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The consequences of a future eustatic sea-level rise on the deltaic coasts of Inner Thermaikos Gulf (Aegean Sea) and Kyparissiakos Gulf (Ionian Sea), Greece

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ABSTRACT

The spatial consequences of future sea-level rise upon the coastal plains of Greece are examined; in particular, those related to the formation and evolution of the river-deltas. For this reason, the fluvially-dominated deltas of the Axios and Aliakmon rivers of Inner Thermaikos Gulf (NW Aegean Sea) together with the wave-dominated delta of the Alfios River (Kyparissiakos Gulf, Ionian Sea), are investigated. Coastal changes are quantified due to the combined effects of the processes of inundation, because of the increased sea level, and subsequent coastal erosion, due to increased exposure to wave action. Predictions of responses to future sea-level rise, of 0.5 to 1 m, are made. In the case of the deltaic coast of the Alfios, exposed to high waves and protected by dune fields, shoreline retreat of up to 700 m is predicted. The low-lying bird-foot type deltas of the Axios and Aliakmon are expected to retreat by more than 2 km. Furthermore, coastline retreat in the case of Alfios is related primarily to the process of shore zone erosion; in the case of the Axios and Aliakmon, it is related to the process of inundation.

1. Introduction

The vulnerability of the Mediterranean coastal zone to sea-level rise has already been investigated (e.g. Jeftic et al., 1992), whilst Nicholls and Hoozemans (1996), using the Global Vulnerability Analysis (GVA), have shown that the southern part of the Mediterranean coast is more vulnerable than its northern part. Moreover, it has been recognised that deltaic zones are the most vulnerable sectors to sea-level rise. Of course, the spatial and socio-economic consequences of a potential sea-level rise upon deltaic coasts depend also upon the rate of local subsidence, riverine sediment supply, human response, etc. Undoubtedly, any sea-level rise, apart from the inundation caused, will modify the nearshore topography, by moving the nearshore zone shorewards; this will cause further changes to wave-induced circulation patterns, which are related to sediment transport processes (Zhang et al., 2004). Therefore, the impact of sea-level rise on lowland coasts is most likely associated with two different mechanisms: (i) inundation that is related mostly to sub-aerial topography and to the rate of sea-level rise; and (ii) erosion, which is controlled by shore zone morphology and nearshore hydrodynamics. Especially for long-term coastal evolution, the rate of sea-level change has been recognised as one of the most important driving factors among marine processes (e.g. Sánchez-Arcilla et al., 2000).

Over the last decades, several studies have been undertaken for the larger Mediterranean deltas, including vulnerability assessment due to sea-level rise, as in the case of R. Nile (Milliman et al., 1989), R. Rhone (Suanez and Provansal, 1996), R. Ebro (Sánchez-Arcilla et al., 1998) and the northern Adriatic Italian coast, including the R. Po delta (Colantoni et al., 1997). In addition, Maroukian (1989) has studied the consequences of sea-level rise along the Greek coast. Further, Gaki-Papanastasiou et al. (1997) have found that, in the case of four Greek river deltas, some 12% of their coastal area will be submerged if sea level rises by 0.5 m. In addition, several conceptual models have been developed and applied, aiming to predict shoreline response to sea-level change e.g. Bruun (1954), Swift (1976), Stive and De Vriend (1995), Davidson-Arnott (2005).

The purpose of the present study is to investigate the spatial consequences of future sea-level rise on two deltaic coasts of Greece, according to the most widely-accepted eustatic scenario, provided by the Intergovernmental Panel for Climatic Change (IPCC); this predicts a sea-level rise from 49 cm (IPPC, 1996) up to 62 cm (IPCC, 2001), due to global warming by 3 °C within the next 100 years. The coastal areas investigated are: (i) the inner Thermaikos Gulf (NW Aegean), where the fluvially-dominated deltas of Rivers Axios, Aliakmon and Gallikos have been formed; and (ii) the northern part of Kyparissiakos Gulf (Ionian Sea) which hosts the wave-dominated deltaic coast of the R. Alfios. Moreover, the present contribution not only estimates the deltaic area that would be inundated, due to sea-level rise, but also provides an assessment of a further coastline retreat induced by coastal erosion, due to the increase in nearshore water depths.

