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Journal of Marine Systems 25 (2000) 47–76

JOURNAL OF MARINE SYSTEMS

www.elsevier.nl/locate/jmarsys

Thermaikos Gulf Coastal System, NW Aegean Sea: an overview of water/sediment fluxes in relation to air–land–ocean interactions and human activities

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Received 12 January 1999; accepted 3 November 1999

Abstract

This study presents an overview of the Holocene formation and evolution of the coastal system of Thermaikos Gulf (NW Aegean Sea). The system is divided into the terrestrial sub-system and the oceanic sub-system; the former represents 90%, while the latter includes only 10% of the total area. This particular coastal zone includes the second most important socio-economic area of Greece and in the southern Balkans, the Thessaloniki region; this is in terms of population concentration (> 1 million people), industry, agriculture, aquaculture, trade and services. The geomorphology of the coastal zone is controlled by sediment inputs, nearshore water circulation, and the level of wave activity. The large quantities of sediments (with yields > 500 tonnes/km^2 per year), delivered annually by the main rivers (Axios, Aliakmon, Pinios, and Gallikos) and other seasonal streams are responsible for the general progradation of the coastline and the formation of the Holocene sedimentary cover over the seabed of the Gulf. Changes to the coastline can be identified on macro- and meso-time scales; the former include the evolution of the deltaic plains (at > 1 km^2/year), while the latter incorporates seasonal changes along sections of the coastline (e.g. sandy spits), mostly due to the anthropogenic activities. The overall water circulation pattern in Thermaikos Gulf is characterised by northerly water movement, from the central and eastern part of the Gulf; this is compensated by southerly movement along its western part. The prevailing climate (winds and pressure systems) appears to control the surface water circulation, while near-bed current measurements reveal a general moderate (< 15 cm/s) southerly flow, i.e. offshore, towards the deep water Sporades Basin. Waves approaching from southerly directions play also a role in controlling the shoreline configuration. Various human activities within the coastal system place considerable pressure on the natural evolution of the coastal zone ecosystem. Thus, the construction of dams along the routes of the main rivers has reduced dramatically the water/sediment fluxes; this caused, for example, retreat of the deltaic coastlines and seawater intrusion into the groundwater aquifers. Similarly, pollution and/or eutrophication of the nearshore marine environment have resulted from the inputs of industrial wastes, urban untreated sewage, and agricultural activities on the coastal plains. This effect is demonstrated by high levels of pollutants, nutrients, and by the increased concentrations of non-residual trace-metals within the surficial sediments. Finally, climatic changes associated with a potential rise in sea level (i.e. 30–50 cm) will threaten a substantial part of the low-lying lands of Thermaikos Gulf. Thus, systematic and thorough

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PII: S0924-7963(00)00008-7

monitoring is needed in order to protect the coastal ecosystem; this will ensure its sustainable development and successful management, in relation to present and future socio-economic activities and climatic changes.

Keywords: coastal system; coastal zone; air–land–ocean interaction; socio-economic activities; Thermaikos Gulf; Aegean Sea

1. Introduction

Coastal areas are of global importance, in terms of their natural resources, ecological communities and as regions of concentrated human activities. The coastal domain hosts some 60% of the human population, on a global scale. A gross estimation of the natural capital of the earth's ecosystems (Costanza et al., 1997) accounts at least US$33 trillion worth of services annually, with the majority of the value currently outside the market system. To this value, which is 1.8 times the current global gross capital product (GNP), the marine coastal and wetland ecosystems contribute US$10.6 trillion/year and US$4.9 trillion/year, respectively.

During the last decades, much attention has been given to the significance of the air–land–ocean interface, in relation to the functioning of global change of the earth's system. Examples are biological feedback effects on the global environment and the availability and sustainability of living resources, for human consumption. Furthermore, the future response of coastal systems to changes in climate and other environmental factors is of direct socio-economic importance. At the same time, pressure upon the coastal ecosystem is in terms not only of natural processes, but also due to man's use of the coastal zone for economic activities. Thus, within the concept of a global change, the Land–Ocean Interactions in the Coastal Zones (LOICZ) Implementation Plan has been established by The International Geosphere–Biosphere Programme (IGBP, 1993, 1995).

Recently, localised efforts have been placed upon an integrated approach to the management of the coastal resources through: (i) the establishment of an interdisciplinary Forum — such as that related to the Dorset coastline (southern UK) (Dorset Coast Forum, 1998); and (ii) the integration and application of numerical models capable of describing the environmental quality throughout a whole coastal system, on a regional scale, e.g. the Belgium coastline and the associated Scheldt terrestrial basin (SALMON, 1999).

It is widely accepted that the coastal zone, including the coastal plains, extends up to the outer edge of the continental shelves; these are located approximately between 200 m above and below sea level, respectively (Cadee et al., 1994). However, within the context of the present investigation, the broader term *coastal system* is introduced; this is in order to accommodate a much larger geographical area, where terrestrial environments (terrestrial sub-system) influence marine environments (oceanic sub-system), and vice versa.

The terrestrial and marine environments of the coastal system (see below), being the products of the interaction between land, sea and air processes, are interrelated and any change to one has a direct impact to the other. Furthermore, the terrestrial sub-system acts mainly as the provider, e.g. water and sediment fluxes, while the marine sub-system plays primarily the role of the receiver. The marine environment influences the weather conditions of the region by affecting the level of precipitation; in combination with temperature, this determines subsequently the vegetation cover and the type of weathering of the landmasses. Furthermore, the oceanic sub-system is involved in the morphometric formation and evolution of the coastline by: (a) affecting the seaward dispersion and deposition of the riverine suspensates (nearshore current and wave activity); (b) participating in the formation and preservation of the estuarine and lagoon environments; and (c) controlling influence on the fate of the coastal aquifers. The terrestrial environment has a more pronounced effect on the ocean sub-system, as the main source of the fresh water/sediment fluxes and the associated nutrients and/or pollutants. These fluxes are dependent upon the area of the landscape, the morphology (high relief), lithological characteristics (e.g. erodibility, infiltration), the climatic conditions (e.g. air temperature, precipitation), and the types of vegetation. In particular, the levels of precipitation and of surface running water, together with the general underlying geology, are related strongly to the formation of the coastal aquifers.

Within the concept of the coastal system, the coastal zone is defined as a strip of land and sea territory of varying width, depending upon the nature of these environments and their particular management needs. Furthermore, the role of the coastal zone has been recognised as a buffer in: (a) providing a filter, to remove pollutants and other material transported from the hinterland, before they enter to the coastal ocean; and (b) protecting the upland areas from storms and flooding, originating from the sea. Finally, the natural boundary between the terrestrial and marine coastal zone (the coastline) changes constantly, in response to terrestrial and marine processes, incorporating any anthropogenic interference.

The present study provides an overview of the Holocene formation and evolution of the Thermaikos Gulf Coastal System, located in the NW Aegean Sea (eastern Mediterranean Sea) (Fig. 1). This coastal system belongs to the southern flank of the Alpine orogenic belt, located within the humid mesothermal climatic zone and within an essentially tideless marine environment. The coastal system is divided into two principal components: (a) the terrestrial sub-system; and (b) the oceanic sub-system. The terrestrial sub-system consists of the hinterland and the subaerial part of the coastal zone; the former represents mainly the catchment areas of the rivers discharging along the coastline of Thermaikos Gulf, while the latter consists mostly of the deltaic plains, the coastal plains and cliffs. The oceanic sub-system includes the inner continental shelf (< 40 m) and the outer shelf/shelf-break area (40–130 m of water depth). Further, the coastal system under investigation (in particular, the coastal zone) accommodates more than 1 million people associated with a variety of economic activities (e.g. agriculture, industry, and trade). Here, the county of Thessaloniki has been established as the second most important (following the province of Athens) socio-economic region of Greece, lying between some of the most important areas of the southern Balkans peninsula.

Within the framework of the various activities of the Research Foci of the LOICZ implementation (IGBP, 1993, 1995), this work presents an integrated synthesis of the spatial and temporal heterogeneity of the Thermaikos coastal system, in terms of: (i) mass (water and sediment) transfer from land to continental shelf and, subsequently, to the deep ocean basin; (ii) the formation and evolution of the coastal zone, in relation to land–air–ocean interaction processes; and (iii) various socio-economic aspects of the region and their impact on the natural environment. More specifically, the following processes are overviewed: (a) river water/sediment fluxes in response to weathering processes, dependent upon the geology and climatology of the river catchments; (b) the shape of the coastline and its recent evolution, as a result of the river/wave interaction and littoral sedimentation processes; (c) the offshore transfer and dispersion of suspended sediment, by the river plumes and sub-surface nepheloid layers; (d) thermohaline and wind-induced water circulation patterns and wave activity; (e) surficial sediment characteristics, includ-

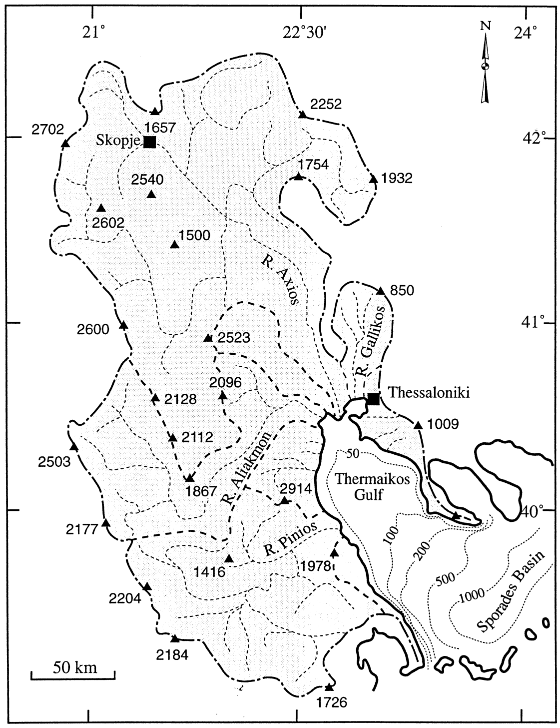

Fig. 1. Geographical map showing the Thermaikos Gulf Coastal System, NW Aegean Sea, eastern Mediterranean (The Times Atlas of the World, 1994), (▲ altitudes in metres; – · –: terrestrial boundary of the coastal system; · · · : boundary of river catchment areas; - - -: bathymetric contours, in metres).

ing pollution phenomena; (f) shelf-sediment accumulation rates; and (g) the consequences of human impact upon the riverine water/sediment fluxes (related to the evolution of the coastal zone and a potential sea-level rise), together with pollution and eutrophication phenomena of the aquatic environment.

2. Terrestrial part of the coastal system

The terrestrial sub-system consists of: (i) the hinterland; and (ii) the sub-aerial part of the coastal zone. It covers a total area of some 47,200 km^2, representing 90% of the total area of the coastal system (Table 1). The hinterland of the Thermaikos coastal system consists mainly of the catchment areas of the rivers and ephemeral streams discharging along the coastline of Thermaikos Gulf. The sub-aerial part of the coastal zone includes mostly the deltaic plains of the aforementioned rivers, some low-relief late Quaternary coastal plains and cliffed areas.

2.1. The hinterland area

The hinterland covers an area of some 44,550 km^2, representing some 85% of the total area of the coastal system and almost the 95% of its terrestrial part (Table 1). The geomorphological and climatic characteristics of the river catchments determine the weathering and fluvial processes (i.e. water/sediment fluxes); these, in combination with the prevailing marine processes, control the overall morphology of the coastal zone.

2.1.1. Geological setting

The geological structure of the terrestrial part of the Thermaikos Coastal System is the result of the Alpine tectogenesis, which terminated in the Miocene some 5.1 Ma ago (McKenzie, 1978). The intensive tectonism, enhanced by intensive weathering processes, has created an area of extreme geomorphological complexity with irregular relief; the topography of the mainland of the Balkan Zone exceeds 2500 m and includes numerous river networks. The most important river networks are those of the Axios (lying mostly within the former Yugoslavia), the Aliakmon (the northwestern mainland of Greece), the Pinios (central Greece) (Fig. 1). Among the smaller rivers, the most important is the Gallikos. In Table 2, the general physiographic characteristics of the aforementioned river catchments (area, relief ratio, water/sediment fluxes, lithology etc.) are listed.

2.1.2. Regional climate and associated weathering processes

The climate of the hinterland region, especially that of the drainage basin areas (Table 2), can be characterised generally as ‘Continental’, becoming ‘Mediterranean’ towards the coastal zone. Mean annual air temperatures vary between 9°C and 17.5°C, while annual rainfall lie between 400 mm and 1300 mm (the latter, especially, at high altitudes). Furthermore, the central part of the drainage basins, associated with high altitudes, is characterised by the exceptionally high differences of absolute temperatures. For example, within the R. Axios catchment area, the temperatures reach −45°C during winter and +30°C in summer, while for the R. Pinios (located in southern latitudes) they vary between −10°C and +45°C.

Different climatic conditions (mainly expressed in terms of air temperature and precipitation) of the catchment areas under consideration are associated with a different type and intensity of weathering processes, including (Leopold et al., 1964): (i) low to intermediate mechanical weathering; (ii) high to intermediate chemical weathering; (iii) intermediate to high weathering, due to running water; and (iv) high weathering, in relation to mass movements caused by high relief. These intensive denudation processes are associated with high sediment yields, exceeding 500 tonnes/km^2 per year (see below). For comparison, a general estimate for Europe overall is a denudation rate of some 42 mm/ka (Walling, 1987); this corresponds to a sediment[1] yield approximately equal to 112 tonnes/km^2 per year.

