— *In* : Transformations and evolution of the Mediterranean coastline —

The importance of the river systems in the evolution of the Greek coastline

by

Serafim E. POULOS and George TH. CHRONIS

Institute of Oceanography, National Centre for Marine Research,
Hellinikon, Agios Kosmas 166 04, Athens, Greece.

ABSTRACT

On the basis of the measured and estimated sediment loads for the principal Greek rivers, some 80-95 million tonnes (mt) are transported annually towards the coastal zone. From this total, suspended sediment load (SSL) represents 60-70%; the remaining 30-40% can be attributed to dissolved (DL) and bed load (BL). The overall figure is expected to exceed 100 mt, when the estimate is applied to the total catchment area of all the rivers and ephemeral streams discharging along the Greek coastline. The high sediment yields of the mountainous river systems constitute the principal source of sediment to the coastal zone: this effect is expressed mainly by the formation of well-developed deltas. The total deltaic area of the 15 major rivers is some 2,350 km^2, representing 2% of the total surface of Greece (131,951 km^2), with a coastal length of some 450 km.

During the 19th century, the water/sediment fluxes of the Greek rivers have been modified extensively by human activities. Thus, the construction of 19 dams for the production of electric power and irrigation/watering purposes has resulted in a dramatic reduction in river sediment supply to the coastal zone. This reduction causes deterioration to the physical delta ecosystem with socio-economical consequences to the coastal populations (*e.g.* coastal retreat, sea water intrusion). Such effects might be enhanced by a potential sea-level rise, due to the "greenhouse effect".

RÉSUMÉ

Sur la base des charges en sédiments mesurées ou estimées pour les principaux fleuves grecs, on estime à quelque 80-90 millions de tonnes (mt) les transports annuels vers les zones côtières. Les charges de sédiments en suspension (SSL) représentent 60-70% de ce total, les 30-40% restants pouvant être attribués aux charges diluées (DL) et aux couches de fond (BL). Quand on applique cette estimation à l'ensemble des zones de captage des fleuves et torrents occasionnels qui se déchargent sur le littoral grec, on peut parvenir à un chiffre global supérieur à 100 mt. La production importante de sédiments des fleuves grecs constitue la source majeure des apports côtiers et se traduit principalement par la formation de deltas bien développés. La surface deltaïque totale des 15 principaux fleuves grecs est d'environ 2 350 km^2, soit 2% de la surface totale de la Grèce (131 951 km^2), avec une longueur de littoral d'environ 450 km.

Pendant le XIX^e siècle, les activités humaines ont modifié considérablement les flux eau/sédiment des fleuves grecs. Ainsi, la construction de 19 barrages pour la production d'énergie électrique et l'irrigation a conduit à une réduction dramatique des apports en sédiments vers la zone côtière. Cette réduction a entraîné une détérioration de l'écosystème deltaïque, avec des conséquences socio-économique pour les populations côtières. De tels effets pourraient être intensifiés par une augmentation potentielle du niveau de la mer, due à "l'effet de serre".

INTRODUCTION

In Europe, 200 out of 680 million inhabitants live within 50 km of the shoreline. Coastal areas are subject to rapid population growth, especially in the Mediterranean basin. Increasing demographic, industrial and environmental pressures indeed threaten the economic investment and living resources of the Mediterranean. The influence of river systems is of fundamental importance to coastal sediment budgets as, through their river network (alluvial valley), they transfer weathered material from the river drainage area to the coastal zone (receiving basin); here the formation of the deltaic plain occurs.

The world-wide flux of sediment from the rivers to the oceans has been reported elsewhere by HOLEMAN (1968), UNESCO (1978), MILLIMAN and MEADE (1983), COLLINS (1986), MILLIMAN (1990) and MILLIMAN and SYVITSKI (1992). Of particular significance within the context of world-wide river sediment supply is the exceptionally high sediment yield associated with small mountainous rivers. Such fluvial systems as those of Greece (POULOS *et al.*, 1996) have their catchments lying adjacent to the receiving marine basins. Further, the sediment budget of southern Alpine Europe, without including the Greek rivers has been calculated to be some 350 mt/yr (MILLIMAN and SYVITSKI, 1992). The latter authors have argued also that small mountainous rivers are more efficient than the larger river systems in delivering sediment to the oceans. Such supply is in relation to their steep channel gradients and their proximity to the weathered source material.

Delta shorelines are those parts of the coastal zone that are undergoing a constant change, following the evolution of the deltaic plain. By definition, a delta is a large accumulation of sediment at the mouth of a river, resulting from deposition of material at the zone of interaction between riverine and marine processes. Since ancient times, river deltas have been of fundamental importance to civilisations, mainly due to the associated extensive and highly productive agricultural lands. Present-day deltas are relatively young in age, having formed only since a rise in sea level of about 100 m during the Flandrian transgression. Greek deltas experience negligible tides; some of them are subjected to restricted wave action as they are formed in semi-enclosed embayments, where the fluvial processes dominate their formation (CHRONIS, 1986; CHRONIS *et al.*, 1991a; POULOS, 1989).

Since the beginning of the 19th century, natural river sediment fluxes have been modified extensively by human activities. Thus, the removal of vegetation cover through extensive cultivation or deforestation (often after forest fires) caused a substantial increase in sediment erosion of land surfaces. On the other hand, the construction of hydroelectric dams and irrigation reservoirs resulted in a dramatic reduction in river sediment supply to the lower reaches of many of the river networks. The latter causes deterioration to the physical environment and, especially, to the delta ecosystem with socio-economical implications (*e.g.* coastal retreat, sea water intrusion) to populations established on the deltaic plains. Such effects could be enhanced by a potential sea-level rise, in response to the "greenhouse effect".

The present contribution provides an original data set on the water/sediment fluxes of river systems which drain the mountainous areas of Greece, the southeastern part of the Alpine Europe. The synthesis investigates the role of the river systems in the evolution of the Greek coastline, providing information on the water discharge, estimating the total sediment input, examining delta formation and investigating the human impact on the coastal zone.

THE GREEK COASTAL ZONE

Greece is traditionally a marine country, whose population lives basically along the 18,400 km of coastline (this figure represents the length of the coastline of both the Greek mainland and the 9,835 islands and non-populated rocks). Almost 33% of the total (10.3 million) population lives within a distance of 1-2 km from the coastline, whilst the remaining 85% is established within a 50 km wide coastal zone. In addition, 35% of the coastal lands are agricultural, representing mostly prosperous deltaic plains and alluvial river valleys. The associated wetland areas (*e.g.* lagoons, salt-marches) are of great importance for the coastal ecosystem.