2. The study areas

The evolution of the deltaic coasts of inner Thermaikos Gulf and Kyparissiakos Gulf, which are formed in an essentially tideless

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(<20 cm) environment (Tsimplis, 1994), as with the remainder of the eastern Mediterranean deltas, depends primarily upon interaction between the fluvial (water/sediment fluxes) and the marine (mostly wave activity) processes; the latter are enhanced in the case of wave set-up conditions, which can reach 1 m in the semi-enclosed Thermaikos Gulf and 0.4 m in the open Kyparissiakos Gulf (Ghionis, 2001; Poulos et al., 2002). The River Axios discharges into the shallow inner Thermaikos Gulf, forming a fluvially-dominated delta, which faces south (Fig. 1). The present-day river channel is artificial, with flood protection levees on either side. The whole delta area is flat, with elevations of less than 1 m above m.s.l. The lower delta is covered by perennial or intermittent marshes and swamps, while the rest of the delta area is wet ground and agricultural land, drained by an extensive channel network. The NE and NW parts of the delta have some low coastal protection levees. During the last decades the deltaic coast has retreated due to reduced sediment supply (Kapsimalis et al., 2005). The Aliakmon River also forms a fluvially-dominated delta, located to the SW of the Axios delta and facing SE. Two older mouths exist to the NE of the present-day mouth. The lower delta is a flat area with elevations of less than 0.5 m above m.s.l., covered by perennial or intermittent marshes and swamps. The whole delta area has elevations of less than 2 m above m.s.l. and the delta front is retreating, due to sediment deprivation following the construction of a series of hydroelectric dams (Poulos et al., 2002). Between the deltas of the Axios and Aliakmon rivers lies the Loudias–Aliakmon deltaic plain. This area used to enclose the old delta of the Loudias River, lowland areas covered by perennial and intermittent marshes and swamps, together with a coastal lagoon that was used for aquaculture. Most of this area has been reclaimed, drained by an extensive channel network and is used for agriculture. Elevations throughout this area do not exceed 1 m above m.s.l.

The Alfios is the largest river of SW Greece and discharges into Kyparissiakos Gulf, forming a cuspate delta. Its mouth is exposed to high-energy waves coming from S, SW and W; mean annual average wave heights and periods are in the order of 1 m and 3 s, respectively, with maximum values in excess of 6 m and 12 s. The sediments of the near-mouth bottom surface are sandy (from gS to S, according to Folk's, 1974 classification). Since the construction of dams (1954 and 1988), the deltaic shoreline of Alfios has retreated at an average rate of 8 m/year, which has produced a maximum shoreline recession of 340 m at the river mouth (Ghionis, 1993). Nowadays, two abandoned old channels exist, on either side of the present-day active channel, with two shallow (maximum depths of <2 m) coastal lakes formed behind barrier beaches: Lake Mouria to the North and Lake Agoulinitsa, to the South of the river mouth. These lakes have been drained artificially and are used for agriculture.

In terms of the incoming wave power, the deltaic complex of the Inner Thermaikos Gulf is located within a low wave energy environment (<30 W/m/year), as compared to that of Alfios river (~25,000 W/m/year); mean annual average wave heights and periods are in the order of 0.5 m and 3.2 s, respectively, with maximum observed values in excess of 3 m and 6.5 s. The sediments of the near-mouth bottom surface are muddy (M), with some sand present (sM) very close to river mouth. Thus, the rivers Axios and Aliakmon have formed bird-foot type deltas (Galloway, 1975), whilst the delta of Alfios river is cuspate in shape. The principal morphological, climatological and hydrological characteristics of the river delta systems examined are listed in Table 1. Furthermore,

Fig. 1. Location of the deltaic coasts investigated (boxed), within Greece.

Table 1
General characteristics of the river systems of Alfios, Axios and Aliakmon.