Another factor that controls weathering processes over the region is the vegetation cover. The climate of the Greek peninsula favours the growth of prairies, grassland, savannah and some forests: coniferous trees are present over the uplands and the mountain-

[1] The specific weight of the sediment has been taken equal to that of the quartz (= 2.65 kg/m^3).

Table 1
Morphometric characteristics of the different parts of the Thermaikos Gulf Coastal System

	Area[a] (km^2)	Constituents (%)	
		Coastal System	Coastal Zone
(A) Thermaikos Gulf Coastal System	52,300	100.0	
(1) Terrestrial part of the system	47,200	90.2	
(a) Hinterland area (> 75 m altitude)	44,550	85.2	
(b) Sub-aerial part of coastal zone (< 75 m altitude)	2650		70.7
(2) Oceanic part of the system	5100	9.8	
(a) Sub-aqueous part of coastal zone (inner continental shelf (< 40 m)	1100	2.1	29.3
(b) Outer continental shelf, shelf break and upper slope (< 200 m)	4000	7.6	
(B) Coastal Zone (1b + 2a)	3750	7.2	100
(C) Coastline length (km)	360		

[a]Based upon topographic maps (1:500,000) and hydrographic (1:200,000) provided by the Hellenic Geographic and Hydrographic Services, respectively.

ous areas. The density of the vegetation is somewhat poor, with some bare areas and the remainder being covered by grazing and partially forested land. Such sparse cover, which is even more depleted during the

Table 2
General characteristics of the main rivers discharging along the coastline of the Thermaikos Gulf Coastline

	Axios	Aliakmon	Gallikos	Pinios
Geomorphology[a]				
Catchment area (km^2)	23,747	9250	930	10,750
Maximum relief (m)	2800	2200	2180	1900
Relief ratio (10^{-2})	1.15	1.7	0.25	1.5
Deltaic plain (km^2)	Approximately 1500			80
Lithology[b]				
Acid (%)	43.5	14.5	53.1	17.5
Mafic (%)	7.7	9.2	4.4	6.2
Carbonates (%)	11.3	15.7	1.0	14.7
Flysch-Molasse (%)	5.6	29.6	0.0	15.8
Neogene-Quaternary (%)	31.9	31.0	41.5	45.8
Climate[a]				
Mean annual temperature (°C)	14.5	16.5	16.5	17.0
Mean annual rainfall (cm)	650	750	480	710
Type	Terrestrial Mediterranean to humid Continental			
Hydrology[a]				
Mean annual discharge (m^3/s)	158	73	39.5	81
Max. annual discharge (m^3/s)	279	137	?	171
Min. annual discharge (m^3/s)	49	21	?	11
High water period (months)	De–Jn	De–Ma	?	De–Ap
Low water period (months)	Jl–No	Jn–No		Ma–No
Sediment fluxes[c]				
Annual yield of SSL (10^3 t/km^2)	1.22	0.46	0.004	0.6
Annual yield of DL (10^3 t/km^2)	0.07	0.13	0.51	0.15

[a]After Poulos et al. (1996a,b) and Poulos et al. (1994).
[b]After Skoulikidis (1993).
[c]After Poulos and Chronis (1997).

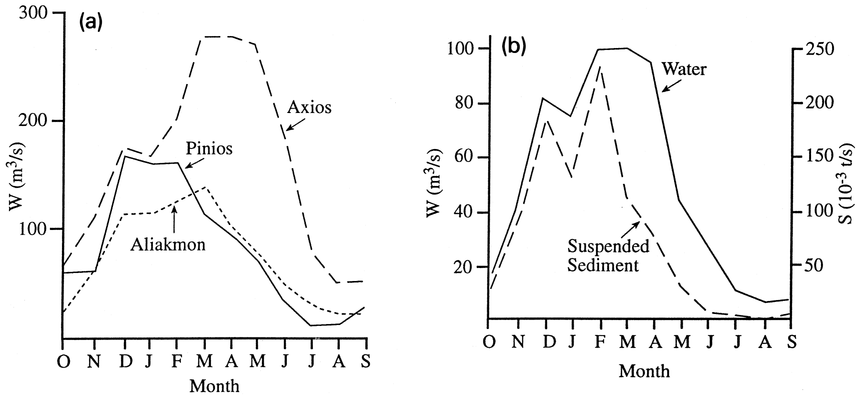

Fig. 2. (a) Monthly variation in water discharge of the Rivers Axios, Aliakmon, Gallikos and Pinios (after Therianos, 1974); (b) monthly variation of water and sediment flux of the R. Aliakmon at Ilariona gauging station (representing a catchment area of 5005 km^2) over the period 1962–1982 (Public Power).

dry summer periods, may be expected to enhance denudation and lead to the release of large amounts of weathered detritus to the river networks (Tzedakis, 1993).

2.1.3. Water and sediment discharges

2.1.3.1. Freshwater inputs. Most of the freshwater inputs to the Thermaikos coastline originate from the Rivers Axios, Aliakmon, Pinios and Gallikos (Table 2). Comparing discharges between the Rivers Aliakmon and Pinios, with those of R. Axios, it can be noted that the high discharges of the former rivers occur between November and May; for the latter, they occur from December to June (Fig. 2a). This pattern relates to the fact that the rivers Aliakmon and Pinios, located further south, have their high discharges coincident with high precipitation levels; the R. Axios peak is related to snowmelt from the mountains of the former Yugoslavia region.

A very important contribution to the water flux is made by flood events; these follow periods of exceptionally high precipitation, or sudden melt of the snow-cover. Mean daily water discharges have been found to range from 5, up to nearly 50, times higher than the corresponding mean monthly values in the case of the rivers Axios and Aliakmon (Poulos et al., 1996a). For example, between 10 and 11 November 1934, the daily water discharges of the rivers Axios and Aliakmon were 2440 and 3280 m^3/s, respectively, while the corresponding mean monthly value for both rivers was 115 and 62 m^3/s (Therianos, 1974).

The chemistry of the water of the aforementioned rivers is controlled mainly by the climate and the petrography of the catchment areas (Katsiou et al., 1989; Skoulikidis, 1993). Thus, the calcium, magnesium, hydrogen, carbonate and chlorine contents (Table 3) originate mainly from the weathering of young (Holocene) sediments. A significant part of riverine magnesium results from mafic rock weathering, while the total silicate content is attributed to mafic and acid rocks. Only a part of the potassium content of

Table 3
Average river water biogeochemical composition (after Skoulikidis, 1993)

	Axios	Aliakmon	Pinios	Gallikos
Ca (mval/l)	2.7	2.7	3.1	3.1
Mg (mval/l)	0.8	1.3	1.5	1.0
Na (mval/l)	0.8	0.2	0.3	1.4
K (mval/l)	0.1	0.1	0.1	0.1
Cl (mval/l)	0.4	0.2	0.3	0.6
SO_4 (mval/l)	0.7	0.3	0.3	0.6
NO_3 (mg/l)	4.9	3.1	4.3	3.7
PO_4 (mg/l)	1.6	0.2	0.3	0.1
SiO_2 (mg/l)	10.1	10.2	13.1	10.3
DO (%)	98.7	104.9	99.7	114.3
DOC (mg/l)	1.4	1.6	1.5	2.3
POC (mg/l)	0.5	0.5	1.1	0.1
Cu (ppb)	4.8	9.3		
Pb (ppb)	4.5	2.0	2.5	4.0
Ni (ppb)	20.0	18.3	18.5	17.0

river water results from the weathering of acid rocks. Carbonates and flysch-molasses play a minor role in controlling the water chemistry. Some sodium and chlorine, originating from the marine spay, are added to the river water through the mechanism of a rain-water contribution.

A positive correlation between river discharge levels and dissolved organic carbon (DOC) concentrations (Skoulikidis, 1993) indicates that the origin of the DOC in the river waters is mainly terrestrial in origin; it is transported as a soil constituent, during flood events. In general, the rivers under investigation experience moderate pollution; the Axios and Gallikos are relatively the more polluted, as they receive domestic and industrial sewage from the city of Thessaloniki, together with the chemicals/fertilisers from the agricultural and industrial activity of the Thessaloniki Deltaic Plain (Georgas and Perissoratis, 1993). The pollutants include primarily sodium, originating from municipal wastewater; nitrate, phosphate, sulphate and potassium, originating mainly from agrochemicals/fertilisers; and chlorine from sewage.

2.1.3.2. Sediment fluxes. On an annual basis, the principal rivers (Axios, Aliakmon, Pinios, Gallikos) provide, in total, some 25×10^6 tonnes of suspended sediment and some 5×10^6 tonnes of dissolved load (Table 2). In addition, some 10–15% on the total sediment load could be attributed to bed load transport input (Poulos et al., 1996a). Thus, the Thermaikos coastal zone receives a cumulative input of $25–30 \times 10^6$ tonnes/year. This amount is a large contribution, particularly when Milliman and Syvitski (1992) have estimated that some 350×10^6 tonnes of suspended sediment is contributed by all rivers to the southern European coastline. However, this latter estimation has not taken into account the loads of the rivers discharging along the Greek coastline, which are considered to supply some $60–70 \times 10^6$ tonnes of suspended sediment load (Poulos and Chronis, 1997).

The high sediment yield of the Greek rivers ($>$ 500 tonnes/km^2 per year) is in response to: (a) the intensive weathering processes, induced by the temperate climatic conditions; (b) large daily and seasonal temperature fluctuations and relatively high precipitation levels; (c) erodible lithology; (d) the mountainous character of the region, with high relief ratios (see Table 2) and (e) the sparse vegetation cover.

Seasonal climatic changes have a direct influence on river-runoff and weathering processes, inducing seasonal variations in sediment transport. For example, monthly variations in the water and sediment fluxes of the R. Aliakmon (Fig. 2b) indicate that sediment flux reaches its highest levels at the beginning (within only 1 or 2 months) of the wet season (Oct.–June), while some months later (when the water levels in the rivers are still high) the sediment flux decreases rapidly to reach its minimum value during the dry summer period (July–Sept.).

The seasonal variations in the sediment fluxes may be explained in terms of sparse vegetation cover and desiccated soil conditions during the dry season. At such times, the land surface becomes vulnerable to erosion, when heavy rains fall at the beginning of the succeeding wet season. Subsequently, during the wet season, the plant cover becomes dense, with a corresponding increase in soil cohesion and a considerable reduction in its erodibility. Hence, it may be concluded that the majority of the sediment load of these mountainous rivers is transported at the beginning of the wet season; the streams subsequently carry less sediment (i.e. there is less weathered material available for transportation). Further, such intensive transport may be expected to take place within only a few days, when floods occur in response to heavy rainfall and/or sudden snowmelt in the mountains.

2.2. Sub-aerial part of the coastal zone

The geomorphology of the sub-aerial part of the coastal zone and adjacent areas is shown in Fig. 3. The coastal-land area of the Thermaikos Gulf Coastal System accounts for some 2650 km^2 (between 0 and 75 m in altitude, above sea level), representing only 5.6% of the terrestrial part of the Coastal System. The length of the associated coastline exceeds 350 km. To the west, especially the southwest, the coastline is bounded by high mountains with altitudes >2000 m; its eastern part is bounded by lower relief, with topographic heights of between 300 m and 1000 m.

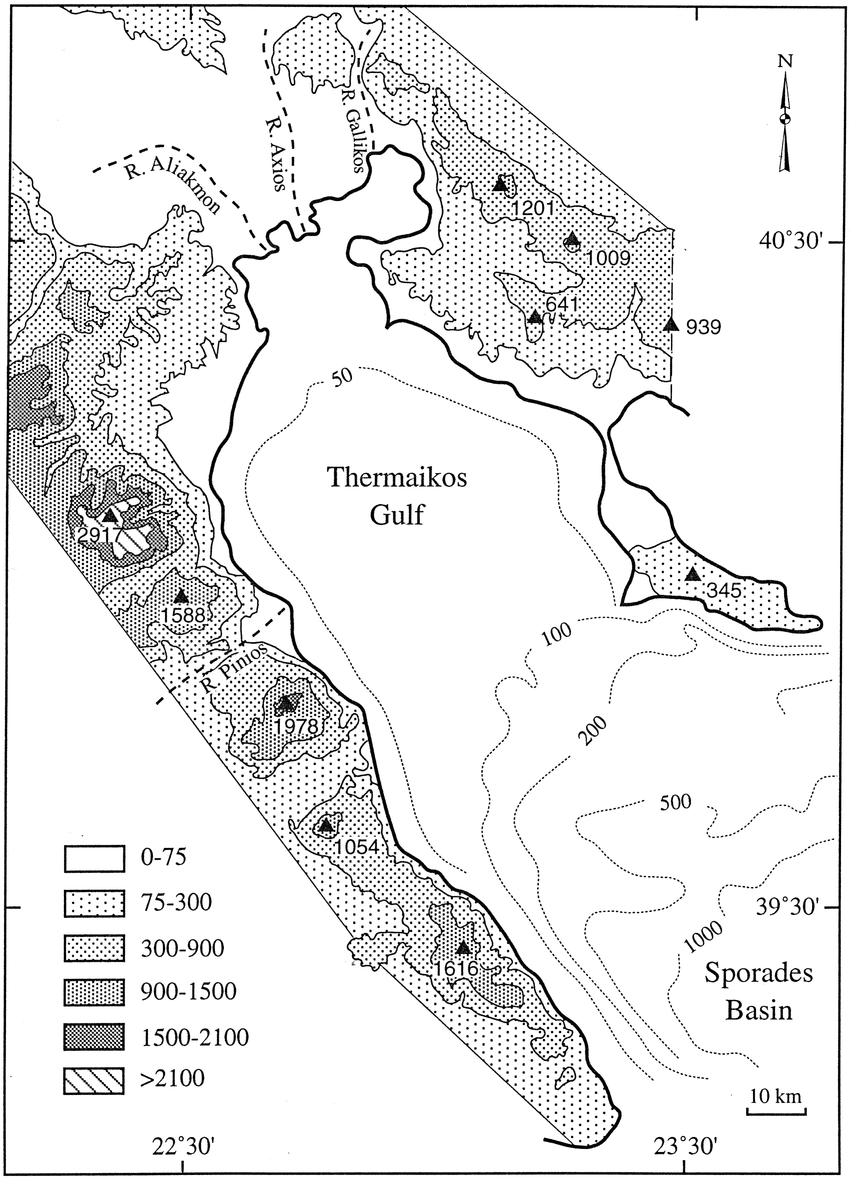

Fig. 3. Generalised topography and bathymetry of the coastal zone (excluding the drainage basins of the main rivers) of Thermaikos Gulf (based upon a topographic map (1:500,000), produced by the Hellenic Army Geographical Service in 1979) and an adjacent bathymetric map (1:50,000).