The geological structure and morphological configuration of the Greek coastline are related to the general geological structure of Greece; this is the result of Alpine tectogenesis, which terminated in the Miocene (24.6-5.1 Ma) when Greece assumed its present shape. Tectonic movements still occur, as indicated by contemporary seismicity and volcanicity throughout the area (MCKENZIE, 1978). This recent tectonism in Greece is dominated largely by the relative northward movement of the African Plate, with respect to Europe. Subduction takes place beneath the European plate, along the Hellenic Trench: the former is located seawards of the western coastline of Greece, passing to the south of the island of Crete. Thus, the Greek coastal zone belongs tectonically to the category of marginal coasts, as they have developed in back-arc basins (INMAN and NORDSTROM, 1971).

The global climatic and sea level changes, especially during the Quaternary (2.0 Ma-present), have influenced strongly the position and configuration of the shoreline. Following the end of the Grimanlian marine regression (18,000 B.P.), when the sea level was >100 m lower than observed today, and during the Flandrian transgression, sea level gradually reached its present level (KRAFT *et al.*, 1982). In Greece, during the late Holocene (6,000 B.P.-present), sea level has remained largely similar to that observed nowadays.

The Greek mainland, as part of the Alpine zone, presents a geomorphological variability due to its complex geology associated with intensive tectonic and eustatic movements; these are expressed by the high and irregular relief of the Greek mainland (> 2,000 m), which has resulted in the development of a large number of river and ephemeral stream networks. The main geomorphological units of the Greek coastal zone are mountainous coasts, coastal plains and deltaic coasts. Coastal plains represent rather flat areas of Quaternary alluvial deposits. A number of successive tectonically-uplifted marine terraces can be observed along the north coastal zone of Peloponnese (DOUTSOS and PIPER, 1990; COLLIER and DART, 1991). In addition, in coastal plains where exist a nearby source of sand and the appropriate wind climate, sand-dunes fields are formed. Mountainous coasts often consist of coastal cliffs, bounded by narrow rocky platforms or sandy beaches. Deltaic coastline are attributed to the development and evolution of the river systems; most of these have formed considerably large deltas and subaqueous alluvial fan-aprons, within only the last few thousand years. In Greece, as in most Mediterranean countries, the cases of natural coastal erosion are limited when compared to other areas of the world which face the open ocean. The most pronounced modern coastal changes are associated with the existence and natural processes of the river systems and, in particular, the evolution of their deltas. On the other hand, the anthropogenic impact on the river systems during the last few decades have caused dramatic modifications of the water/sediment fluxes towards the coastline; this follows the construction of dams, reservoirs and alteration of river routes.

THE GREEK RIVER SYSTEMS

The Greek coastline incorporates the mouths of more than 90 small and large rivers, plus ephemeral streams. Most of these systems drain the Greek mainland, whilst a few (Axios, Nestos, Evros) extend their network outside the Greek borders to include areas of the southern Balkans (Figure 1). In general, the Greek rivers drain mountainous regions, with high relief often exceeding the 2,000 m. Their catchment areas experience a climatic type which lies between "terrestrial Mediterranean" and "humid continental", with an average level of annual precipitation varying between 600 and 1,800 mm.

Water fluxes

The water discharges from 16 large and 8 smaller rivers are listed in Table I, together with the corresponding watershed areas, upstream of the

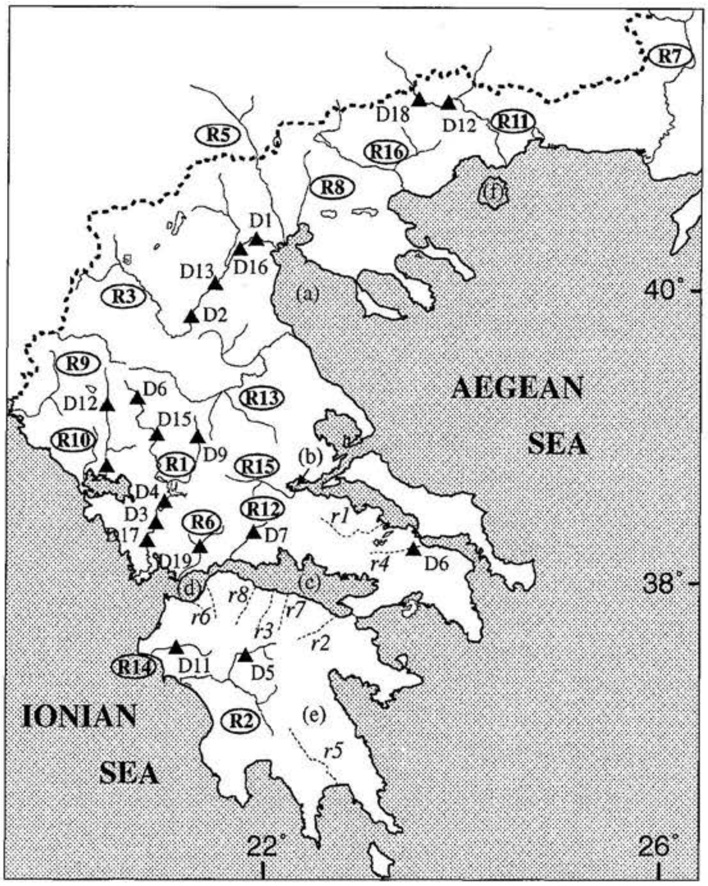

Figure 1 – The geographic location of the major (Ri) and smaller (ri) river systems discharging along the Greek coastline and the associated dams (Di).
R1: Acheloos; R2: Alfios; R3: Aliakmon; R4: Arachtos; R5: Axios; R6: Evinos; R7: Evros; R8: Gallikos; R9: Kalamas; R10: Louros; R11: Nestos; R12: Mornos; R13: Pinios (Thessalias); R14: Pinios (Peloponnese); R15: Sperchios; R16: Strimon; r1: Asopos (Biotia); r2: Asopos (Korinthias); r3: Bouraikos; r4: Charadros; r5: Evrotas; r6: Glaukos; r7: Krathis; r8: Kifissos; r9: Selinountas; D1: Asomaton; D2: Ilariona; D3: Kastraki; D4: Kremasta; D5: Ladonas; D6: Marathon; D7: Mesochora; D8: Mornos; D9: N. Plastira; D10: Pantanassa; D11: Pinios dam; D12: Platanovrisis; D13: Polifito; D14: Pournari; D15: Sikia; D16: Sfikias; D17: Stratou; D18: Thissaurou; D19: Agiou Dimitriou.

respective gauging stations. Annual average discharge varies from 7 up to 188 m^3/s (for the large rivers) and between 1 and 7 m^3/s (small rivers); these represent an annual flow to the oceans of some 35,000 10^6 m^3. This quantity may well represent a minimum as the discharges of most of the rivers have not been measured at the river mouths; therefore, they do not represent the whole of the surface of the catchment areas with percentages varying from 98 %, down to 65 % (see also Table III).

TABLE I
Mean Annual water discharge and outflow of rivers along the Greek coastline.