River system	Alfios	Axios	Aliakmon
Geomorphology			
Catchment area (km^2)	3665	23,747	9250
Maximum relief (m)	2224	2800	2200
Relief ratio ($\times 10^{-2}$)	3.10	1.15	1.70
Deltaic plain (km^2)	110	390	120
Receiving basin	Kyparissiakos Gulf (Ionian Sea)	Inner Thermaikos Gulf (NW Aegean Sea)	
Maximum depth of shelf waters (m)	130	35	
Climate (delta)			
Mean annual temperature (°C)	18.5	14.5	16.5
Mean annual rainfall (mm)	1000	800–1200	600–1600
Winds (dominant direction)	S, SW, W, NW	S, SE	
Type	Mediterranean	terrestrial Mediterranean	
Water fluxes $^{(1)}$			
Mean annual discharge (10^6 m^3)	2113	5030	2292
Max. annual discharge (10^6 m^3)	4573	8800	4320
Min. annual discharge (10^6 m^3)	662	1545	662
High water period (months)	Nov–Apr	Dec–Jan	Dec–May
Low water period (months)	May–Oct	Jul–Nov	Jun–Nov
Sediment fluxes			
Suspended sediment load (10^{6}t/year)	~2.5$^{(2)}$	13.2 $^{(2)}$	6.2 $^{(3)}$
Total sediment load (10^6 t/year)	>3.0	17.5	8.7

Key: (1)—measured values, after Therianos (1974); (2)—estimated value, after Poulos et al. (1996); (3)—extrapolated value from the total catchment area, based upon *in-situ* measurements over part of the drainage basin.

the overall modern evolution of these deltaic coasts has been described: in the case of Thermaikos Gulf, by Kapsimalis et al. (2005) and Poulos et al. (1994); and, in the case of Kyparissiakos Gulf, by Ghionis and Ferentinos (1992), Ghionis (1993, 2001) and Poulos et al. (2002).

The three deltaic coasts under study are not stable over time; they are adjusting continuously to changes in sediment yield and to human intervention (mainly, canalisation and land reclamation).

3. Materials and methods

The methodology followed in this investigation attempts to quantify coastal changes, as the combined results of (i) inundation, due to the increased sea level; and (ii) coastal erosion, due to increased exposure to wave action.

The estimation of the coastal area that will be inundated, because of increased sea level, is based usually upon large-scale topographic maps (1:5000 to 1:1000). In the present study, the area inundated by a sea-level rise of 0.5 m and 1 m has been deduced from topographic maps at a scale of 1:5000, provided by the Hellenic Army Geographical Service; these are based upon aerial photographs, taken in 1979.

To ensure that the topographic and bathymetric data correspond to the same profile, the nearshore bathymetry was derived from Hellenic Navy hydrographic charts of Thermaikos Gulf (published in 1979) and Kyparissiakos Gulf (published in 1986).

The estimation of shoreline retreat, due to erosion, is a much more difficult task. Several attempts have been made over the years to model shoreline response to sea-level rise. The simple conceptual model that was proposed by Bruun (1954) for sandy coasts, together with its later modifications to apply to other environments such as barrier islands (Dean and Maurmeyer, 1983) and cohesive coasts (Bray and Hooke, 1997), have been used extensively to explain and to predict coastal response to sea-level change (e.g. Bruun, 1962; Schwartz, 1965, 1967; Bruun and Swartz, 1985; Bray and Hooke, 1997; French, 2001).

According to Bruun's (1954) model, a rise in sea level would be followed by: a) a shoreward displacement of the beach profile as the upper beach is eroded; b) movement of the eroded material from the upper beach and deposition of an equal volume of sediment on the lower part of the profile on the nearshore bottom; and c) a rise of the nearshore bottom as a result of this deposition, equal to the rise in sea level (Bruun and Swartz, 1985). The horizontal displacement (recession) of a shoreline (R), due to an increase in sea level (S), is given by:

$$R = \frac{L}{B+h}S = \frac{1}{\tan\phi}S$$

where h is the depth of closure, L is the cross-shore distance from the shoreline to the depth of closure, B is the berm height and φ is the average slope angle of the profile.