2.2.1. *Climate*

The climate of the coastal zone of Thermaikos Gulf can be described as a semi-arid Mediterranean type, with rather cold winters. Air temperatures range between 0°C and 38°C, while the mean annual precipitation is some 480 mm (in the city of Thessaloniki). The mean monthly variations in air temperature and precipitation in Thessaloniki are shown in Fig. 4. In addition, the climate of the Thermaikos coastal zone is affected by the wind regime. Northerly

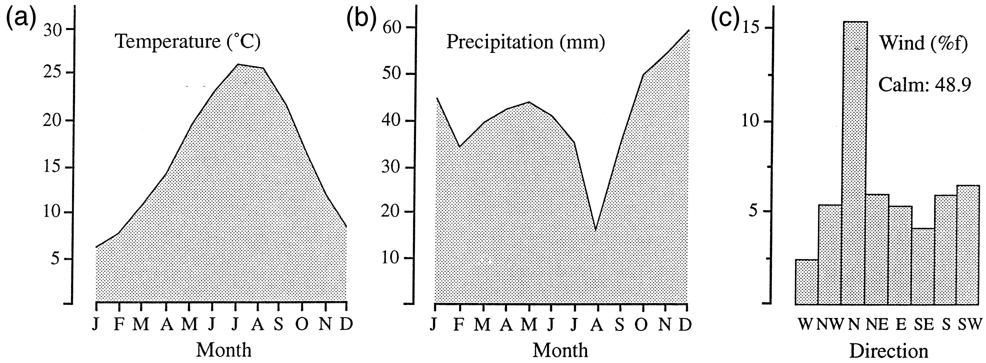

Fig. 4. Mean monthly variation of air temperature (after Flocas and Arseni Papadimitriou, 1974) (a), precipitation (after Angouridakis and Machairas, 1973) (b), and annual distribution of wind speed and direction (after Livadas and Sahsmanoglou, 1975) (c), in the City of Thessaloniki.

winds blow throughout the year and are enhanced during the winter; these are Balkan cold air masses (named locally the Vardaris wind), originating from the north/northwest and following the valley of the Axios River. During the summer, the wind climate is dominated by the presence of the ‘‘Etesians’’;[2] these blow from the north/northeast and are relatively strong (> 6 m/s). When the ‘‘Etesians’’ are not present, small-scale ‘‘sea breezes’’ (of 5–10 cm/s), generated by differential heating between the land and the sea, blow from the south and the southeast. Overall, the northerly component of winds has the highest frequency of occurrence during every month of the year (Fig. 4).

2.2.2. Geological setting

The Thermaikos Gulf system forms the northwestern continental margin of the Aegean Sea. The region is a back-arc area in relation to the Hellenic Arc-trench; it belongs geologically to the Axios/Vardar and Pelagonian geotectonic zones and developed within the Quaternary (1.8 My–present). The shoreline configuration has been developed during the Holocene, following the termination of sea level rise some 6000 years BC (Piper and Perissoratis, 1991).

The lithology of the coastal zone of Thermaikos Gulf and the surrounding area is summarised in Fig. 5. The eastern coastline, from the Ak. Paliourion to the City of Thessaloniki, consists mainly of Mio-Pliocene (10–1.8 My) lacustrine to terrestrial deposits, changing towards the south to marine deposits. The north/northwesterly coastline is formed by fluvial and deltaic deposits of Holocene age. The western shoreline, between the Aliakmon and Pinios Deltas, is formed of recent to present Quaternary (< 1.8 My) formations, consisting mainly of alluvial and fluvial deposits. The southernmost part of the western coastline consists of limestone (mainly dolomitic), marbles, gneisses, schists, amphibolites and metamorphic schist–chest formations, of the Pelagonian zone of Triassic–Jurassic age (230–140 My).

2.2.3. Coastal geomorphology

The topographic relief of the coastal land area varies considerably and is controlled by a number of interrelated factors (and/or processes): the general geological and tectonic evolution of the region, especially within the Quaternary; the underlying lithology; climatic conditions and the associated weathering processes; and the presence of various river networks. Within the context of a global distribution, the coastal zone under investigation, as part of the coast of southeastern Europe, can be characterised (after Carter, 1988) as a coastal plain developed on a wide continental shelf. It can be further distinguished geomorphologically into: (i) deltaic (Holocene)

[2] The Etesians are northerly winds, associated with clear skies; they blow during the warm period (May–September), reaching occasionally gale force in strength (> 10 m/s). The mechanism of their generation is best explained by Lascaratos (1992).

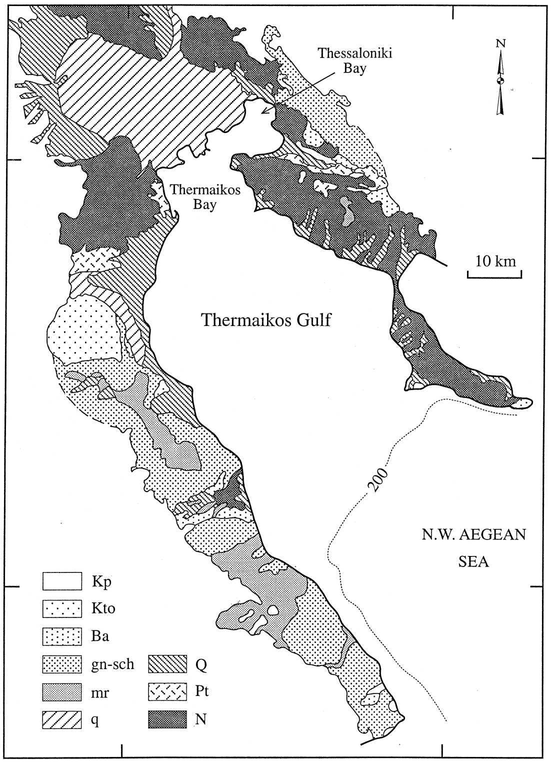

Fig. 5. Lithology of the coastal zone region of Thermaikos Gulf based upon a geotectonic map produced by the IGME, 1989. [Key: Q: recent to present formations; mainly alluvial deposits, fluvial deposits, fans, dunes, volcanic agglomerates; Q1: coastal, fluvial, deltaic and moved deposits; Pt: old alluvial deposits, scree, talcus cones and terraces, mainly of Pleistocene age; N: marls, mainly limestones, clayey marls, sands, sandstones, conglomerates of Neogene and (locally) Pleistocene age; Kp: limestones and dolomites of Pelagonian zone; Kto: limestones of the Olonos and Pindos zone; Ba: basic, ultra basic igneous rocks; Gn: sch–gneisses, amphibolites together with crystalline schists; and Mr: marbles, crystalline limestones and cipolins].

plains, (ii) alluvial (Quaternary) coastal lowlands; (iii) low cliffed coasts; and (iv) high cliffed coasts. The latter two categories often incorporate pocket beaches. Thus, on the basis of the aforementioned classification, the coastal zone of Thermaikos Gulf can be divided into different geomorphological sectors (Fig. 6), as described below.

Sector I extends between Ak. Sepia, to the south, and the commencement of the R. Pinios delta, to the north. The region incorporates mostly high cliffs, with slopes > 10%, associated with the high altitudes (> 2000 m) of the nearby mountains and their hard lithological rock-types (mostly metamorphic, of the Pelagonian Zone). Along this cliffed coastline there are some pocket beaches, formed by local ephemeral streams. In addition, within the northern part of Sector I there is a coastal area (see Fig. 5) consisting of relatively low cliffs and a broad coastal alluvial plain; its presence is associated with an ephemeral stream, which used to connect the (artificially dried, nowadays) Lake Boibis, with the open sea. In general, coastal Sector I is associated with large nearshore water depths (> 200 m), while it is exposed to long easterly wave-fetch distances.

Sector II includes basically the sub-aerial deltaic plain of the R. Pinios (Fig. 6), formed by the fluvial deposits of the R. Pinios within the Holocene. The lobate-shape of its shoreline reflects the dominance

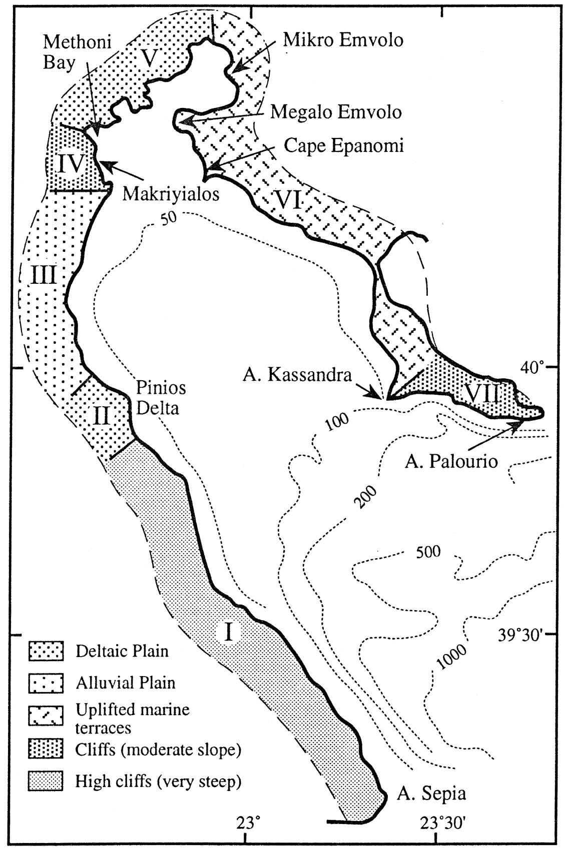

Fig. 6. Schematic representation of the different geomorphological regions of the sub-aerial coastal zone of the Thermaikos Gulf.

of the marine processes, in relation to long wind/wave fetches and the deep bathymetry of the narrow shelf (see Fig. 1) (for further discussion, see below).

Section III is located between the northern end of the R. Pinios delta and the promontory Ak. Atherida, towards the north (Fig. 6); the latter is the natural boundary, along the western coastline, between the outer and inner shelf of Thermaikos Gulf. The central and northern part of this coastal area represents a coastal plain of low relief (slopes $<1\%$); it consists of alluvial deposits of a number of ephemeral streams with the largest being Mavroneri (with a catchment area of some 150 km^2). The coastline is somewhat straight, being sandy and wider to the south. The latter characteristic is indicative of northerly littoral sediment transport, from the R. Pinios delta area. The southern part (Fig. 5) of this sector is characterised by a narrow coastal plain, related to the proximity of Mount Olympus (2800 m).

Sector IV forms the western coastline of the inner shelf of Thermaikos Gulf (or Thermaikos Bay), located between Ak. Atherida and Methoni Bay (at the commencement of the R. Aliakmon delta). The coastal zone consists of a narrow coastal plain, extending some hundreds of metres to landwards; it is associated with rather shallow water depths (<35 m) and is exposed to limited wave fetch distances. The coastal plain is interrupted by the presence of a 20-m high cliff, consisting of grey sandstone, conglomerate, sands and marls; these are of Wurm–Rissio in age (Faugeres, 1977). Sedimentologically, the section is characterised by: (i) coarse material mostly sands of local origin; and (ii) fine-grained material (mainly silts), allochthonous in origin. Coarse-grained sediments on the beach of Makriyialo originate from weathering of the aforementioned Quaternary cliff; this is supported by the presence of massif and speckled type of augite, which is the erosional product of the aforementioned cliff. Conversely, the silts may be attributed to the southerly transport of fine-grained material from the mouths of the rivers Axios and Aliakmon; this is indicated by the presence of green and denticulate augite originating from the volcanic rocks of the R. Axios catchment area (Chronis, 1981).