	River	Gauging station	Drainage basin [1]	Mean annual discharge	Mean annual flow	Sampling period	R
			km^2	*m^3/s*	*$10^6\ m^3$*		
Larger Rivers							
1	ACHELOOS	Kastraki	4,118	188	5,988	1937-70	a
2	ALFIOS	Alfiousa	3,374	67	2,100	1949-56	a
3	ALIAKMON	Prodromos	6,075	73	2,292	1962-71	a
4	ARACHTOS	Arta bridge	1,855	69.8	2,202	1962-72	a
5	AXIOS	Polykastro	22,450	159	5,031	1926-65	a
6	EVINOS	Mpanias	906	25.5	804	1968-74	b
7	EVROS	Adrianoupoli	27,465	103	3,250	1944-56	a
8	GALLIKOS	Thessaloniki	1,122	39.5	1,240	1952-65	a
9	KALAMAS	Kioteki	1,481	51	1,619	1963-71	a
10	LOUROS	Pantanasa	343	19.3	609	1955-70	a
11	NESTOS	Temenos	4,393	43.3	1,366	1964-90	b
12	MORNOS	Steno	430	7.3	481	1952-65	a
13	PINIOS (Th.)	Yiannouli	7,081	81	2,529	1903-56	a
14	PINIOS (Pel.)	Kavasila	794	14	445	1937-50	a
15	SPERCHIOS	Kompotades	1,158	62	743	1932-59	a
16	STRIMON	F. Roupel	10,937	110	3,440	1929-56	a
		Sub-total	*93,982*		*34,139*		
Smaller Rivers							
17	ASOPOS (Bio.)	Kalogirou	227	0.7	23	1947-56	a
18	ASOPOS (Pel.)	Mpotsika	106	1.6	50	1951-56	a
19	BOURAIKOS	Zachlorou	183	3.7	116	1963-68	a
20	CHARADROS	Marathon	137	0.5	16		a
21	EVROTAS	Bibari	springs	1.7	54	1961-67	a
22	Glaukos	Kournampelo	66	1.2	39	1955-66	a
23	KRATHIS	Tsiblos	79	2.2	69	1961-67	a
24	SELINOUNTAS	M. Makelarias	131	2.2	70	1971-73	a
		Sub-total	*929*		*437*		
		TOTAL	**94,911**		**34,576**		

(1) The watershed area represents that part of the total catchment area which correspond to the measurements fo water discharge (see also Table V)
a/ after Theranios (1974); b/ data available from the Public Power Corporation (PPC).

River discharges fluctuate seasonally, with their maxima occurring between late autumn and early spring and their minima in late summer. Periods of maximum discharge are associated with high precipitation and/or snowmelt in the neighbouring mountains. Hence, the western Greek rivers like the Arachthos and Louros have their maximum discharges in December. In contrast, the Pinios and Sperchios rivers, which extend across central and eastern Greece, have their maxima occuring later, in January. The Axios, Aliakmon, Strimon and Nestos rivers, which drain the mountainous regions of northern Greece and the southern Balkan zone have their maximum discharges in spring. A similar trend is shown by the smaller rivers, which are characterised generally by a wet season between December and April;

during summer (July-September) their discharges are at a minimum (<1 m^3/s).

Another interesting observation relates to the contribution of flood events to the water fluxes of the rivers, in response to intensive rainfall and/or sudden snowmelt in the mountains. For example, daily water discharges for the period 1935-1979 of the R. Axios have been measured, several times, to be between 1,000 and 2,500 m^3/s; for comparison, the corresponding mean monthly values were between 75 and 200 m^3/s (KONSTANTINIDES, 1989). Hence, the mean daily discharges vary from 5 to nearly 50 times higher than the corresponding mean monthly values. Similar ratios between flood events and mean flow conditions have been reported also for the R. Aliakmon (KONSTANTINIDES, 1989) and R. Sperchios (ZAMANI and MAROUKIAN, 1979) and are likely to apply to the other Greek rivers, as they drain similar physiographic areas and climatic zones.

Sediment fluxes

The riverine sediment fluxes are of great importance in the formation, configuration and evolution of the delta shoreline, which is the most variable part of the coastal zone. Unfortunately, there is only limited data available for most of the rivers discharging along the Greek coastline. The annual suspended sediment discharge and yield from 12 watersheds (of 6 different Greek rivers) are presented, together with the corresponding water discharges in Table II. As can be seen, the Greek watershed is characterised by annual yields between 65 and 3,945.4 t/km^2, with an average value of some 700 t/km^2. These levels are similar to those presented earlier by MILLIMAN and SYVITSKI (1992) for the smaller rivers draining southern Alpine Europe, with yields in the range of 90-4,150 $t/km^2/yr$ and a mean value of 1,100 $t/km^2/yr$. For comparison, the larger rivers of the world are

TABLE II

Measured values of the mean annual water and suspended sediment discharge (SSD) and corresponding yield of suspended sediment load (SSL) of parts of 12 catchments of Greek rivers.

	River	Gauging station	Catchment Area	Sampling Period	Mean Annual discharge		Annual yield of SSL
					Water	SSD	
			km^2		m^3/s	$10^{-3}t/s$	t/km^2
1	ACHELOOS	Mesochora	633.5	1969-73	23.4	1.96	97.6
2	ACHELOOS	Avlaki	1,349	1965-84	57.1	26.2	612.5
3	ALIAKMON	Ilariona	5,005	1962-82	52.5	73.4	462.5
4	ALIAKMON	Grevena	817.7	1962-82	13.1	1.95	75.2
5	AOOS	Konitsa	665	1963-83	25.1	17.0	806.2
6	ARACHTHOS	Arta	1,855	1962-76	64.3	231.9	3,942.4
7	EVINOS	Mpania	906	1969-74	26.4	1.9	66.1
8	KALAMAS	Soulopoulo	661.4	1969-75	25.1	4.83	230.3
9	KALAMAS	Raveni	1,264.2	1969-72	47.6	17.1	426.6
10	KALAMAS	Kioteki	1,481.4	1966-74	52.5	60.8	1,294.3
11	NESTOS	Temenos	4,393	1965-82	46.6	21.9	157.2
12	NESTOS	Papades	3,278	1965-83	35.24	10.7	102.3

associated with sediment yields of between 31 and 1,080 t/km^2/yr, *e.g.* Amazon (190.5), Mississippi (95.7), Niger (60), Nile (37), Danube (84), Yangtze (250), Hwanghe (1,080), Irrawady (662) and Indus (500).

The observed variation in suspended sediment load (SSL), even between parts of the same catchment area, is associated strongly with the lithological and morphological characteristics (POULOS *et al.*, 1996). For example, the exceptionally high sediment yield of the Arachthos River (3,945 t/km^2/yr) is the combined result of its high relief ratio (3.77 10^{-2}) and the easily erodible sedimentary lithology of its catchment area, which is underlain mainly by sedimentary rocks (siliciclastic + alluvial ≈ 80%). In contrast, the lower sediment yield of the Aliakmon (462 t/km^2/yr) may be explained by the relative abundance of igneous (12%) and metamorphic (6%) rocks, combined with a much lower relief ratio (1.7 10^{-2}). Similarly, the relatively low yield (157 t/km^2/yr) of the R. Nestos is attributed to the abundance of metamorphic and igneous rocks (>35%) underlying the catchment and a relief ratio of 1.6 10^{-2}.

