	0.58	1.04	0.60	1.07	1.43
3-5	0.66	0.56	3.30	2.87	1.35	0.44	3.03	1.47	2.41	0.78	1.69	0.60	0.76	0.60	3.40	2.09
6-7	0.06	0.12	0.38	0.25	0.04	0.08	0.32	0.58	0.16	0.05	0.12	0.04	0.07	0.09	0.30	0.22
≥8	0.03	0.04	0.15	0.03	0.01	0.02	0.05	0.04	0.00	0.00	0.00	0.00	0.03	0.02	0.06	0.05

Results and Discussion

Longshore sediment transport rate (by volume) - induced by the oblique wave approach.

The study area is exposed to waves approaching from the NW, N, NE and E. The calculated parameters of the wave climate are characterised by peak period (T_s) between 1 and 6 sec and significant wave heights (H_s) below 3.0 m for the different groups of wind speed (on the Beaufort scale) and directions (Table 3). The relatively higher values of the wave period and height are associated with the relatively stronger NE winds blowing over a longer fetch distance.

The estimated potential longshore sediment transport per metre of coastline varies, therefore, in quantity and direction within the different physiographic units (A, B, C, D) of the study area (Table 4), due to their different orientation and exposure to different wind conditions and fetch directions (NW, N, NE, E). The major annual sediment movement is from east to west and is attributable to the waves approaching from the NE varying from 1.9×10^{-3} m^3/s (unit A) to 5×10^{-3} m^3/s (unit D). It is interesting to note the opposite (from W to E) sediment transport induced by the waves approaching from the NW and N.

Furthermore, the seasonal distribution of the potential longshore sediment transport rates shows that the direction of nearshore transport is towards the west, with the exception of the summer period. At all units the highest rates of longshore transport occur in winter. On an annual basis, the overall longshore transport rate in the study zone (units A to D) is towards the west, accounting for approximately 4×10^{-3} m^3/s; this corresponds to a total volume of some 125×10^3 m^3/yr. Analogous estimate values of longshore sediment transport have been reported elsewhere in the Mediterranean Sea; for example, along the littoral zone of the R. Ebro delta 30-230 $\times 10^3$ m^3/yr are moving (JIMENEZ & SANCHEZ-ARCILLA, 1993) whilst the annual net longshore sediment transport from the R. Nile delta to the Israeli coast has been estimated

Table 4
Seasonal/annual potential longshore sediment transport rate ($10^{-3} m^3/s$) of each of the physiographic units (A-D) for the different fetch directions (+: transport from W to E).

		Q_l				
		NW	**N**	**NE**	**E**	**TOTAL**
Unit A	Winter	103	118	-743	-186	-707
	Spring	94	68	-472	-234	-543
	Summer	181	48	-174	-30	26
	Autumn	110	87	-513	-175	-491
	ANNUAL	489	321	-1902	-624	-1716
Unit B	Winter	264	-107	-1637		-1479
	Spring	241	-62	-1040		-861
	Summer	462	-44	-384		35
	Autumn	282	-79	-1131		-928
	ANNUAL	1249	-291	-4192		-3234
Unit C	Winter	179	222	-1381	-185	-1165
	Spring	163	128	-878	-233	-820
	Summer	313	91	-324	-29	50
	Autumn	191	163	-954	-174	-774
	ANNUAL	845	604	-3536	-621	-2709
Unit D	Winter	292	-46	1949		-1703
	Spring	266	-26	-1239		-999
	Summer	511	-19	-457		35
	Autumn	312	-34	-1347		-1069
	ANNUAL	1381	-125	-4992		3736
Total area (A-D)	**Annually**	**3964**	**509**	**-14622**	**-1245**	**-3923**

by Delft Hydraulics (in 1994) to be between $170x10^3$ m^3/yr and $540x10^3$ m^3/yr (GOLIK, 1997).

Of course, the estimated above rates of longshore sediment transport along the coast of the NE Peloponnese do not coincide with the actual amounts of moving sediments within the surf zone of the investigated coastal zone, as this is related to the available total sediment budget. But, it provides the overall direction of sediment movement which will have a "residual" morphological effect on the coastline configuration (see also below), the areas where these changes may have a more pronounced effect and the periods (season) when high transport rates occur. Within this frame, high rates of sediment movement and associated coastline changes are expected to take place during the autumn/winter period when (i) the transport rates are high, due to the prevailing NE winds, and (ii) high riverine sediment fluxes whice is the case for all the rivers in this geographical area (POULOS *et al.,* 1996).

Coastline changes due to human activities

Within the coastal zone of the study area the natural equilibrium between marine processes, coastline configuration and available sediment budget has been disturbed significantly by the various anthropogenic activities in recent decades; this has inflicted drastic changes on the coastline (Fig. 3).

The comparison of aerial photographs taken in 1965 and 1973, when the nearshore circulation pattern was undisturbed by human activities (when sediments moved naturally), shows that the coastline of this particular coast was undergoing small-scale changes. A general progradational trend is attributed to units C and D due to their proximity to the major source of sediments (R. Peiros mouth) in combination with the westward sediment movement. Some retreat observed in unit A may be explained by its longer distance from the mouth of the R. Peiros, the reduced rate of sediment transport and the seasonal reversal of the littoral drift.