Sector V forms the north/northwestern coastline of Thermaikos Bay consisting of the deltaic plain of the Rivers Axios, Aliakmon and Gallikos. This deltaic coastal plain has been formed within the Holocene, presenting a very low relief $<0.25\%$. The coastal configuration of the deltaic plain, with a bird-foot shape at the river mouths, indicates the dominance of fluvial (water/sediment) over marine (waves, longshore currents) processes (see below); this is related to the shallow offshore waters (<25 m) and its exposure only to high waves, approaching from the south. Further, the sedimentary material of the R. Aliakmon is relatively finer (sandy silts), when compared with that of the R. Axios (silty sand).

Sector VI incorporates almost the whole of the eastern coastline of Thermaikos Gulf, extending from the City of Thessaloniki (Mikro Emvolo) to the promontory of Ak. Kassandra. The region is characterised generally as a low relief coastal plain, associated with some low-cliffed areas; it can be sub-divided further into the following sub-sectors.

(i) Sub-sector VIa (east coast of Thessaloniki Bay) relates to a sheltered and shallow water (<25 m) embayment, with limited wave activity. This stretch of coastal zone presents a rather low relief ($<1.5\%$).

(ii) Sub-sector VIb (east coast of Thermaikos Gulf) extends between the cape of Megalo Emvolo and the promontory (sandy spit) of Ak. Epanomi; it is characterised generally by a relatively steeper relief ($\sim 5\%$) and rather shallow water depths (<40 m).

(iii) Sub-sector VIc (Ak. Epanomi–Ak. Kassandra) is characterised by coastal zone slopes of between 2% and 5%, while the adjacent water depths exceed 80 m.

Sector VII is basically a cliffed coastline, extending between Ak. Kassandra and Ak. Paliourion, facing the open NW Aegean Sea and experiencing, therefore, deep water conditions (water depths >200 m). Geomorphologically, it is a cliffed coast bounded by a lower and more erodible mountainous lithology, when compared with that of the high-cliffed coastal zone of Sector 1 (see Figs. 3 and 5).

2.2.4. Ground water

The use of ground water is associated mainly with the irrigation of the extended agricultural (mostly deltaic) areas and the provision of water to the population established in the coastal zone. Generally, the aquifers of the deltaic plains are supplied by water from lateral infiltration of the main rivers. In general, the supply of freshwater to the Thessaloniki deltaic plain is satisfactory after an extended irrigation plan for the management of the water of the rivers (Axios, Aliakmon and Gallikos). Some localised problems, which have been occurred periodically, are associated with the occurrence of long periods of relatively lower levels of precipitation and/or arbitrary human utilisation of the groundwater. Nowadays, diversion of the R. Acheloos into the R. Pinios is being considered. Such a diversion and the subsequent surplus of freshwater would increase the agricultural productivity of the Thessalia plain (the agricultural area surrounding the city of Larisa) and that of the Pinios delta.

Hydrogeological investigations undertaken in the Thessaloniki deltaic plain have revealed the presence of three different aquifers (Knithakis and Tzimourtas, 1987): (i) a shallow phreatic aquifer, at about 10 m depth and a thickness of 6–8 m; (ii) an intermediate artesian aquifer, usually observed at between 40 m and 60 m (locally 30–80 m); and (iii) a deep artesian aquifer, lying at a 100–200 m depth. The shallow phreatic aquifer receives water from the rivers, streams, rainfall and through irrigation activities. The intermediate and deep artesian aquifers receive also water from such lateral water movement and as intake from the marginal (highland) areas surrounding the plain. Furthermore, the shallow phreatic horizon is characterised by high salinisation and alkalisation, due to the marine origin of the surficial sediments. Similarly, the intermediate artesian aquifer is not suitable for drinking, as it receives sodium chlorate through infiltration of the surface waters. The deep artesian aquifer exhibits satisfactory quality; it is used for domestic use by the habitants of the city of Thessaloniki and its suburbs. Moreover, overpumping of the ground water in the region of Kalochori (a few kilometers to the northeast of the mouth of the R. Gallikos) for supply of the city of Thessaloniki, has enhanced the subsidence (some 2.5 m over the past 30 years) of this part of the coastal deltaic plain. Such movement is in response to the natural compaction of the sedimentary sequences and the reduction in sediment load delivered by the river (IGME, 1989).

2.2.5. Coastline changes

The most active parts of the Thermaikos coastal zone are those related to the evolution of the river deltas and the formation of sandy spits. The former is associated primarily to the riverine sediment fluxes, while the latter is a combination of the presence of headlands and the prevailing nearshore hydrodynamic conditions.

2.2.5.1. Deltaic coasts. The sub-aerial deltaic plains of the rivers Axios, Aliakmon, Pinios, together with those of the Gallikos and Mavroneri, form the most active part of the shoreline. In particular, the deltaic complex of the rivers Axios, Aliakmon and Gallikos form the Thessaloniki plain, which is of great socio-economic importance to Greece.

Historical evidence dating from the 5th century BC indicates the rapid progradation of the aforementioned deltaic complex. At this time, the ancient towns of Skidra (to the west) and Pella[3] (to the north) were located originally adjacent to the sea. Nowadays, the city of Pella is located some 30 km to the northwest of the present coastline. Southerly progradation of the deltaic complex plain, between the 5th century BC and today, is presented schematically in Fig. 7. Furthermore, on the basis of the comparison of hydrographic charts (Poulos et al., 1994), it has estimated that only within the last 150 years (between 1850 and 1987) has the coastal deltaic plain of R. Axios prograded to seawards; this has produced new land, of the order of 175 km^2. Similarly, the R. Aliakmon deltaic plain has increased by some 140 km^2. These values correspond to annual growth rates of 1.3 and 1.0 km^2/year for the rivers Axios and Aliakmon, respectively. Such deltaic progradation is associated with high sediment fluxes related to: the high relief of the hinterland area; and relatively erodible lithology and climatic conditions over the river catchment areas (implying intense weathering processes and high rates of sediment transport). In contrast, the smaller deltaic plain and (predicted) lower progradation of the deltaic plain of R. Pinios is attributed to the presence of deep waters in front of the river mouth. Further, the small

[3] The city of Pella was the capital of Macedonia, during the reign of the Alexander the Great.

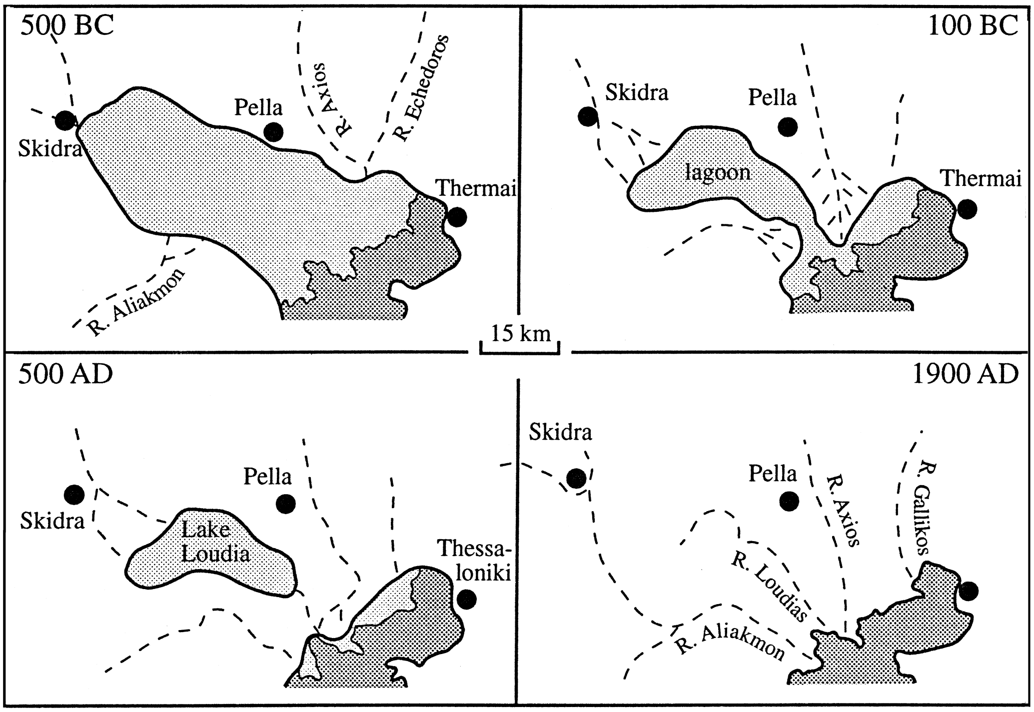

Fig. 7. The evolution of the Thessaloniki deltaic plain within historical times (since 500 BC) (after Konstantinidis, 1989).

ephemeral rivers discharging along the Katerini coastline have controlled the formation of the low relief coastal alluvial plains. Similarly, along the Chalkidiki Peninsula, most of the beaches located in front of the low cliffs are related to the action of ephemeral streams and longshore currents.

The evolution and the associated morphology of the deltaic coastline, in the case of the essentially tideless environment of the Greek waters, results mainly from interaction between the water/sediment discharge and the prevailing wave activity. Thus, the deltaic shorelines of the Rivers Axios and Aliakmon are subjected to much lower monthly wave power (< 30 W/m^2) than that of the R. Pinios (70–1454 W/m^2) (Fig. 8). This pattern relates to the restricted wave fetches within the semi-enclosed and shallow embayment of Thermaikos Bay; in contrast, the R. Pinios is exposed to long wave fetches (Poulos et al., 1993).

Moreover, the monthly distribution of water discharge and wave power for the mouths of the Rivers Axios and Aliakmon is out of phase (Fig. 8): the peak discharges occur between late autumn and early spring, while wave energy maximum occur between mid-spring and mid-autumn. Thus, during the first period, fluvial processes dominate the evolution of the deltas; at such times, progradation of the river mouth areas may be expected to occur. In summer, when the wave power is relatively higher and the river discharge is at its lowest levels, (marine) wave activity becomes the dominated factor. However, the low levels of wave activity mean that the resulting longshore currents are not strong enough to redistribute the sediments deposited earlier; this results in the formation of the bird-foot shape of the deltaic coastline, which is similar to that of Mississippi (Galloway and Hobday, 1983). In contrast, in the case of the R. Pinios, the period of high water discharge (December to March) coincides with that of high wave power. Hence, in this case, the fluvial sediment input is likely to be reworked by waves and associated longshore currents; this creates a lobate shape to the deltaic coastline, which is similar to that of the R. Ebro (Spain).

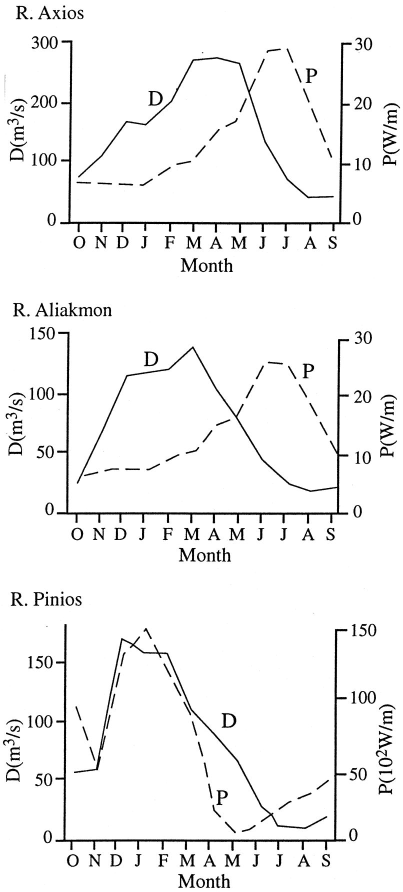

Fig. 8. Seasonal variation of the incoming mean offshore wave power (P) and river water discharge (D) for the Rivers Axios, Aliakmon and Pinios (after Poulos et al., 1993).

2.2.5.2. Sandy spits. Along the coastline of Thermaikos Gulf, there are a number of small or larger sandy spits; that of the Ak. Epanomi (Fig. 9) is the largest and undergoing substantial seasonal changes. Such changes relate to the fact that the promontory of Ak. Epanomi forms the natural boundary between the inner Thermaikos shelf (characterised by shallow waters and limited wave fetches) and the outer Thermaikos shelf (associated with deeper waters and long wave fetches, especially to the south).