SEDIMENT LOAD ESTIMATION

The quantitative evaluation of the total amount of sediment carried by any river network involves the determination of material transferred: (i) in suspension (SSL: suspended sediment load); (ii) in solution (DL: dissolved-load); and (iii) as bed-load (BL: bed load).

Suspended Sediment Load (SSL)

The estimation of the SSL of the Greek rivers is based, here, upon the statistical analysis of an established relationship between the observed mean annual water discharge (m^3/s) and the corresponding sediment fluxes (10^{-3} t/s) of the catchment areas, as presented in Table II. The relationship between annual suspended sediment and water discharge shown in Figure 2a is described by the equation:

$$Y = 7\ 10^{-3}\ X^{2.775}\ (r^2 = 0.74) \qquad (1)$$

where, Y is the suspended sediment flux (in 10^{-3} t/s),) and X is the water discharge (in m^3/s). This regression was derived on the basis of a "least squares" analysis.

Using equation (1) and assuming that the drainage basins of the other rivers respond similarly to weathering processes, the SSL has been estimated for the Greek rivers for which *in situ* measurements are not available (Table III). In addition, an estimation of the SSL has been derived also using equation (2) (after POULOS *et.al.*, 1996):

$$S = 1954\ A^{0.88} \qquad (r^2 = 0.80) \qquad (2)$$

where S is the SSL (in tonnes) and A is catchment area (in km^2) (Figure 2b).

Equation (2) expresses the relationship between annual suspended sediment loads and catchment areas, for 35 mountainous rivers draining countries of southeastern Europe (Greece, Italy, Albania, Turkey), with catchment areas smaller than 10^5 km^2. The high level of correlation is to be expected as the catchment areas of all the 35 rivers have a similar geological setting; they were formed during the Alpine Orogenesis and are subjected to the same temperate climatic conditions, characterised by similar rainfall/runoff conditions and weathering processes. Using equation (2) and

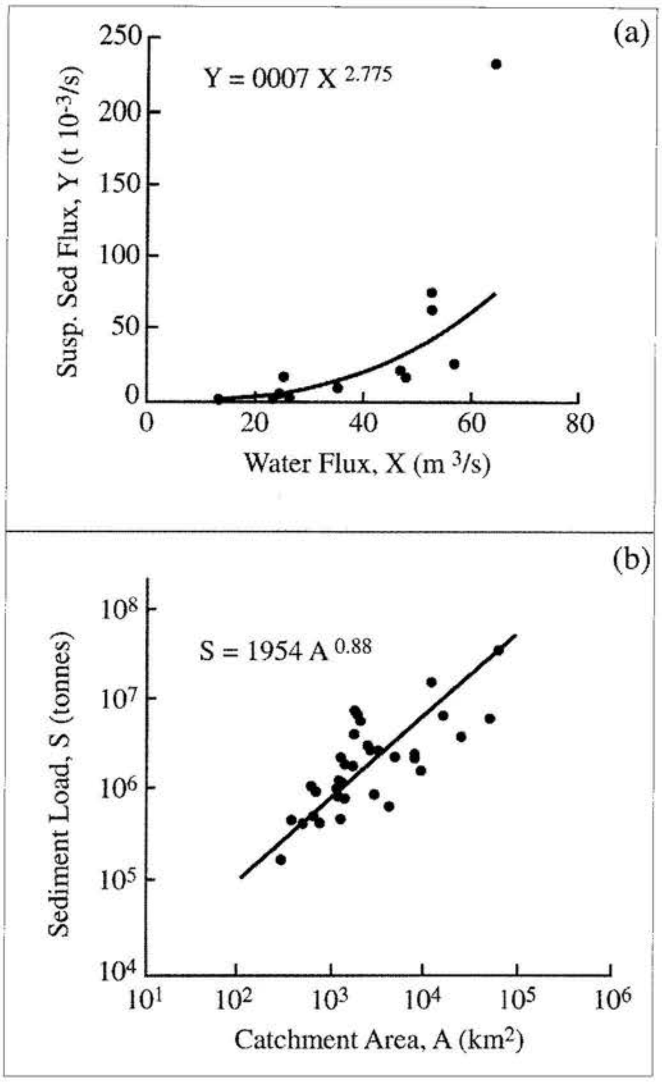

Figure 2 – (a) Annual sediment flux relationship with water flux, for Greek river watersheds, and (b) annual suspended sediment load relationship with catchment area, for rivers draining Italy, Albania, Greece and Turkey (after POULOS *et al.*, 1996).

assuming again that the total area of the drainage basins responds similarly to weathering processes, the SSL has been estimated for the Greek rivers and is presented also within Table III (together with the estimates derived from equation (1) and the field measurements).

The sum of the measured and calculated values of the suspended sediment load, carried by the 15 principal rivers discharging along the Greek coastline is of the order of 60-70 million tonnes (mt) per annum. This figure

TABLE III

Mean annual suspended sediment load, yield, associated water discharge and corresponding drainage basin (B) and its percentage relatively to the total catchment area.

	River	Gauged drainage basin (B)	Total catchment area (T)	B:T	Mean Annual Water discharge	Mean Annual SSL (M)	(N)
		km^2	km^2	%	m^3/s	10^6t	
1	ACHELOOS	4,118	5,470	75.3	188	2.53[a]	
3	ALIAKMON	6,075	9,250	65.7	73	2.80[a]	
3	ALFIOS	3,374	3,600	93.7	67	2.58	2.49
4	AXIOS	22,450	23,747	94.5	157	27.41	13.18
5	ARACHTHOS	1,855	1,895	97.9	69.8	7.31[a]	
6	EVROS	27,465	52,900	51.9	103	8.51	
7	EVINOS	635	1,070	59.3	27.6	0.22	15.74
8	KALAMAS	1,481	1,826	81.1	51	1.92[a]	0.57
9	LOUROS	343	785	43.7	19.3	0.08	
10	MORNOS	430	1,010	42.6	7.3	0.01	0.33
11	NESTOS	4,874	6,178	78.9	88	0.78[a]	0.4
12	PINIOS (Thes.)	7,281	10,750	65.9	81	4.4	
13	PINIOS (Pel.)	794	913	87.0	14	0.04	4.78
14	SPERCHIOS	1,158	1,780	65.1	62	2.1	0.7
15	STRIMON	10,937	16,550	66.1	110	10.2	0.97
	TOTAL	**93,130**	**137,724**	**67.6**		**72.9**	**61.50**

(M) after use of equation (1); (N) after use of equation (2): a: measured values

is expected to be higher, as both the measured and the calculated values do not correspond to the total surface area and water discharge of the catchment areas but only to a part (50-98%) of them.