Following the construction of the port in 1971-72, rapid erosion of the coastline occurred in the regions downdrift of the port. During the period 1973-87, coastal retreat in unit A and sub-unit B1 exceeded 20 m and 50 m, respectively. The reason for this is twofold: (i) most of the transported sediment was blocked by the eastern breakwater of the port, and (ii) the river sediment supply (secondarily) was reduced due to extensive dredging of aggregates from its channel. The latter may also have been responsible for the erosional phenomena observed in unit C, located updrift of the port. In contrast, localised coastal accretion in unit D, is explained by the westerly diversion of the river mouth, in the early 80's. In addition, over this period, sandy material by-passing the eastern breakwater was deposited within the port, mainly at its entrance where a bulbous sand spit was formed, eventually inhibiting access to the port. Extensive coastline retreat west of the port had important economic consequences, as a wide sandy beach in front of the White Castle Hotel (for location see Fig. 1) was eroded, causing a deterioration in local tourist amenities.

In 1991-92, in order to respond to the general coastal erosion and to stop the siltation of the small harbour, the authorities extended the existing port breakwaters and constructed some groins (20-50 m in length) in the units A and C (see Fig. 3). This development re-established safe navigation to the port but altered the sediment distribution pattern causing, once again, changes to the

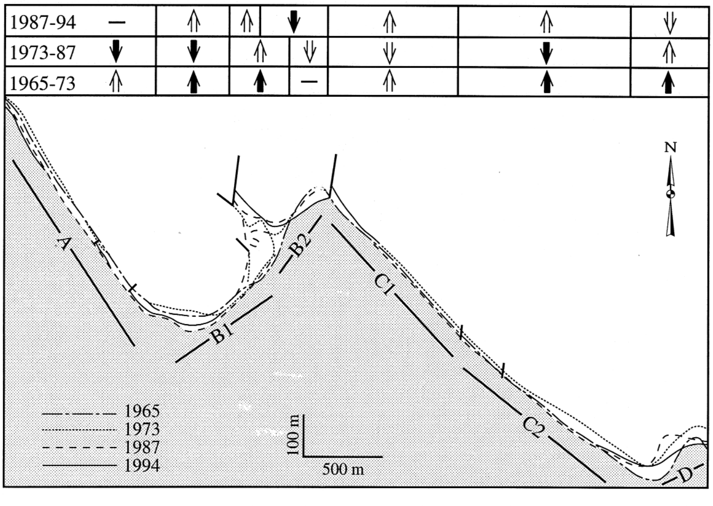

Fig. 3: Schematic presentation of coastline changes for the period 1965-1994, as indicated by aerial photographs obtained by the Hellenic Geographic Service (solid black and white vectors indicate large and moderate coastline changes, respectively).

general coastline configuration. Thus, between 1987 and 1994, extended coastal accretion (>15 m) occurred in the regions located updrift of the groins, especially in sub-unit C, accompanied by a further retreat (>5 m) adjacent and downdrift from them. In particular, the construction of the groin on the promontory updrift of the port resulted in an extended coastline retreat of more than 30 m in the coastal zone downdrift and adjacent to this groin. In contrast, a sandy beach 40 m wide was formed seawards of the northeastern breakwater of the port (sub-unit B2). Currently, considerable quantities of sand are mined from this newly formed beach, taken for the needs of the local building industry. Finally, the recovery of the coastline in unit A, following the construction of the groins, is only minimal as most of the westward littoral drift has been blocked in the areas updrift of the port.

Conclusions

The natural longshore sediment transport in the investigated sedimentary coastal cell of the NW Peloponnese (Greece) is controlled mainly by the oblique approach of wind-induced waves and their seasonal variation. Deep-water waves have significant wave period and height up to 6 sec and <3 m, respectively. Estimated transport rates (by volume) vary in terms of both place and time, according to the orientation of the approaching wave-crests and the seasonal variations of the local wind climate. An overall estimate of the annual rate of potential sediment transport accounts for some 125x10^3 m^3/yr of sediment (from east to west). Besides this, the major contributor to the local sediment budget is the R. Peiros with an estimated sediment flux in the order of 100x10^3 m^3 per annum.

The construction of the small harbour, for the needs of the local fishing community, and the arbitrary abstraction of aggregates from the R. Peiros have dramatically changed the configuration of the coastline by altering the longshore sediment pattern and reducing riverine sediment fluxes. The lack of any conclusive management plan which takes into consideration the pattern of sediment movement in the littoral zone has transformed the entrance of the port into a major depo-centre of transported material, causing its blockage. These human activities have given rise to some serious socio-economic problems since they lead to deterioration of tourist amenities in the area, loss of property, and the subsequent outlay of large amounts of money for the implementation of coastal protection measures. It seems today that a new state of equilibrium is being reached between coastline configuration and marine processes, without a significant recovery of the loss (tens of metres) of coastal land. So, after 25 years of human interference in the natural evolution of this coastline the following question arises: was the construction of the port absolutely necessary and socio-economically justified?

It is imperative, therefore, that any human activity on the coastal zone should follow a conclusive management plan that takes into consideration its impact on natural evolution and ensures sustainable development of the coastal zone. This demands the strengthening of collaboration between environmental scientists and decision-makers involved in coastal management schemes.

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