The Epanomi sandy spit, formed initially on a headland, is attributed to the action of a biomodal wind/wave field. Northerly winds predominate during winter inducing moderate sediment transport rates in response to the limited wave-fetches. Thus, the northern section of the spit undergoes gradual small-scale changes. In summer, the southerly and southeasterly wind-induced waves are associated with very long fetches (hundreds of km); these cause intensive longshore sediment transport along the southern part of the spit. Such transport causes substantial changes in the sub-bottom profile of the spit, especially following a storm. The differences in magnitude of the changes that take place to the southern and northern part of the spit are shown on Fig. 9. To the south, the difference between the winter and summer subaqueous profile exceeds 4 m at a distance of 100 m to seawards; along the northern side, it is less than 1 m and is restricted to within a distance of <30 m. In addition, the summer subaerial profile along the northern beach has undergone only a minimal increase; along the southern side of the spit it has increased by almost 1 m. Seasonal variation in the hydrodynamical conditions, described previously, are reflected also by the granulometry of the spit: coarse material (coarse sand, pebbles) is abundant along the southern side, while

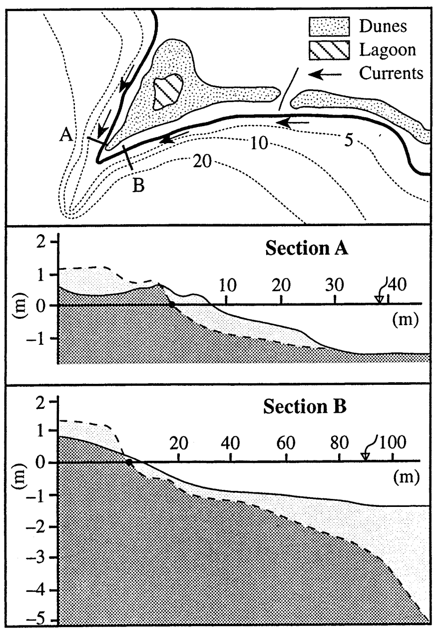

Fig. 9. Physiographic characteristics of the Epanomi sand-spit and seasonal changes in its subaquous northern (A) and southern (B) beach profile [Key: —: summer profile; - - -: winter profile] (after Chronis, 1981).

fine-grained material (mostly fine sand) dominates the northern side (Chronis, 1981).

3. Oceanic part of the coastal system

The oceanic part of the Coastal system (0–200 m water depth) accounts for some 5100 km^2, representing almost 10% of the total area of the Thermaikos Gulf Coastal System and approximately two third of the area bounded by the 75 m topographic contour and the 200 m isobath. The sector can be divided further into: (i) the inner continental shelf, with water depths of < 40 m, consisting mostly of Thessaloniki and Thermaikos Bays; and (ii) the outer shelf/shelf-break area (open Thermaikos Gulf), where water depths lie between 50–200 m. Thus, the inner shelf area (subaquous part of the coastal zone) covers an area of 1100 km^2, representing 21% of the oceanic part of the Coastal System and almost the 30% of the total area of the coastal zone (Table 1).

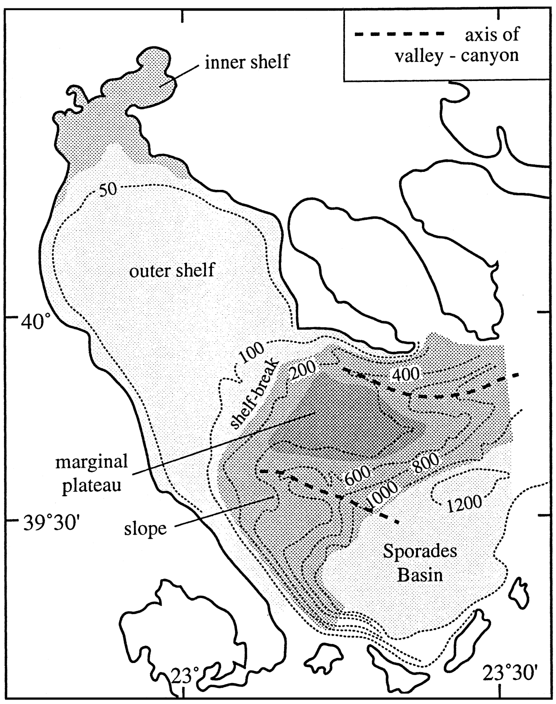

Fig. 10. Physiographic regions of the subaquous part of the coastal zone of the Thermaikos Gulf Coastal System (after Lykousis et al., 1981).

The outer shelf area covers a much larger area, about 4000 km^2.

On the basis of the interpretation of bathymetrical and morphological characteristics of the seafloor (Lykousis et al., 1981), the subaqueous part of the Coastal System can be divided into the following physiographic regions (Fig. 10): (i) the continental shelf area, which extends to the shelf break (at about 130 m water depth); and (ii) the continental slope which extends to the deep Sporades Basin (with water depths of up to 1200 m). The shelf is divided further into the inner (< 40 m) and the outer shelf, while on the slope two distinctive regions are present: (a) the marginal plateau, defined by the 500 m bathymetric contour; and (b) the canyon and valley systems, which intersect across the slope.

3.1. Oceanographic setting

3.1.1. Water masses

The properties of the seawaters within the Thermaikos Gulf Coastal System vary seasonally, following corresponding variations in air temperature, freshwater inputs, wind climate and the general circulation and mixing of water masses. Within the inner shelf (Thermaikos Bay), the surface water temperatures vary between 25°C (summer) and 9°C (winter): surface salinity are 35 psu and 28 psu during summer and winter, respectively. Near-bottom water temperature and salinity values are generally more stable throughout the year, at around 21°C and 36 psu in summer and 9°C and 38 psu during winter (Robles et al., 1983).

An extended hydrological survey undertaken in June 1987, involving 85 CTD stations and incorporating the whole of the deep water part of the Thermaikos System (Durrieu de Madron et al., 1992), has revealed the existence of the following water masses (Fig. 11): (i) surface waters (SW) (< 40 m), with $T > 13.5$°C and high spatial variability in salinity, due mainly to the presence of the rivers — within the upper part of the SW, a thermocline/halocline layer is present, at depths of around 20 m; (ii) shelf bottom waters (SBW) over the continental shelf (water depths > 40 m) and, especially, near to the sea bed (80–120 m) — these are cold (T < 12.5°C) and of low salinity (S < 38.6 psu) and their

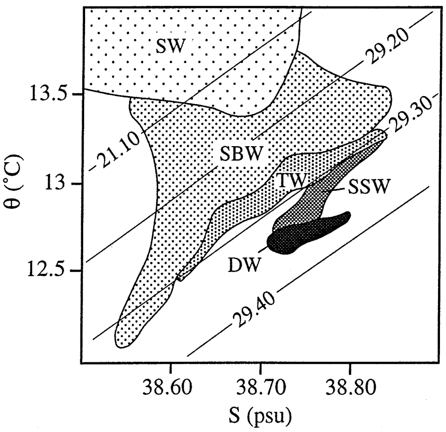

Fig. 11. Temperature (potential)–salinity diagram of the different water masses of Thermaikos Gulf (after Durrieu de Madron et al., 1992). [Key: SW: surface waters; SBW: shelf bottom waters; TW: transitional water mass; SSW: sub-surface water mass; DW: deep-water mass].

density varies between 29.26 and 29.34; (iii) a transitional water mass (TW) near the shelf break and over the deep basin, at between 100 m and 200 m of the upper part of the water column — this appears to be of relatively constant density (29.28 ± 0.02), despite the significant variations in both temperature and salinity; (iv) a sub-surface water mass (SSW) observed between water depths of 200–600 m — here, the temperature decreases, with depth, from 13.3°C down to 12.6°C, while the salinity is reduced slightly from 38.83 to 38.70 psu; (v) a deep water mass (DW) extending below 600 m and up to 1000 m within the water column, having temperatures of 12.7 ± 0.01°C, salinities 38.7–38.8 psu and a density increasing slightly with depth (from 29.34 to 29.38 psu).

3.1.2. Water movement

Thermaikos Gulf, as part of the northern Aegean Sea, is a microtidal marine environment. Recent analyses have shown that the major semi-diurnal constituents M2 and S2 rarely exceed 10 cm and 7 cm, respectively. Similarly, the major diurnal tidal constituents (K1 and S1) presently are of exceptionally small amplitudes around 2.7 cm and 1.7, respectively (Tsimplis et al., 1995). Moreover, harmonic analyses of the tides within the Thessaloniki Bay have revealed the following amplitudes and phases (Tsimplis, 1994): M2 (9 cm, 78°); S2 (6.1 cm, 98°); K1(2.6 cm, 357°); and O1(1.3 cm, 328°). Finally, records of restricted duration of water level fluctuations have attributed to strong sea breezes from the south (short period oscillations) and to rapid changes of barometric pressure (long period oscillations) (Wilding et al., 1980).

Within such an essentially tideless environment, water movements are governed by the thermohaline circulation, mixing of different water masses and the prevailing wind climate. It has been observed generally that more saline, clear (free of suspensates) and relatively dense waters, which originate from the open waters of the north Aegean Sea, enter the outer shelf of Thermaikos Gulf over the central and eastern part of the plateau; then they turn towards the northeast flowing parallel to the Chalkidiki Peninsula, finally entering the inner Thermaikos Bay (Fig. 12a). Conversely, fresh (less saline) waters flow towards the south, along the western coastline. This southerly flow consists of water discharges from the

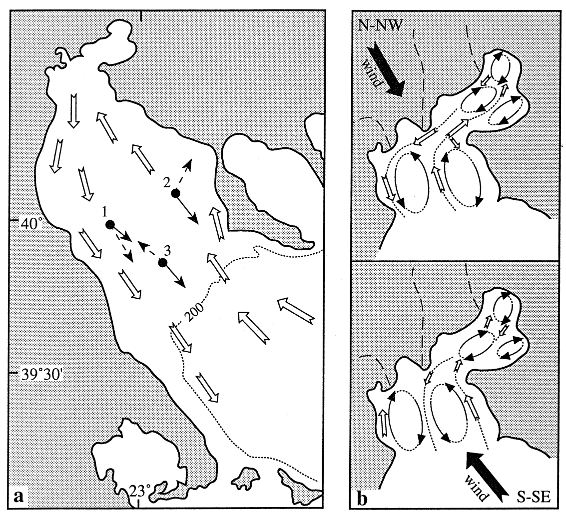

Fig. 12. (a) General circulation patterns of the surface waters of Thermaikos Gulf (after Balopoulos et al., 1987), (RRS Discovery Cruise 137); (b) shallow (solid vectors) and deep-water (open vectors) circulation patterns of the inner shelf (Thermaikos and Thessaloniki Bay) (after Ganoulis, 1987). [Key: ●: current meter stations].

Table 4
Current meter observations in outer Thermaikos Gulf (R/V *Discovery*, 5–6/83)

Station	Currents						
	D (m)	*Z* (m)	< 1.7[a] (%)	Minimum (cm/s)	Maximum (cm/s)	Mean (cm/s)	Direction (°)
Surface							
CM 1	75	50	20	< 1.7	15.8	6.5	170
CM 2	85	50	27	< 1.7	13.0	6.5	80
CM 3	105	95	40	< 1.7	18.9	9.3	335
Bottom							
CM 1	75	5	32	< 1.7	8.2	4.2	125
CM 2	85	5	01	< 1.7	8.8	5.0	145
CM 3	105	5	32	< 1.7	7.1	4.0	135

[a] Current meter's rotor threshold value; *D*: water depth; *Z*: distance above seabed.

Rivers Axios and Aliakmon, together with an additional input from the R. Pinios, farther to the south. Moreover, this southerly movement of surface waters is particularly enhanced during winter, due to the prevailing northerly winds (see above) and the increased river water discharges (February–July) (Fig. 2). Similarly, the dominance of the south/southwesterly sea breezes, in summer, move water masses from the central and eastern part of the Gulf towards the innermost part of the embayment.

Measurements of surficial currents are in accordance with the circulation pattern described above, although the directions are somewhat variable. In contrast, near-bed current measurements, obtained during different seasons, have shown that there is a general and southerly persistent movement of bottom waters over the shelf; this continues down the slope and along the main submarine valley/canyon systems towards the Sporades Basin (Poulos and Panagiotopoulos, 1997). Such water movements are indicated by observations obtained from the outer shelf (water depths > 50 m) in May 1983 (R/V *Discovery*) and June 1987 (R/V *Aegaio*). Current speeds are in the order of 5–20 cm/s near the water surface and up to 9 cm/s near the seabed (Table 4).

In particular, surface water circulation over the inner shelf (water depths < 40 m) is influenced strongly by the prevailing wind conditions. On the basis of a depth-integrated hydrodynamical model, a 2-gyre system (Fig. 12b) is considered to be established in Thermaikos Bay. Water moves south along the east and west coastline, under N–NW winds; it moves in the opposite direction (northwards) in the case of S–SW winds (Ganoulis, 1987). During the presence of a persistent northerly wind, the general surficial flow throughout the whole embayment is towards the south. The presence of a gyre, characterised by turbid waters, in the western part of the Bay has been also identified in satellite (LANDSAT) imagery (Balopoulos et al., 1986).

3.1.3. Wave activity

Wave heights, and especially the direction of wave propagation, is governed by the existing wind regime; this is demonstrated clearly by the wave and wind roses presented in Fig. 13. Waves related to southerly winds are considered to be the most important in terms of their magnitude; these are associated with the longest fetches (∼ 170 km). Hence, high waves of long wavelength (swell) are to be expected

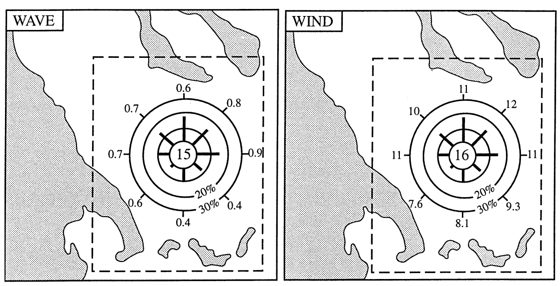

Fig. 13. Wave and wind roses relating to Outer Thermaikos Gulf and the Sporades basin area (abstracted from Athanasoulis and Skarsoulis, 1992).