Dissolved Load (DL)

Field measurements of mean annual dissolved load for ten Greek rivers are presented in Table IV, together with the associated water discharge and corresponding catchment areas. The annual dissolved load varies between 0.17 (Louros) and 2.63 (Evros) million tonnes, with an average overall value of some 1.2 mt. In order to investigate the relationship between the suspended and dissolved load, their corresponding annual yields are compared in Table V. Unfortunately, measured values for both SSL and DL are available only for three rivers. Thus, to a first approximation and using average values of the sum of SSL and DL, a ratio of SSL:DL = 1:0.2 is derived.

From published material, it is known that in arid and semi-arid regions, where the vegetation is sparse and the sediment production is high, the dissolved load constitutes only a relatively small part of the total load. For example, the dissolved load percentages for the Ganges, Yellow, Indus and Nile rivers have been estimated at 12.3%, 3.5%, 11.5% and 13.5%, respectively (MEYBECK, 1988). In contrast, in areas where precipitation and runoff are higher and there is abundant vegetation, the contribution of the dissolved load increases. Thus, the Amazon, Congo, Mississippi and Changjiang

Table IV

Measured values of the annual dissolved load, water flow and the corresponding catchment area (after Skoulikidis, 1996).

	River	Watershed station *km²*	Mean annual flow *$10^3 m^3$*	Mean annual dissolved load *$10^6 t/$*
1	Acheloos	5,540	5,670	1.55
2	Aliakmon	9,210	3,130	1.18
3	Axios	24,622	4,900	1.71
4	Evros	50,425	6,800	2.63
5	Gallikos	1,122	1,240	0.57
6	Louros	768	610	0.17
7	Nestos	6,111	3,140	0.78
8	Pinios	10,225	3,220	1.56
9	Sperchios	1,517	740	0.52
10	Strimon	16,722	4,100	1.51

Table V

Annual yield of suspended sediment load and dissolved load of Greek rivers, based upon field measurements.

	River	Annual Yield of SSL *$10^3 t/km^2$*	Annual Yield of DL *$10^3 t/km^2$*	Ratio SSL/DL
1	Acheloos	3.94	0.28	1:0.07
2	Aliakmon	0.46	0.13	1:0.28
3	Aoos	0.81		
4	Axios		0.07	
5	Evinos	0.07		
6	Evros		0.05	
7	Gallikos		0.51	
8	Kalamas	1.29		
9	Louros		0.22	
10	Nestos	0.16	0.13	1:0.8
11	Pinios		0.15	
12	Sperchios		0.34	
13	Strimon		0.09	
	Average	1.12	0.20	1:0.18

rivers, which drain semi-humid and humid areas, are characterised by dissolved load percentages of 24.5%, 47%, 29.8%, and 34% of the total sediment load, respectively (Meybeck, 1988). Moreover, Leopold *et al.* (1964) have stated that catchment areas with topographic elevations in excess of 1,000 m have dissolved loads ranging from 1.2% to 12% of the total load.

On the basis of the ratios presented above (between SSL and DL for the Greek rivers) and the fact that their catchments areas have maximum elevations in excess of 2,000 m (associated with high relief ratios), it would appear that 20% of the (total) load may be attributed reasonably to the dissolved load component.

Bed Load (BL)

There is a lack of field data concerning the bed load transported by Greek rivers; this limitation applies to most rivers of the world. On the basis of published information presented by other investigators (Blatt *et al.*, 1972; Unesco, 1985), it has been accepted generally that some 10% of the total (solid) sediment load is a reasonable estimate for the bed load constituent. For comparison, the river Ebro (Spain), a river with many geological and climatological similarities with the large Greek river systems, has a SSL = 2.8 mt (Maldonado, 1975) and a BL = 0.7 mt (Guillen *et al.*, 1992); these provides a ratio SSL:BL = 4:1. Assuming that some 15% of the total load is attributable to dissolved load, then the percentage of the BL to the total sediment load amounts to 15%. Of course, within particular environments this proportion may be much higher; this is the case of the Shangyou (China), where the BL is as much as 30.5% of the total load (Qian and Dai, 1980).

Within the context of the present study and according to the information presented, it seems reasonable, therefore, to assume that some 10-20% to the total annual sediment load may be attributed to bed load movement of the principal Greek rivers; however, this requires further investigation. On the other hand, the amount of BL in the case of the small ephemeral rivers, such as those which drain the high relief (steep gradients) and erodible lithology of the northern Peloponnese, susceptible to episodic flooding and proximal to the source, is expected to be much higher than this figure.

Total Sediment Load

On the basis of these various assessments, it seems likely that the derived suspended sediment load (Table III) represents some 60-70% of the total sediment load. The remaining 30-40% would represent the dissolved and bed sediment load of the rivers.

On the basis of the measured and estimated sediment loads for the principal Greek rivers, some 80-95 mt is transported annually towards the coastal zone. Interestingly, this value is almost equal to 1/4 of the SSL value (350 mt) presented by Milliman and Syvitski (1992), for the rivers draining the Alpine Europe; this did not take into account the rivers discharging along the Greek coastline. Besides, the figure derived here may turn out to be even greater than 100 mt, if the sediment load provided by the total catchment area of all the rivers and ephemeral streams discharging along the Greek coastline are combined.

The sediment fluxes follow, as expected, the same seasonal variability as the associated water discharges. Hence, their highest sediment discharges occur at the beginning of the wet season (October-December). Towards the end of the wet season, when there is still substantial runoff, the sediment flux decreases drastically to become only minimal during the dry (summer) period. Such seasonal variation in sediment flux may be explained in terms of the sparse vegetation and desiccated soil conditions which are associated with the dry season (June-September). At such times, the land surface becomes vulnerable to erosion, when heavy rains fall at the beginning of the succeeding wet season. Landslides occur commonly, as the result of rapidly fluctuating rainfall and regional tectonic activity (seismicity, volcanism, etc.). The plant cover becomes dense during the wet season, with a corresponding increase in soil cohesion and a considerable reduction in its erodibility. Hence, whereas detritus is removed readily and is transported by the river network during the beginning of the wet season, the streams subsequently carry less sediment – as there is less weathered material available for transportation.

GREEK RIVER DELTAS

The high sediment fluxes of the mountainous river systems discharging along the Greek coastline (see above), combined with their ability to deliver large quantities of sediment to the coastal zone (due to the proximity of their catchment areas to the river mouth and their high hypsometric gradients) leads to the formation of well-developed deltas (see Figure 3). Delta formation is enhanced also by the relative tectonic stability of the receiving basins, located within non-active back-arc embayments, and the dominance of fluviatile over marine-induced transport processes (POULOS *et al.*, 1993).