However, the Bruun model is based upon a number of assumptions, which are rarely met in natural beaches, as summarized below:

- It is applied to a two-dimensional profile, normal to the shoreline. All the sediment transport is in an on-offshore direction and is the result of wave action alone. Longshore sediment transport and aeolian sediment transport are not taken into account.
- The coastal profile is an equilibrium profile developed on erodible sandy sediment. The average shape of the profile is controlled entirely by the wave climate and sediment size.
- The sediments landward of the shoreline are easily erodible, with similar properties to the nearshore sediments.
- The wave regime has sufficient power to maintain the ability to erode and redistribute the coastal sediments, over the entire profile, both during and after the sea-level rise.

Because of the above limitations, the Bruun model has received considerable criticism in the literature (e.g. SCOR Working Group, 1991; Thieler et al., 2000; Pilkey et al., 2000; Kroonenberg et al., 2004) and, recently, Cooper and Pilkey (2004) have proposed that the Bruun model has no power for predicting shoreline change and should be abandoned. Other models have been proposed (e.g. Swift, 1976; Stive and De Vriend, 1995; Davidson-Arnott, 2005) that address some of the shortcomings of the Bruun model. Nonetheless, the latter is still used widely, mainly because of the simplicity of the numerical expression of the model, the ease of application and the lack of any easily applied alternative models.

In the present study, the morphology of the river deltas and the complex processes of their nearshore zones preclude the use of simple conceptual models of coastal response to sea-level rise, with the exception of the northern end of the Alfios river delta. Here, a Bruun-type model could be used with reasonable accuracy. The estimation of the shoreline position is based mainly upon the analysis of the topographic and geologic conditions of the delta areas, as well as previous detailed studies of the nearshore hydrodynamic and morphodynamic conditions in Kyparissiakos Gulf (Ghionis and Ferentinos, 1992; Ghionis, 1993, 2001) and in NW Thermaikos Gulf (Poulos et al., 1993). The reasoning behind these estimates is explained in detail in the Results and discussion section.

4. Results and discussion

In the event of a sea-level rise, significant parts of the deltaic coasts investigated will be inundated and shoreline will retreat. The estimates of inundated areas and shoreline retreat, following a sea-level rise of 0.5 m and 1 m, are summarized in Table 2, incorporating Bruun model estimates of shoreline recession. The expected 'new' shorelines and the corresponding inundated areas are presented schematically in Fig. 2.

4.1. Alfios delta (Kyparissiakos Gulf)

A significant part of the northern side of the mouth of the R. Alfios (approx. $650 \cdot 10^3$ m^2), from the present-day channel to the northern old

Table 2
Estimated coastline retreat due to sea-level rise (inundation and coastal erosion).

Coastal area	Sea level rise (m)	Shoreline retreat Bruun's model (m)	Shoreline retreat due to:		Total shoreline retreat (m)	Inundated area (10^3 m^2)
			Sea-level rise (m)	Coastal erosion (m)		
Alfios delta (north side)	0.5	51.1	175	15	190	224.10
	1.0	102.2	810	110	700	682.93
Alfios delta (south side)	0.5	54.5	15–30	0–15	30	34.50
	1.0	109.0	10–100	400	400–450	343.50
Axios delta	0.5	52.7	250–2000	0	250–2000	10,825.00
	1.0	213.6	2000–2500	0	2000–2500	28,482.00
Aliakmon delta	0.5	63.6	50–1750	0	50–1750	4875.00
	1.0	195.4	250–2500	0	250–2500	8950.00
Loudias–Aliakmon deltaic plain	0.5		500–2750	0	500–2750	8900.00
	1.0		5000–6500	0	5000–6500	25,575.00

channel (Fig. 2a), is a relatively flat, gently sloping area, with an elevation of less than 1 m above m.s.l.; this will be inundated by the sea, in the event of 1 m sea-level rise. The area consists of easily erodible sands, to gravely sands, arranged in a series of shore-parallel beach ridges. Consequently, a new beach is expected to form at the landward limit of this area, at a distance of 350–810 m from the present shoreline. If there is an adequate supply of sediment, the shoreline orientation will adjust to the new hydrodynamic conditions and the maximum shoreline retreat is expected to be approx. 700 m, at the mouth of the river. Since no significant changes of either the wave regime or the sediment composition are expected, the new beach will have similar geometric and textural characteristics as that of the present-day beach. The existing old beach ridges are fragmented, discontinuous, partially eroded and dissected by old (abandoned) river channels and therefore are not expected to provide any protection against shoreline retreat and inundation of the low elevation areas.