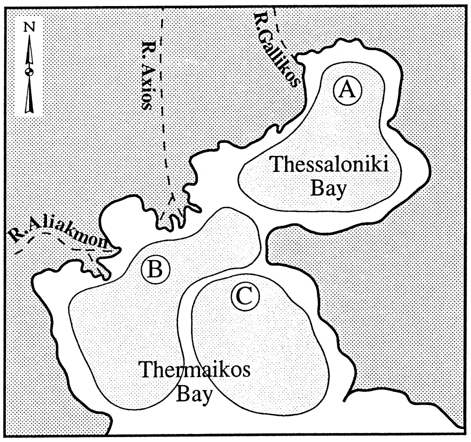

Fig. 14. Schematic representation of the water masses, of different nutrient concentrations, of the inner Thermaikos shelf: (A) Thessaloniki Bay; (B) northwestern Thermaikos Bay; (C) southeastern Thermaikos Bay (after Balopoulos and Friligos, 1993).

only from southerly directions. In contrast, the northerly components of the wind spectrum have a high frequency of occurrence; despite their smaller fetches, they generate surface gravity waves influencing, consequently, the general water surface circulation of Thermaikos Gulf. The wave field of the outer shelf, primarily within the Sporades Basin, is characterised by a mean annual wave height of 0.5–0.7 m. The frequency of occurrence (%), for different wave heights (H) on an annual basis is as follows: $H < 1$ m (80%), $H < 2$ m (95%), $H > 3$ m (1%), and for $H > 4$ m (5%) (Athanasoulis and Skarsoulis, 1992).

3.1.4. Nutrients

The aquatic environment of Thermaikos Coastal System is characterised, in general, by high nutrient concentrations throughout the year. Especially in the inner shelf areas (A–C; for locations see Fig. 14), nutrients are present at levels well above the background values referred to the open Aegean Sea (Table 5); most of the ratios (mean/background values) are > 2, while in some cases they exceed 4 (Balopoulos and Friligos, 1993). Furthermore, phosphate, ammonium and nitrate values are higher in Thessaloniki Bay (Area A), than in Thermaikos Bay (Areas B and C); this is attributed mainly to the detergents supplied from the existing sewage outfall of the city of Thessaloniki and the relatively small amounts provided by the river inputs. Ammonium and nitrate

Table 5
Mean annual nutrient concentrations[a] (water column averages in μM) in inner Thermaikos Gulf

		Phosphate (PO_4^{3-})	Silicate (SiO_4^{4-})	Ammonium (NH_4^+)	Nitrate (NO_3^-)
Area A[b]	Max	0.84 (Su)	6.02 (Sp)	2.13 (Au)	1.56 (Au)
	Min	0.35 (Sp)	0.98 (Au)	0.54 (Sp)	0.67 (Sp)
	Mean	0.53	3.08	1.46	1.17
	Ratio	4.4	2.5	4.1	2.8
Area B	Max	0.30 (Su)	4.69 (Wi)	1.86 (Au)	2.04 (Wi)
	Min	0.21 (Sp)	3.62 (Sp)	0.50 (Sp)	1.14 (Sp)
	Mean	0.25	4.32	1.04	1.49
	Ratio	2.1	3.5	2.9	3.5
Area C	Max	0.15 (Au)	4.90 (Sp)	1.38 (Au)	1.13 (Sp)
	Min	0.13 (Su)	1.03 (Au)	0.44 (Su)	0.72 (Su)
	Mean	0.14	2.77	0.71	0.90
	Ratio	1.2	2.3	2.0	2.1
Aegean	Bgd[c]	0.12	1.22	0.36	0.42

[a] Concentrations values represent integrated mean nutrient values taken for the whole water column of all the stations of each physiographic area during five successive oceanographic cruises (Nov. '75, Feb. '76, May '76, Aug. '76) (abstracted from Balopoulos and Friligos, 1993).

[b] Geographical locations of Areas A–C are shown in Fig. 14.

[c] Typical concentration values of the Aegean Sea (after Friligos, 1981).

(the oxidation product of ammonium) maxima occur during the autumn, due to the faster rate of decomposition of organic compounds. The northwestern part of Thermaikos Bay hosts the highest silicate values throughout the year, as it is influenced mostly by the discharges of the rivers Axios and Aliakmon; increased silicate levels coincide with periods of high river discharges (Dec.–May). Phosphate and ammonium increased levels are usually observed within the Thessaloniki Bay (Area A). The comparatively low nutrient levels observed in the eastern part of Thermaikos Bay is explained by the general water circulation, with clearer and oligotrophic Aegean Waters to entering Thermaikos Gulf along its eastern coastline (see above).

During a recent survey (Dec. 1995–Mar. 1996), the mean nutrient concentrations of the water masses of the inner part of Thessaloniki Bay was found to be slightly increased (PO_4: 0.85; SiO_4: 4.1; NH_4: 2.4) over the earlier levels, with the exception of NO_3 (0.8) (after Psylidou Giouranovits et al., 1998).

3.2. Sedimentology

3.2.1. Suspended sediment (river plumes and nepheloid layers)

The presence of suspended sediments within the Thermaikos Gulf Coastal System is related primarily to the riverine water/sediment inputs and, secondarily, to coastal erosion in response to wave and current activity; their seaward dispersion is associated with the general water circulation pattern (as described previously). In general, most of the suspended sediment is transferred and accumulates towards the south; this influences the development of the seabed sedimentary cover over the inner shelf and, primarily, the western part of the outer shelf.

In particular, the plumes of the Rivers Axios and Aliakmon overlie most of the inner shelf (Thermaikos Bay), on an annual basis; this is shown schematically by the distribution of the lower-salinity surface waters (Fig. 15a). Thus, during winter and spring when the rivers (Axios and Aliakmon) are at their highest discharge levels, the 34 psu isohaline contour is forced by up to 10 km to the southeast, away from the river mouths. Similarly, the dispersion of the R. Pinios plume indicates the influence of the riverine sediments over the western and central part of the outer shelf (Thermaikos Gulf) (Fig. 15b). Hence, river plumes overlie almost the whole of Thermaikos Bay and most of the inner continental shelf area.

Suspended particulate matter (SPM) is present not only in the surface waters, but relatively high SPM concentrations are presented as nepheloid layers as well, near the sea bed and at intermediate levels within the water column. Indeed, measurements undertaken during a period of low river discharge (early July 1987), over the whole of the study area,

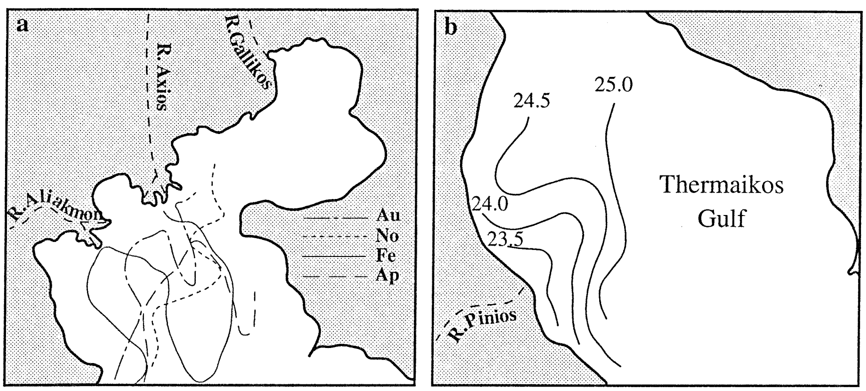

Fig. 15. River plume dispersion seawards: (a) the river mouths of the Axios, Aliakmon, Gallikos, based upon the seasonal pattern of the salinity contour of 34 psu (modified from Poulos et al., 1996a,b); and (b) the mouth of R. Pinios, as shown by the isopycnal contours (after Balopoulos et al., 1993). [Key: Au: August; No: November; Fe: February; and Ap: April].

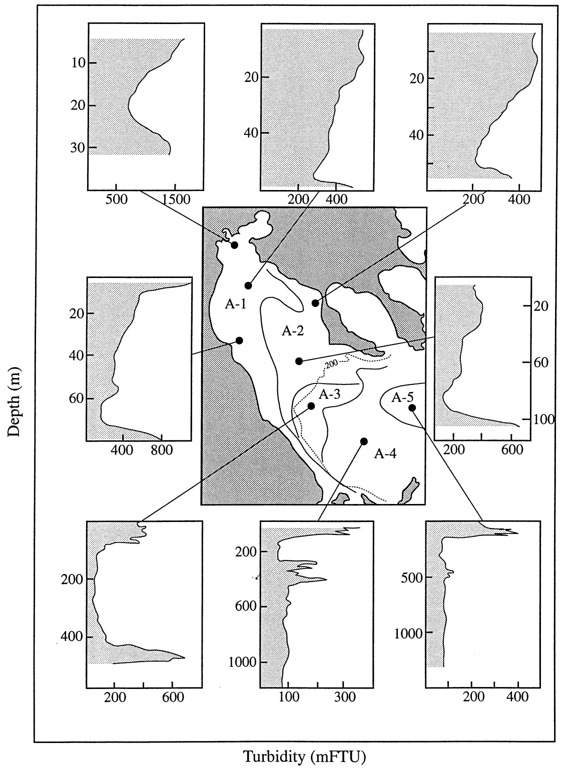

Fig. 16. Regions of relative presence of surface, intermediate and near bed nepheloid layers (after Chronis et al., 1987), with representative profiles of suspended matter (transmisometry) from Thermaikos Gulf and the adjacent Sporades Basin [Note 100–200 mFTU ≅ 0.3 mg/l].

have revealed the presence of surficial, intermediate and bottom nepheloid layers. According to the spatial distribution and vertical location of these layers, five different areas (Fig. 16) have been identified by Chronis et al. (1989) and Durrieu de Madron et al. (1992): *Area 1* — influenced strongly by the river outflows, with surficial and bottom nepheloid layers present (concentration $C > 0.8$ mg/l); *Area 2* — associated with lower values of suspended matter (< 0.8 mg/l), within both the surficial and bottom nepheloid layers, while the latter appear not to be in direct contact with the sea bed; *Area 3* — located over the slope and containing benthic nepheloid layers, with concentration up to 0.6 mg/l; *Area 4* — associated with weak intermediate nepheloid layers ($C \cong 0.25$ mg/l), lying in water depths of between 300 and 600 m; finally, *Area 5*, which covers the northeastern part of the Sporades Basin — characterised by the presence of low surface turbidity values and the absence of intermediate and near-bed nepheloid layers. In general, Areas 3, 4 and 5 contain surface turbidity concentrations in the order of 0.4–0.5 mg/l. Higher values of SPM are expected to occur during the beginning of the wet season (December–February) and following flood events (as discussed previously). In general, the surface nepheloid layers are associated to the river water/sediment outflows and to localised coastal erosion phenomena. The mechanisms of formation of intermediate nepheloid layers are related to the stratification and general circulation of the water masses, while nepheloid layers observed near bed are attributed to associated current activity (which either inhibits settling or causes resuspension).

3.2.2. Recent sea bed sediments

3.2.2.1. Grain size. On the basis of sedimentological analyses (sediment texture and composition) undertaken by various investigators (Chronis, 1986; Lykousis et al., 1981; Lykousis and Collins, 1987; Lykousis and Chronis, 1989), the surface sediments of the Thermaikos Gulf marine sub-system have been classified broadly into four major sedimentary provinces (SP) (Fig. 17): (i) western shelf muds and

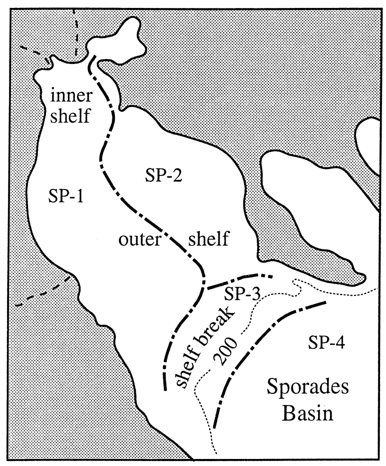

Fig. 17. Sedimentary provinces (1 to 4) of the sea bed of the Thermaikos Gulf (after Lykousis and Chronis, 1989).

sandy muds; (ii) eastern shelf muddy sands; (iii) outer shelf-shelf break sandy clays and clayey sands; and (iv) slope-basin muds.

Sedimentary province 1 (SP-1) covers the western part of both the inner and outer shelf, where sedimentation processes are dominated by the water/sediment outflows of the major rivers (Axios, Aliakmon, Pinios) and other ephemeral streams along the western coastline of Thermaikos Gulf (see Fig. 1). River plumes transport seaward large quantities of suspended sediments; then, these are deposited through gravitational (differential settling) and physicochemical (flocculation) processes (Poulos et al., 1996b). Coarser material is deposited closer to the river mouths, with the finer-grained sediments farther offshore. Mud (silt/clay = 1:1) is the dominant sedimentary material present, having a mean grain size of 0.01 to 0.02 mm. The sand fraction of the deposits is generally 20% of the whole, being terrigenous in origin; this is indicated by the relatively low (about 25%) carbonate content at the sediments. The carbonate-free sand fraction is 0.18–0.125 in size. The clay fraction consists mostly of the clay minerals illite (> 50%) and smectite (> 40%).