Greek river systems, despite the small size of their catchment areas relative to those of the large river systems of the world, have well-developed deltas. This interpretation may be continued by comparison of the ratios between the areas of the deltaic plains (D) to those of the catchments (C). The ratios (D:C), presented in Table VI, range from 0.06 10^{-2} (Strimon) up to 14 10^{-2} (Louros), with an average value of 5 10^{-2}; these are comparable to those of Mississippi (0.87 10^{-2}), Hwang Ho (4.87 10^{-2}), Nile (4.17 10^{-2}), Irrawady (8.14 10^{-2}) and Indus (3.11 10^{-2}) rivers (POULOS *et al.*, 1996). Further, the Holocene (over the last 6-7,000 years) deltaic accumulation rates, based upon geophysical evidence, lie within the range of 0.5 m/ka (bottomsets) to 3 m/ka (foresets) seawards of the mouths of the rivers

TABLE VI

Morphometric characteristics of the principal river-deltas in Greece.

	River/ delta	**Receiving basin**	**Catchment area (C)** *km²*	**Delta area (D)** *km²*	**Delta shoreline** *km*	**Ratio D:C** *10^2*
1	ACHELOOS	Patraikos Gulf	5,470	270	80	4.9
2	ALFIOS	E. Ionian Sea	3,600	110	40	3.0
3	ALIAKMON	Thermaikos Bay	9,250	120	16	1.3
4	ARACHTOS	Anvrakikos Gulf	1,895	245	25	12.9
5	AXIOS	Thermaikos Bay	23,750	400	35	1.7
6	EVINOS	Patraikos Gulf	1,070	90	40	8.4
7	EVROS	NW Aegean Sea	52,900	190	20 [a]	0.4
8	KALAMAS	E. Ionian Sea	1,826	80	30	4.4
9	LOUROS	Anvrakikos Gulf	785	110	15	14.0
10	NESTOS	N. Aegean Sea	6,178	435	62.5	7.0
11	MORNOS	Korinthiakos Gulf	1,010	28	14	2.8
12	PINIOS (Th.)	Thermaikos Gulf	10,750	70	20	0.7
13	PINIOS (Pel.)	E. Ionian Sea	913	85	22.5	9.4
14	SPERCHIOS	Maliakos Gulf	1,780	104	25	5.8
15	STRIMON	N. Aegean Sea	16,550	10	10.5	0.06

(a) this area represents only the Greek part of the deltaic plain of R. Evros

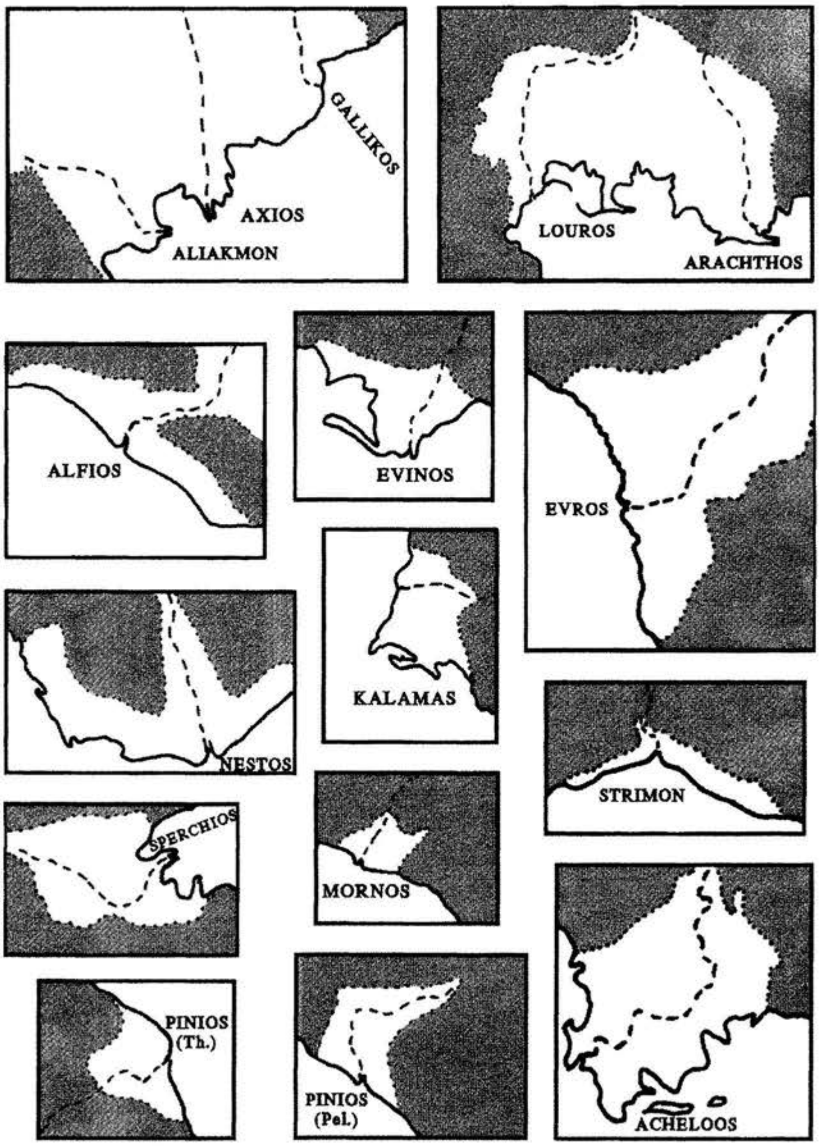

Figure 3 – Plan view of the major Greek river-deltas based upon a geological map of Greece (1:500.000) produced by the Institute of Geological and Mineral Exploration, Athens (1989).

Axios, Aliakmon and Pinios (LYKOUSIS, 1991; CHRONIS *et al.*, 1991b) and 1.2-2.3 m/ka offshore of the Louros and Arachthos deltas (POULOS *et al.*, 1995). Such accumulation rates are analogous to those presented by STANLEY (1988) for the Nile delta (0.2-6 m/ka), which is the largest delta located in the eastern Mediterranean Sea.

The total deltaic area of the 15 major rivers (Table VI) is about 2,350 km^2, representing 2% of the total surface area of Greece (131,951 km^2). The length of the deltaic shoreline is about 455 km, which is 0.3% of the total length of the Greek coastline. That part of the shoreline constantly changes, following the evolution of the deltaic plain. For example, the annual accretion rate of the deltas of Axios and Aliakmon rivers has been estimated by POULOS *et al* (1994) to be 1.3 and 1.0 km^2, respectively, whilst that of R. Sperchios is 0.13 km^2 (ZAMANI and MAROUKIAN, 1979), over the last 150 years.

The shape and general configuration of the shoreline of Greek deltas is the result of interaction between fluvial and marine forces as their receiving basins are subjected to only minimal tidal range (POULOS *et al.*, 1993). Thus, delta coastlines vary from fluvial to wave-dominated, according to the triangular morphologic classification proposed by GALLOWAY and HOBDAY (1983). Delta coasts developed within semi-enclosed and protected embayments and characterised by high sediment fluxes, as in the case the Axios, Aliakmon, Acheloos, Arachthos and Kalamas rivers, are characterised as fluvially-dominated and elongated in shape; these are characteristics which are similar to those of the modern Mississippi delta. The delta of R. Alfios, facing the open Ionian Sea, has a cuspate shape and is wave-dominated. Deltas which are lobate in shape and are fluvial/wave-dominated are those of the Pinios and Nestos rivers; this is an expression of the equilibrium of fluvial and wave processes.