Farther to the north, the present-day beach has an average width of 60 m and is backed by the old Lake Mouria barrier system, which exceeds 3 m in elevation above m.s.l. The barrier system already shows signs of wave erosion and significant damage to coastal-front properties. The inundation caused by a 0.5 m and 1.0 m rise of sea level will produce a shoreline retreat of 50 m and 100 m, respectively. These values are in almost complete agreement with the Bruun model predictions (51.1 m and 102.2 m), but since they are due only to inundation, it is evident that in this case the Bruun model underestimates the total shoreline retreat. If the Bruun model is conceptually correct, the shoreline retreat will be accompanied by erosion and a lowering of the elevation of the present-day upper beach, because of the predicted landward translation of the present-day beach profile. This evolution will expose the old barrier to increased wave action, undermining and erosion. If sufficient sediment is available, a new equilibrium beach may be formed, with its shoreline located approximately 20 to 40 m landwards of the position predicted by Bruun's model. If there is insufficient sediment available to form a new stable beach, then severe erosion of the old barrier, together with extensive damage to the coastal properties, are expected. If, on the other hand, the conceptual model proposed by Davidson-Arnott (2005) is correct, then a sea-level rise will result in a shoreline retreat accompanied by a net onshore migration of sediment and a landward migration of the foredune. In this case, the new shoreline position will be approximately where the Bruun model predicted (but with incorrect reasoning) and no significant erosion of the old barrier system will occur.

On the southern side of the mouth of the Alfios river, the narrower (10–40 m) present-day beach is backed by the Agoulinitsa barrier system, which is underlain by a layer of cohesive muddy overbank deposits. Between the present and the old channel, the barrier consists of: a wide (500 m) flat area, with an average elevation of 1.5 m above m.s.l.; two shore-parallel ridges at the seaward and landward ends of the flat area; a shore-parallel depression (<1 m elevation above m.s.l.); and an oblique ridge (2.2–4.2 m elevation) between the two outer ridges. The seaward ridge is 30–50 m wide, with elevations of between 2.1 m and 2.7 m, whilst the landward ridge is 25–60 m wide with elevations of between 2.7 m and 3.9 m above m.s.l.

If the sea level rises by 0.5 m, then the riverbank deposits close to the south mouth of the river will become submerged. The ephemeral spit at the south side of the river mouth will move landwards, keeping pace with the shoreline retreat; if it is deprived of the longshore sediment supply from the south, it will be destroyed. The shoreline is expected to retreat approximately 30 m, almost up to the top of the present beach where the muddy layer acts as a stabilising factor. An additional zone of the Agoulinitsa barrier system, 30–40 m wide, will be eroded partially, whilst a new beach will form at the base of the seaward ridge. The same shoreline changes are expected for the coastal area to the south of the old channel. Approximately $34.5 \cdot 10^3$ m^2 of the coastal area will be inundated.

If sea level rises by 1.0 m, approximately $40 \cdot 10^3$ m^2 will be submerged in the area of the spit and the nearby riverbank deposits. Initially, the seaward ridge will be bypassed by sea water entering through the river mouth and the riverbank deposits, as well as through the southern old channel. The area around the old channel ($35.5 \cdot 10^3$ m^2) and the shore-parallel depression ($25.25 \cdot 10^3$ m^2) will also be flooded. Subsequently, the seaward ridge will be eroded by wave action and the shoreline will move landwards (425–475 m): a new beach will form at the base of the landward ridge. The slope of the nearshore bottom will be controlled by the muddy layer underlying the Agoulinitsa barrier system; it will be reduced from 0.9°, to approximately 0.13°.

Furthermore, the shallow depression (0.9 m average elevation, $241 \cdot 10^3$ m^2 area) will be flooded, either by sea water entering through the southern old channel, or by water from the raised groundwater table. The sea-level rise above the level of the old muddy overbank deposits will facilitate a salt water intrusion and salinisation of the surficial groundwater table, causing extensive damage to agricultural activities in the delta area.