Southerly movement of these sediments is induced by the water circulation, while the higher levels of finer-grained sediments (clay) over the southern part of the inner Thermaikos Plateau is related to the presence of an anticlockwise gyre (Balopoulos et al., 1986). Near-bed nepheloid layers are present over this region, indicating the abundance of suspended material and the action of near-bed current activity; this inhibits the rapid deposition of the suspensates. Elsewhere, observed current velocities are lower than 10 cm/s (Poulos and Panagiotopoulos, 1997); these, together with a series of photographs of the sea bed (Lykousis and Collins, 1987) are not indicative of any erosional processes of the sea-floor. Further, in response to the high sedimentation rate (especially in the western part of the Province), there is evidence of only minimal bioturbation.

Sedimentary province 2 (SP-2) covers the eastern part of the shelf, with the sand fraction dominating the sediment cover (with percentages > 50%). The Province includes the eastern half of the outer shelf (Thermaikos Gulf), where the sand content varies at between 60% and 85%; this includes the relatively narrow band along the eastern shoreline of the inner part of the shelf (Thermaikos Bay and Thessaloniki Bay). The mechanisms of sedimentation are associated with the absence of surface turbid waters and/or nepheloid layers, and the general northerly movement of sediment-free open seawaters. Lykousis and Chronis (1989) have found that the proportion of sand increases generally towards the eastern coastline; here, it is believed that there are most of the sources for the coarse-grained terrigenous sediments, provided by the easily erodible Neogene rocks of the coastal zone. The silt content is less than 20% and 40%, over the outer and inner shelf, respectively; the clay content is, in general, < 20%. Differential settling appears to be the principal mechanism controlling sediment deposition, with the coarser material deposited nearer to the coastline. The low mud content and its relatively high mean grain size (< 0.03 mm) is related to the fact that the sediment-laden river plumes do not extend over the eastern part of the shelf, with the exception of some fine-grained material originated from the R. Pinios during peak river discharges.

Sedimentary province 3 (SP-3) includes the southern part of the outer shelf, most of the shelf break area and part of the marginal plateau. The Province reveals the most complicated sedimentary pattern, in terms of both texture and composition; this reflects the complicated hydrodynamic conditions that usually prevail at shelf breaks. The sand fraction varies at between 35% and 90%; this consists partially of terrigenous and partially of biogenic origin. Thus, the mean size of the ‘‘untreated’’ sand fraction in the analyses is much greater (0.35–0.18 mm) than after treatment (0.12–0.18 mm); this is due to the presence of shell fragments. The silt and clay content varies between 2% and 25% and from 5% to 45%, respectively, while the mean size of mud fraction is 0.015–0.03 mm. In addition, high percentages of sand (60–90%) are present in the sediments of the southern and southeastern part of the outer shelf, in water depths of 90–110 m. The well-sorted and well-rounded character of the sand grains, in combination with the presence of large amounts of heavy minerals, leads to the conclusion that these deposits represent relict sands deposited during the late glacial period (Würm) (Lykousis and Chronis, 1989).

The biological texture of the seabed is conducive to the presence of hemipelagic sedimentation processes. Similarly, the very low amounts of material deposited are indicated by the presence of relict sands (Lykousis and Chronis, 1989) (as discussed previously). Intensive benthic activity over parts of the outer shelf is indicative of well-oxygenated near-bed waters which, in combination with burrowing activity (as indicated by the sea bed photographs), may contribute significantly to the action of diagenetic processes within the sediment deposits (Lykousis and Collins, 1987). On the other hand, vertical turbidity profiles of this region have revealed the presence of an intermediate nepheloid layer (350–450 m) extending towards the Sporades Basin; this layer indicates water movements related to current activity or the presence of internal waves. Further, seabed photographs obtained from the canyon floor reveal some erosion of the seabed sediments; this has been attributed to high near-bed current activity.

Sedimentary province 4 (SP-4) covers the lower reaches of the continental slope (extending to the Sporades Basin) and is distinct in its sedimentary character. The sediment cover consists almost entirely of material of biogenous origin, as indicated by the high carbonate content (40–45%); this is related to the relatively high coccolith composition of the muds (mean grain size 0.005–0.01 mm) and to the entirely biogenous sand fraction (Lykousis et al., 1981). Clay is the dominant constituent (with percentages between 55% and 70%), followed by silt (from 30% to 40%); the sand fraction is generally very low ($< 5\%$). Seabed photographs reveal the presence of biological activity, in a tranquil environment free from suspended matter; this indicates the absence of near-bed currents and oxygenation of the deepwater masses (Lykousis and Collins, 1987). Thus, the very low percentage (if not the absence) of very fine-grained sediments here is indicative of the fact that most of the terrigenous sediments are deposited within the coastal zone of Thermaikos Gulf.

Holocene sequences cover most of the inner shelf and a large portion of the western part of the outer shelf (SP-1). The thickness (in milliseconds of two-way travel time) of the outer deposit reaches 30 ms close to the river mouths; this thins to 2–5 ms at distances > 15 km to seawards (Fig. 18). This pattern implies a mean sedimentation rate, during the

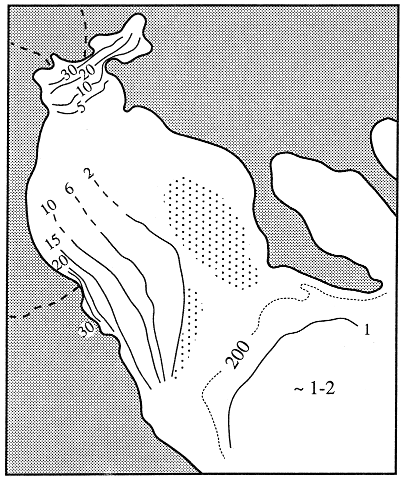

Fig. 18. Isopleaths of deltaic accumulations within the Holocene, in the Thermaikos Gulf Coastal System (after Lykousis and Chronis, 1987).

Holocene, of the order of 3 m/ka near to the river mouths and 0.5–0.2 m/ka over the prodelta area. The thickness of the Holocene sequence in the deep (Sporades) basin is much less, being 1–2 ms; this corresponds to a mean sedimentation rate of 0.05–0.15 m/ka (Lykousis and Chronis, 1989). Similar thickness of Holocene cover have been reported for the offshore areas of other Mediterranean river systems, e.g. Rhone (30 ms), Ebro (20 ms) and Po (20–30 ms) (Chronis et al. 1991).

3.2.2.2. Trace metals. Coastal sediments are important materials for the storage of pollutant elements of anthropogenic origin. Thus, the higher non-residual[4] concentrations of trace metals in the surficial sediments observed in the northwestern part of inner Thermaikos Bay and in Thessaloniki Bay, when compared with the values of the open Aegean Sea (Table 6), have been considered as the ''anthropogenic fingerprints'' on the bottom deposits (Chester and Voutsinou, 1981); these are related to agricultural, industrial and urban activities. This assumption is strengthened by the observation that the values of

[4] Non-residual trace metals are not part of the silicate matrix; they have been incorporated into the sediment from aqueous solution by processes such as adsorption and organic complexion (the latter includes those originating from polluted waters).

Table 6
Concentrations (ppm) of non-residual trace metals in the surface sediments of inner Thermaikos Gulf (Thessaloniki Bay, northwestern Thermaikos Bay and southeastern Thermaikos Bay)

		Thessaloniki Bay		NW Thermaikos Bay	SE Thermaikos Bay	Aegean Sea
No. of samples:		5[a]	12[b]	18[a]	5[a]	12[c]
Mn	Min	554	535	602 (Ga)	204	
	Max	1118	1322	1853 (Al)	845	
	Av	787.6	826	1125.6	408.6	280
Ni	Min	36	76	53 (Ax)	35	
	Max	48	115	160 (Al)	77	
	Av	44.2	95	79.7	52.8	28
Co	Min	12		13 (Ax,Ga)	7	
	Max	14		20 (Al)	13	
	Av	13		14.7	9.5	
Cr	Min	61	196	61 (Ax)	31	
	Max	107	265	103 (Al)	96	
	Av	76	221	75.8	52.8	
Cu	Min	20	57	20 (Al)	4	
	Max	37	162	31 (Ax)	14	
	Av	26.2	79	23	9.6	13
Pb	Min	60	46	40 (Al)	13	
	Max	228	113	112 (Ax)	38	
	Av	123.4	64	69.4	27.8	38
Zn	Min	92	193	53 (Al)	23	
	Max	158	549	299 (Ax,Ga)	50	
	Av	120.8	296	102.2	31.2	45
Cd	Min	nd	0.55	nd (Ga)	nd	
	Max	1.4	4.59	3.0 (Ax)	0.29	
	Av	0.54	1.33	0.7	0.06	

nd: not detected; Ax: R. Axios; Al: R. Aliakmon; Ga: R. Gallikos.
[a]After Chester and Voutsinou (1981).
[b]After Anagnostou et al. (1998).
[c]After Smith and Cronan (1975).

trace metals, measured in 1979 by the above mentioned authors, has been found by Anagnostou et al. (1998) to have increased during the field campaign in 1995.[5]

The highest non-residual concentrations (after Chester and Voutsinou, 1981) of Cd (1.4 ppm), Pb (228 ppm) and Zn (158 ppm) have been observed (primarily) in the sediments of inner Thessaloniki Bay (Table 6). Mn (1853 ppm) and Ni (160 ppm) are more abundant over the northwestern part of inner Thermaikos Bay, with their highest values close to the mouth of the R. Aliakmon. Further, Cu ($>$ 95 ppm) is distributed more evenly within northwestern Thermaikos Bay and Thessaloniki Bay (where it is found to have its maximum value). Similarly, Co and Cr concentrations do not vary substantially within the aforementioned regions; their highest values of 20 ppm and 107 ppm have been observed near the mouth of R. Aliakmon and within Thessaloniki Bay, respectively.

The spatial distribution of the trace metal concentrations shows clearly that the abundance of Cu, Pb, Zn (especially close to the mouths of R. Axios and R. Gallikos) may be attributed to anthropogenic sources, i.e. domestic sewage, together with industrial discharges. In contrast, the lowest values of these trace metals are found near the mouth of the R. Aliakmon; the latter observation, combined with a relative abundance of Mn, Ni, Co and Cr in the

[5] Some difference in the values of trace metals between the two investigations might be attributed to the different analytical methods used.

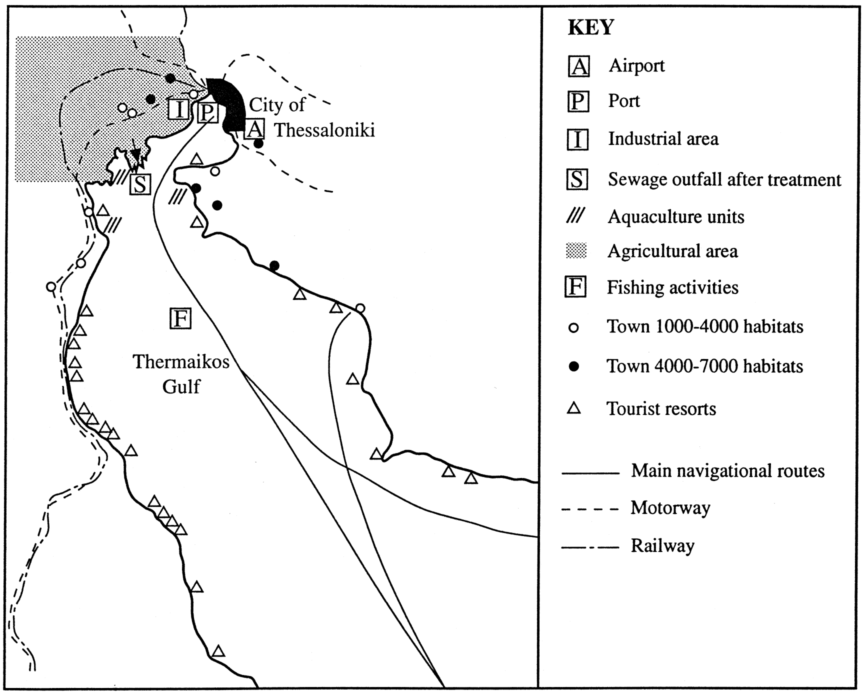

Fig. 19. Schematic representation of the existed infrastructure and the various human activities along the coastal zone of Thermaikos Gulf.

region, indicates their relationship to the petrographic character of the surrounding catchment area, as it drains a generally non-industrialised region.

4. Socio-economic activities and their environmental impact

4.1. Socio-economic activities

The coastal zone of Thermaikos Gulf Coastal System is of great socio-economical importance, as more than one-tenth of the total population of Greece (10.5 million inhabitants) live here. Most of this population is concentrated within the county of the City of Thessaloniki, having almost 1 million inhabitants and being the second metropolitan centre of Greece; likewise, it is one of the largest in the southern Balkans. This region incorporates significant agricultural, industrial, tourist and trade (including services) development (Fig. 19). Hence, the county of Thessaloniki presents a high figure of density population (270 inhabitants/km^2), while the mean value for Greece is only 77.7 inhabitants/km^2. The region of Chalkidiki is characterised by a relatively low-density population (some 30 inhabitants/km^2),[6] while the eastern coastal zone of inner Thermaikos Gulf has 77 inhabitants/km^2 (a figure close to the average value for the whole country). In contrast, the eastern coast of the outer Thermaikos Gulf is the most rare populated area with <15 inhabitants/km^2.