ANTHROPOGENIC INFLUENCE

Within the past century, natural river sediment fluxes have been modified extensively by human activities. Thus, a substantial increase in sediment erosion has been caused by the removal of vegetation cover, through extensive cultivation or deforestation of land. This increases the kinetic energy of the rainfall, constraining the gradual infiltration. For example, denudation following a forest fire in the Chalkidiki area (northern Greece) was found to be five times greater than under forest growth (THEOCHAROPOULOS and AGGELIDES, 1991). Elsewhere, deforestation of the Nepal mountains has increased the Brahmaputra river sediment flux by some 30% (MILLIMAN and SYVITSKI, 1992).

Further, an increase in river sediment supply can be caused also by the diversion and realignment of river routes, as in the case of the R. Axios. In this case, the annual growth (which was some 0.9 km^2/yr) increased to 4.3 km^2/yr following the diversion and alignment of river's main distributary (POULOS *et.al.*, 1994).

In contrast, the construction of hydroelectric dams and irrigation reservoirs, since the beginning of the 19th century and especially during the last 50 years, has resulted in a dramatic reduction in river sediment supply to the lower reaches of many of the drainage networks and, eventually, to the coastal zone. The latter causes deterioration of the physical environment eco-system and has socio-economical implications (*e.g.* coastal retreat, sea water intrusion) for populations established on the deltaic plains. Such effects might be enhanced also by a potential sea-level rise, due to the "greenhouse effect".

In Greece, 19 hydroelectric dams have been built and/or are under construction, with some of these used also for irrigation purposes. The first and oldest of the dams is that of Marathon, on the small R. Charadros; this was constructed in order to provide water to the city of Athens. The characteristics of the Greek dams are listed in Table VII, whilst their locations are shown in Figure 1. In addition, rivers whose drainage areas extend into neighbouring countries incorporate a number of smaller dams; these lie beyond the Greek borders and are used basically for irrigation purposes. The R. Axios, for example, contains about 12 smaller dams constructed along its course within the former Yugoslavia (Michalopoulos, pers. com.).

TABLE VII

Dams of rivers discharging along the Greek coastline after LIAKOURIS (1995) and the CIGB/ICOLD (1998)

Dam	**River**	**Gross capacity of reservoir** *($10^6 m^3$)*	**Year of Completion**	**Use**
ASOMATON	Aliakmon	53	1985	H/Y -I
ILARIONa	Aliakmon	520	(#)	H/Y
KASTRAKI	Acheloos	950	1969	H/P
KREMASTA	Acheloos	4,500	1965	H
LADONAS	Alfios	57.6	1955	H
MARATHON	Haradros	41	1931	W
MESOCHORA	Acheloos	358	(#)	H
MORNOS	Mornos	780	1978	W
N. PLASTIRA	Acheloos	400	1959	H-I
PANTANASSA	Louros	1.1	1954	H
PIGAI AOOU	Aoos	260	1986	H
PINIOS (Pel.)	Pinios Ilias	420	1967	I
PLATANOVRISIS	Nestos	93	(#)	H-I
POLIFITO	Aliakmon	1,937	1974	H-I
POURNARI	Arachthos	865	1978	H-I
SFIKIAS	Aliakmon	103	1985	H
STRATOU	Acheloos	80	1985	H/Y -I
THISAUROU	Nestos	705	(#)	H-I
AG. DIMITRIOY	Evinos	?	(#)	W-I

(#) under construction; H/Y: hydroelectric; I: irrigation; W: watering

Unfortunately, no data are available concerning the variation in sediment flux before and after the construction of the Greek dams. From other publications, it is known that the dammed Nile and Colorado rivers hardly deliver any sediment to the adjacent seas. Similarly, the Indus supplies nowadays only 50 of its original 250 million tonnes of sediment, whilst the Rhone river carries as much as 5% of the load transported before dam construction (MILLIMAN and SYVITSKI, 1992).

Nevertheless, the damming of rivers and the subsequently diminished sediment fluxes are expected to have a profound effect on the formation and recent evolution of deltas, resulting in the retreat of their coastlines. This effect is indicated by the growth rate of the R. Aliakmon which, from 1.1 km^2/yr for the period 1850-1956 has been reduced by 50% to become 0.6 km^2/yr for the period 1956-1987; during this time, two major dams have been constructed (POULOS *et al.*, 1994).

Another example of coastal regression is provided by the R. Axios, where a deltaic area of about 90 km^2 associated with the old mouths (abandoned after route diversion) of the river has been subjected to flooding (Poulos *et al.* 1994). Similarly, sea water intrusion, enhanced by overpumping of the deltaic groundwater has been reported for a part of the coastal deltaic plain front (IGME, 1989).

EVOLUTION OF THE GREEK COASTLINE

The morphological configuration and evolution of the Greek coastline depend upon the water/sediment fluxes of the numerous rivers and ephemeral streams, the lithology (erodibility) of the coastal zone, the bathymetry of the adjacent continental shelf, the prevailing oceanographic conditions, i.e. wave and current activity, and in some cases the recent tectonic and volcanic activity. Coastal changes associated with the three main geomorphological categories: (i) coastal cliffs, (ii) coastal plains, and (iii) deltaic coasts are controlled by different land-ocean interaction processes. The stability of the coastal cliffs depends upon to their lithology, slope and to the incoming wave energy. High cliffs (>25 m), as in the case of the Gulf of Patras (NW Peloponnese) composed mainly of unconsolidated sand, present an average rate of retreat of several cm per year (Piper *et al.*, 1982). In contrast, lower coastal cliffs consisting of metamorphic rocks along the western coastline of outer Thermaikos Gulf appear to be rather stable (Chronis, 1986). In many cases, cliffs of erodible lithology and exposed to the wave activity host a narrow (usually sandy) beach formed by the products of cliff-erosion.

The accretion or erosion of coastal plains is controlled principally by the wave and current activity in the littoral zone. Coastal plains within sheltered embayments, such as those of Amvrakikos Gulf, inner Thermaikos Bay, experience very low wave energy and, therefore, remain relatively unchanged. On the other hand, erosion has been observed in areas exposed to the open sea and associated with a deep continental shelf, as in the case of the area to the north of the mouth of the R. Pinios (outer Thermaikos Gulf).