4.2. Axios and Aliakmon deltas (Inner Thermaikos Gulf)

In the case of sea-level rise by 0.5 m, the lower part of the Axios delta ($10.825 \cdot 10^6$ m^2) will be inundated (Fig. 2c) and the shoreline will retreat (Fig. 2d), by approximately: 2 km in the southern part of the delta; 250 m in the SW part; and 200–600 m in the SE part. Because of the very shallow waters and the low wave energy environment, no significant wave-induced erosion is expected at the landward end of the inundated area.

If the sea level rises by 1.0 m, the entire delta area ($28.482 \cdot 10^6$ m^2) will be inundated and the shoreline will retreat, by approximately: 5.5 km in the central part of the delta; 2 km in the W part; and 3.5 km in the E part. Once again, no significant wave-induced erosion is expected at the landward end of the inundated area.

The evolution of the deltaic coast of the R. Aliakmon is analogous to that of the R. Axios, as they present similar geomorphological and hydrodynamic characteristics. Thus, in the case of sea-level rise by 0.5 m,

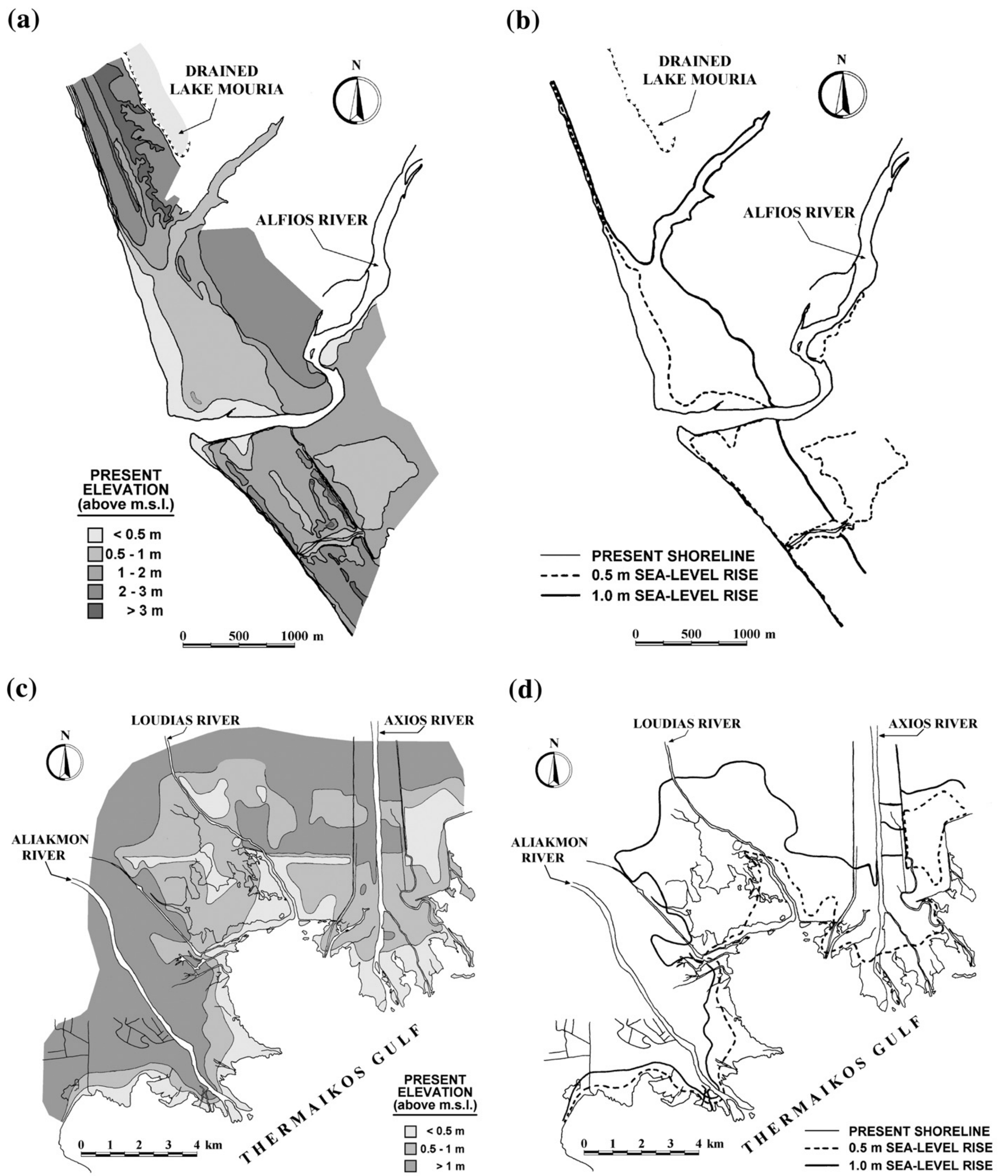

Fig. 2. Elevation map of the Alfios (a) and Axios and Aliakmon (c) river delta areas together with estimated shoreline positions (b and d, respectively) following a 0.5 m and 1.0 m sea-level rise.

the lower part of the delta ($4.875 \cdot 10^6$ m^2) will be inundated (Fig. 2c) and the shoreline will retreat (Fig. 2d), by approximately: 1250 m, at the present mouth location; 1750 m at the northern old mouth; and 50–750 m over the remainder of the delta area. Because of the very shallow waters, the low wave energy environment and the infrequent storms from the S and SE sectors, no significant wave-induced erosion is expected at the landward end of the inundated area.

If the sea level rises by 1.0 m, an area of $8.950 \cdot 10^6$ m^2 will be inundated and the shoreline will retreat, by approximately: 1450 m at the present mouth; 2500 m at the northern old mouth; and 250–1250 m over the remainder of the delta area. Once again, no significant wave-induced erosion is expected at the landward end of the inundated area.

With respect to the low-lying (elevations <1 m above m.s.l.) deltaic plain located in between the deltas of Axios and Aliakmon, if the sea level rises by 0.5 m, an area of $8.9 \cdot 10^6$ m^2 will be inundated (Fig. 2c). The shoreline will retreat by approximately 500 m in the SW part of the area and by 1000–2750 m in the NW part (Fig. 2d). Because of the very shallow waters (with the −1 m contour being located some 2 km offshore), together