More than 1000 industrial units which occupy some 50,000 employees are established in the county of Thessaloniki; amongst these, the 35 largest are a refinery, a steel mill, a canning factory, paper-mills and chemical and cement industries. This industrial activity accounts the 31% of the 26% of the GNP of Greece attributed to industry, in 1994.[7] Furthermore, tourist activities are taking place along the coastline of Chalkidiki, Pieria and some parts of the eastern

[6] Source: National Statistics Service of Greece (census 1991).

[7] Source: EPILOGI (The Greek Economy 1997 — The Counties of Greece) (in Greek).

shoreline of Thessaloniki Bay. Such activities involve a great number of hotels and pensions, including commercial shops and entertainment facilities. Such villages are host to a seasonal (summer) population of over 45,000 tourists (Georgas and Perissoratis, 1993).

Low-lying land areas (including the Thessaloniki deltaic plain), subjected to reclamation and subsequent soil improvements during the past 50 years, are some of the most productive agricultural lands in Greece. Thus, the agricultural production (in tonnes) of the coastal plain area, relative to the total production of the Thessaloniki district (percentage in brackets) for various crops, was (Prefecture of Thessaloniki, 1986): rice — 76,000 (100%); sugar beet — 27,400 (81%); cotton — 31,600 (80%); and cereals — 48,400 (21%). Also, in the county of Thessaloniki, there is a huge level of cultivation of maize, tomatoes and tabacco. Hence, the agricultural activities of this region represent one-third of the 12% (in 1994) of the GNP attributed to the agriculture. In addition, aquaculture (especially that related to mollusc production) flourishes along the Thermaikos Bay; this produces, annually, some 1000–2000 tonnes of oysters and molluscs. It has to be emphasised that this region produces about 80% of the total mussel production of Greece, accounting for some 27,000 tonnes in 1996; the latter corresponds to 3.5% of the total annual production of the E.U.[8]

The infrastructure that supports the various socio-economic activities involves a well-developed transportation network; this includes railways and motorways, which are under further development (e.g. Egnadia motorway) with the objective of connecting the southern Balkan countries to the Aegean Sea, and the eastern countries (e.g. Turkey) with the Ionian Sea. Finally, air transport is served by Mikra Airport, while the Port of Thessaloniki is one of the largest in the eastern Mediterranean; the total annual cargo load here is in excess of 10 million tonnes. Among this infrastructure is also the installation of a biological treatment of urban sewage, expected to be in full operation within 1999, together with a series of hydroelectric and irrigation dams along the courses of the Rivers Aliakmon and Axios. Thus, the R. Axios incorporates 13 dams along its length (12 outside the Greek boarders and one within Greece at a distance less than 30 km from its mouth); likewise, the R. Aliakmon contains four main hydroelectric dams.

[8] Source: Alieftika Nea 12/96 (magazine, in Greek).

4.2. Human impact on coastal environment

Anthropogenic activities within the coastal system of Thermaikos Gulf have initiated deviations to the natural evolution of the terrestrial and aquatic ecosystems. Thus, the reduction in water/sediment fluxes to the coastline, due to the construction of dams for electricity generation and irrigation purposes, has initiated degradation of the coastal zone. In addition, eutrophication and pollution of the aquatic environment have occurred, in response to the untreated flow of fertilisers, agrochemicals, industrial and domestic sewage. Moreover, future climatic changes related (also) to the 'Greenhouse Effect' and associated with a predicted increase in air temperature and sea level, could cause large-scale changes (with radical consequences) within the Thermaikos Gulf Coastal System.

4.2.1. Reduction in river water / sediment fluxes

During the past 50 years, the reduction in water and sediment fluxes, in response to the dam construction along the route of the Rivers Axios and Aliakmon, has affected considerably the evolution of their deltaic coastal zones. Thus, the growth of these deltas has effectively ceased, while abandoned parts of the deltaic plain are subsiding due to compaction of the sedimentary sequences (Poulos et al., 1994). The latter phenomenon is more pronounced in the area between the old mouths of the R. Axios and R. Gallikos, where some 90 km^2 of land has been subjected to flooding (IGME, 1989). This process has been enhanced by overpumping of the deltaic groundwater, to meet the needs of the City of Thessaloniki, and the extended abstraction of aggregates from the lower route of the R. Gallikos (for the construction industry). Further, the drastic reduction in water discharge, and/or disturbance of its natural seasonal flow regime depletes the supply of river water to the sub-surface aquifers; this, in turn, leads to the intrusion of saline water into the sub-surface parts of the plains, deteriorating the phreatic water and soil quality (as discussed in Section 2.2.4). Finally, any reduction in surface freshwater flow reduces the ability of the rivers to carry and dilute waste materials, increasing the possibility of occurrence of pollution and/or eutrophication.

4.2.2. Waste discharges

The coastal ecosystem receives discharges of untreated anthropogenic wastes, related to domestic waters, industrial effluents and agricultural discharges. For example, Thessaloniki Bay used to receive daily some 150×10^3 m^3 of domestic and 60×10^3 m^3 of untreated or partially treated industrial wastes, respectively (Psyllidou Giouranovits et al., 1998). In addition, the R. Loudias, acting as the main drainage canal for the main agricultural sector of the Thessaloniki Plain (Konstantinidis, 1989), transports vast amounts of pesticides, insecticides, fertilisers and some amounts of untreated industrial effluents. Thus, the increased levels of trace metals observed in the surficial bottom sediments (Section 3.2.2) and the high nutrient levels (Section 3.1.4) in Thessaloniki Bay and within the northwestern nearshore zone of Thermaikos Bay, might be expected to be associated with pollution and/or eutrophication phenomena. Besides, some of the pollution in the inner Thessaloniki Bay is related also to the large activities of the Port of Thessaloniki, where there are two anti-pollution vessels to tackle accidental marine pollution (related mostly to oil spills). Moreover, Georgas and Perissoratis (1993) have stated that fishing activities have been banned in the waters of the inner Thessaloniki Bay, as they are seriously polluted by industrial and domestic sewage,[9] while estuarine environments along the deltaic coastline are still attracting fish due to high eutrophicity.

4.2.3. Climatic changes

Future climatic changes, associated with a predicted increase in air temperature and sea level on a global scale, could cause large-scale changes (with radical consequences) within the coastal zone of the Thermaikos Gulf area. Thus, a possible climatic shift towards more arid climatic conditions (with longer summers and lower precipitation levels) will have a series of environmental impacts, such as: degrading the soil structure (i.e. by increasing salt accumulation in the top soil), a general sort of freshwaters inducing lowering of the water table, and different (possibly) stratification of coastal and shelf water masses. Subsequently, the bio-climatic zonation will gradually shifts northwards, with several species forced to migrate or disappear and new ones to appear; the latter may include bacteria and insects.

However, such impacts are not expected to be detected until around 2030–2040, when an air temperature increase of 1–2°C will induce a sea-level rise of 10–20 cm (Jeftic et al., 1992). A further increase in mean sea level (by > 0.5 m, related to a total increment of 2–3°C of air temperature) might be catastrophic for the region, with important economic repercussions (Georgas and Perissoratis, 1993). A large area of the coastal agricultural zone will be flooded permanently, while additional areas will suffer from temporal floods (in response to exposure to storm surges). Similarly, the lagoons that are present nowadays, adjacent to the mouths of the Rivers Axios and Aliakmon, will disappear; marshes will be converted into lagoons. The coastal section of the reclaimed agricultural Thessaloniki Plain (defended today by a 1.5–2.0 m high dike) and the coastal section of the County of Thessaloniki, including the developing industrial zone (protected now by a 1.0–1.5 m high concrete sea wall) will be threatened if additional measures are not taken. Finally, there will be an increased risk of diseases, in relation to the development of ‘‘swampy’’ areas containing warm anoxic stagnant waters.

4.3. Regional management / scientific objectives

Taking into account the vulnerability of the coastal system, in response to human impact and climatic changes, an integrated regional management programme concerning the socio-economic and environmental issues should be established; this could be set

[9] Nowadays, a biological treatment plant for the sewage of the city of Thessaloniki is in operation.

against a background of any future planned socio-economic development and ecosystem protection. Such an approach has to place, in order: the demands of energy; the required future infrastructure, in terms of transportation by land, sea and air (motorways, railways, ports, marinas and fishing resorts, the expansion of the airport at Mikra); the growth and density of the population; agriculture development; industrial activities; tourism; and, fishing and aquaculture. Further, such a plan has to incorporate the associated environmental issues, such as: reduction in the water/sediment riverine fluxes; treatment of city, industrial and agricultural wastes; safe sea transport and the use of the Port of Thessaloniki; coastal changes, in response to the disturbance of the littoral sediment; clear and safe bathing waters, for swimmers and sea-sports; and response to future climatic changes.

Such an integrated approach to coastal system management requires, as its scientific objectives, the careful monitoring of localised and long-term changes in: weather pattern and their seasonality; freshwater/sediment yields and fluxes; underwater quality and water-table elevation; soil quality and the salinisation of any reclaimed nearshore lands, nearshore sediment dynamics; the identification of background levels of nutrients in the water column and trace metals on the surficial sediments; and the monitoring of the faunal and floral communities.

5. Synthesis and conclusions

The coastal zone of Thermaikos Gulf, hosting more than 1 million people, is the second most important socio-economic area of Greece and one of the most important in the southern Balkans. The fertile deltaic (Thessaloniki) plain (>1500 km^2) provides a variety of crops, while the coastal zone accommodates a large number of industrial, tourist and trade enterprises. The adjacent seas are used extensively for maritime transportation, fish production, and fish-farming (mostly mussels).

The Thermaikos Gulf coastal area, as in the case of any coastal zone, forms only part of a broader geographical unit: The Thermaikos Gulf Coastal System. This complex geo-system consists of a variety of terrestrial and oceanic sub-units, covering a total area of some 52,300 km^2. Of this area, some 90% belong to the terrestrial sub-system and 10% to the oceanic sub-system. The coastal zone is regarded to consist of the lower part (altitudes <75 m) of the terrestrial sub-system (2650 km^2) and the shallow part (water depth <40 m) of the oceanic sub-system (1100 km^2); thus, its total area of 3750 km^2 represents only 7% of the whole system.

The present configuration of the coastal zone of Thermaikos Gulf is associated with: (i) the riverine water and sediment fluxes, dependent primarily upon the climate and geology of the hinterland region; (ii) the coastal geomorphology (e.g. cliffs); (iii) the prevailing wind conditions, which relate to the surface water circulation pattern and the nearshore wave and wave-induced current activity; (iv) the overall thermosaline circulation of the water masses; and, (v) anthropogenic activities.

The observed coastal changes can be distinguished as *macro-scale*, being primarily inter-annual in character (e.g. the deltaic coasts), and (seasonal) *meso-scale* (as in the case of the sandy spits). Thus, progradation of the deltaic coast of Thermaikos Bay, by some 35 km within only the last 2000 years (a macro-scale change), is in response to the high sediment loads delivered by the Rivers Axios, Aliakmon and Gallikos. On the other hand, meso-scale coastal changes may be attributed either to the seasonal fluctuations of the wave-induced longshore transport, as in the case of sandy spits, and the localised anthropogenic influence, i.e. the construction of small ports.

The high levels of terrigenous fine-grained sediments delivered by the Rivers Axios, Aliakmon and Pinios and smaller streams, apart from their controlling influence on coastal evolution are responsible for the modern (Holocene) sedimentation patterns over the subaqueous part of the Thermaikos Gulf Coastal System. The associated sediments in suspension are dispersed seawards and are then deposited from the surface (plumes) and near-bed high-density nepheloid layers. Terrigenous sand deposition is restricted to nearshore areas, originating mainly as the products of coastal erosion and supplied by ephemeral streams. Especially close to the river mouth areas, the Holocene sedimentary cover has a thickness of between 5 m and 20 m.

The substantial amounts of freshwater carried annually, by the various river systems and other smaller streams, not only contribute to the evolution of the coastal zone via the transport of high sediment loads but also have a major influence on the functioning of the whole coastal environment by: supporting the ground water table; influencing the estuarine environments and lagoons, at the river mouth areas; participating in the offshore dispersion of the fine-grain sediment; enriching nutrients in the waters of the nearshore areas; influencing the coastal water circulation patterns; and, finally, being used in various human activities, i.e. agriculture, irrigation, electric power production, etc.

Any coastal system, particularly its coastal zone, is vulnerable to both natural and human-induced changes. Thus, the various socio-economic activities within the coastal system of Thermaikos Gulf have a distinct impact on the natural evolution of the terrestrial and aquatic environment. Construction of dams has reduced drastically the water/sediment fluxes to the coastline, causing degradation of the coastal zone. Likewise, the untreated flow of fertilisers, agrochemicals, industrial effluents and domestic sewage has caused eutrophication and pollution in the aquatic environment. These phenomena are more pronounced in Thessaloniki Bay and northwestern Thermaikos Bay, where increased levels of non-residual trace-metals have been observed. Finally, a future climatic shift towards more arid climatic conditions, together with a rise in sea level, will have a series of environmental impacts, such as: coastal retreat; reduction of freshwater inputs; a northward shift of the bio-climatic zonation; degradation of the soil structure; and a change in the prevailing nearshore hydrodynamic regime. Hence, any future socio-economic activities and possible climatic changes should be considered carefully, within a regional programme of coastal management and environmental protection, in order to secure sustainable development of the Thermaikos Gulf Coastal System.

Acknowledgements

The authors are grateful to Mrs. Kate Davis for the artistic preparation of the figures.

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