Compared with the previous two categories, deltaic coasts are associated with the most pronounced (in time and space) coastal changes; these are the result of the interaction between riverine and marine processes. Obviously, a key factor there is the large amount of sediment (some 100 mt/yr) delivered by the large and smaller rivers discharging along the Greek coastline, similarly their reworking by the incoming waves and wave-induced littoral currents. Within the last two centuries, the most distinctive changes of the deltaic coasts have been associated with the active (progradation) or the abundant (retreat) river-mouth areas. Coastline changes of selected mouths of Greek river/deltas are presented schematically in Figure 4. The active mouth of R. Acheloos following its diversion in the early 1940's has prograded seawards (1945-1960) more than 1 km; the abandoned mouth area has retreated 500-700 m (Piper and Panagos, 1981). Similarly, the deltaic plain in the area of the abandoned mouth of R. Axios has diminished by 95 km^2 between 1956-1987, when the area of the active mouth has prograded some 25 km^2 (Poulos *et al.*, 1996). Psilovikos *et al.* (1988) have reported the retreat (400-500 m) of a sandy spit near the old mouth of R. Nestos, from 1945 to 1968.

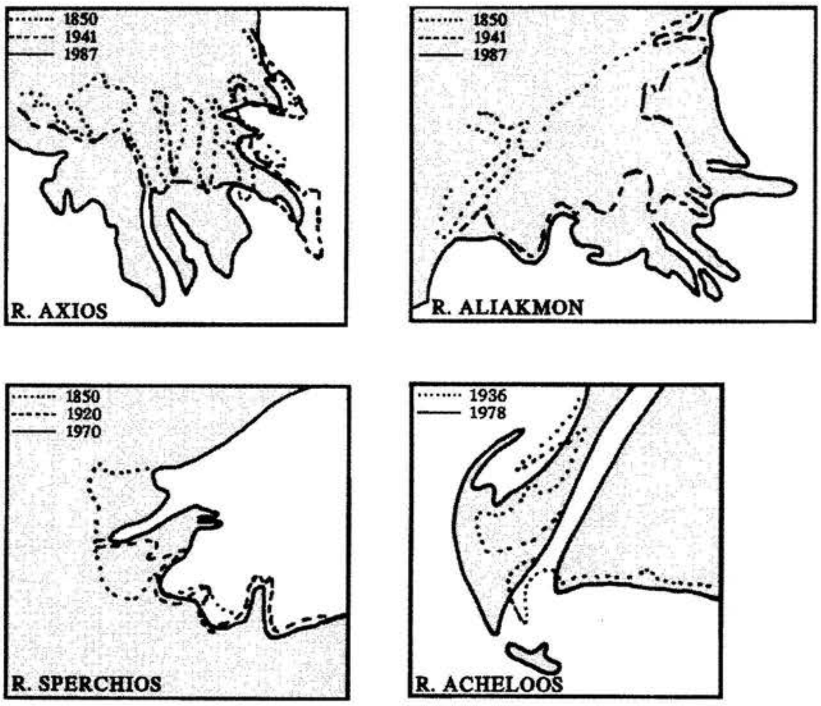

Figure 4 – Schematic presentation of the coastline evolution within the historical times of the deltas of the rivers Axios and Aliakmon (POULOS, 1989), Sperchios (ZAMANI and MAROUKIAN, 1979) and Acheloos (PIPER and PANAGOS, 1981).

Nowadays, human impact modifies the configuration of the Greek coastline on a localised scale. Thus, the construction of ports and marinas alters the hydrodynamic regime and the sediment budget, often inducing erosive phenomena. Examples are the sandy coastline of the western Thermaikos coastline (northwards the mouth of R. Pinios) and along the western coastline of the Peloponnese (R. Alfios); both are exposed to relatively high wave activity. Many "isolated" beaches, following the settlement of populations undergo erosion due to: (i) the interruption of the natural feeding of the coast from the adjacent landmasses; (ii) the abstraction of beach material (gravels and sand), to be used in various constructions (usually for buildings). On the other hand, anthropogenic impact on the river systems has caused dramatic modification of the water/sediment fluxes towards the coastline. Such changes follow the construction of dams and reservoirs, the alteration of river routes, dredging of the river channels. At the same time, the extraction of groundwater accelerates the natural subsidence of deltaic plains, as in the case of the old mouth of R. Axios (POULOS *et al.*,1996).

Perhaps, the most impressive coastal change – due to its minimal duration (a few minutes) – is attributable to seismic activity. Thus, during the most recent (June 1995) earthquake in the Gulf of Corinth (6.2 Richter in magnitude), a coastal strip of land several meters in width was cut off and slid towards the deep waters of the Gulf.

CONCLUSIONS

The 18,400 km length of the Greek coastal zone is of vital socio-economical importance, as it concentrates one third of the total population (10.3 million) within 1-2 km of the coastline. The formation of the Greek coastline reflects the general geological evolution of the Greek mainland, a result of the Alpine tectogenesis which terminated in the Miocene (5.1 Ma B.P.). Its present shape was adopted following the Flandrian transgression and during the Holocene, when sea level reached its present position (the last 6,000 years). Tectonically, the Greek coastal zone belongs to the category of marginal coasts, as it has developed in back-arc basins (after INMAN and NORDSTROM, 1971) with active tectonism still occurring. The Greek coastline can be divided geomorphologically into the following broad categories: (i) coastal cliffs, (ii) coastal plains, and (iii) deltaic coasts. The formation and evolution of each of these categories is governed by different land-ocean interaction processes.

The recent evolution of the Greek coastal zone is the result of the interaction between the land and ocean processes with the surimposition – drastic in some cases – of anthropogenic activities. Parts of the coast developed within sheltered and shallow marine embayment dominated by the land processes, *i.e.* riverine water/sediment fluxes. Coasts facing the open sea, with deep waters, undergo the action of the waves and currents; their evolution depends further upon the coastal lithology and the presence or absence of river mouths, the major source of sediments to the coastal zone.

In Greece, most of the coastal changes are associated with the evolution of the deltaic coasts. Thus, the influence of the river systems is of fundamental importance for the evolution of the coastal zone. On the basis of the measured and estimated sediment loads for the principal Greek rivers, a total of some 80-95 mt is transported annually towards the coastal zone. This figure is expected to exceed 100 mt when the estimate is applied to the total catchment area of all the rivers and ephemeral streams discharging along the Greek coastline. Furthermore, the most pronounced coastal changes within historical times are provided by the seaward progradation of the active, combined with the retreat of the abandoned, mouths of river-deltas. Overall, Greek deltaic coastal plains over the last 150 years prograde annually in the range of 0.1 to 1.3 km^2.

Within the last century, human activities have played an important role in the evolution of the coastline, on meso- and micro-scales, mainly by: modifying the river water/sediment fluxes towards the coast, changing river routes, enhancing subsidence of coastal plains, through overpumping of ground water, altering the littoral natural circulation, with the establishment of various constructions (ports, marinas). Occasionally, rapid coastal changes are caused by intensive seismic activity.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. Michael Collins for his critical reading of the manuscript and his constructive comments. Thanks are extended to Mrs K. Davis for the preparation of the figures and to Dr N. Skoulikides for providing useful information and data concerning the Greek rivers.

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