with the low wave energy environment and the infrequent storms from the SE, no wave-induced erosion is expected at the landward end of the inundated area. Furthermore, a sea-level rise of 1.0 m will inundate an area of $25.575 \cdot 10^6$ m^2 and will cause a shoreline retreat of approximately 5000 m in the SW part and of 6500 m in the NW part of the area. Once again, no wave-induced erosion is expected at the landward end of the inundated area.

5. Conclusions

Sea-level rise within the range of 0.5–1.0 m will cause significant shoreline retreat at all of the deltaic coasts examined; the latter varies from some hundreds of metres (R. Alfios), to a few kilometers (R. Axios and Aliakmon). Furthermore, coastline retreat in the case of Alfios delta is due mostly to erosion accompanying and/or following sea-level rise and, secondarily, to the process of inundation; this is due to its coastal morphology, which is characterised by the presence of sand dunes and relatively high slopes of the backshore zone, attributed to its exposure to intensive wave activity. In contrast, the deltas of the rivers Axios and Aliakmon, being of low relief and almost flat (as they have been formed in a relatively shallow area, protected from high waves), will suffer from coastline retreat almost exclusively by the process of inundation: wave energy will be dissipated over the extensive surf zone. The substantial loss of deltaic land will also cause damage to the agricultural economy of the area, which may be worsened further by the process of salinisation of the groundwater and, especially, of the phreatic horizon.

Finally, in terms of coastal zone management related to sea-level rise, in the case of deltaic coasts, the following should be taken into consideration: (i) large deltaic coastal areas will be lost, in response to the processes of inundation and marine erosion; (ii) the further study of the erosional processes during and after sea-level rise is needed, as the existing models, based more or less on Bruun's model, provide inconsistent and unrealistic results in delta areas, since most of the assumptions on which the latter is based are not supported; (iii) damage to fluvially-dominated deltas is due mainly to inundation, whilst shoreline retreat in wave-dominated deltas is amplified by wave erosion; and (iv) not only coastal topography, but also geological, sedimentological and hydrodynamic conditions, should be taken into account for the assessment of the effects of sea-level rise.

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