DETERMINATION OF LONG-TERM MORPHOLOGICAL CHANGES IN A HUMAN AFFECTED COASTAL SYSTEM USING G.I.S., INNER THERMAIKOS GULF, GREECE

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ABSTRACT

Morphological evolution of the inner Thermaikos Gulf over the last 150 years is revealed by the comparison of five historical bathymetric maps. Large-scale patterns of coastline evolution and sea-floor erosion and/or deposition were investigated with the use of a Geographical Information System (GIS). The observed morphological changes have been related to the deltaic processes, local hydrodynamic conditions and human implications. Three evolutionary stages were distinguished: Stage I (1850-1916) which corresponds to a natural phase of a rapid deltaic progradation and sea-floor deposition, with an average accumulation rate of $6.5*10^6$ m^3/yr of sediment; Stage II (1916-1956), when the coastal system was affected progressively by human development (i.e. change and straitening river courses), high accretion rates ($18*10^6$ m^3/yr) occurred; and stage III (1956-2000), which is characterized by significant coastline retreat and sea-floor erosion ($2.5*10^6$ m^3/yr) mainly due to river daming.

ΠΕΡΙΛΗΨΗ

Στην εργασία αυτή μελετάται η εξέλιξη της μορφολογίας του εσωτερικού Θερμαϊκού Κόλπου κατά τη διάρκεια των τελευταίων 150 ετών, σε σχέση με την ανθρώπινη παρέμβαση. Ειδικότερα αποτυπώνεται ο τρόπος προέλασης του συστήματος των δελταϊκών πεδίων των ποταμών Αξιού και Αλιάκμονα, καθώς επίσης και των αλλαγών του πυθμένα του κόλπου, συγκρίνοντας ιστορικούς και σύγχρονους βαθυμετρικούς χάρτες με τη βοήθεια ενός Γεωγραφικού Συστήματος Πληροφοριών. Η εξέλιξη του υποθαλάσσιου χώρου μπορεί να διακριθεί σε τρία στάδια. Το Στάδιο I (1850-1916) αντιστοιχεί στη φάση της προέλασης των δέλτα μέσω φυσικών διεργασιών με ένα μέσο ρυθμό ιζηματογένεσης που φτάνει στα $6.5*10^6$ $μ^3$/έτος στον εσωτερικό κόλπο. Το Στάδιο II (1916-1956) χαρακτηρίζεται από μια διαρκώς αυξανόμενη παρέμβαση του ανθρώπου στο ποτάμιο σύστημα. Τα ποικίλα εγγειοβελτιωτικά έργα (αποξήρανση της Λίμνης των Γιαννιτσών και οι διευθετήσεις των κοιτών των ποταμών Αξιού και Λουδία) συνέβαλλαν στην αύξηση του ρυθμού συσσώρευσης των ιζημάτων στον κόλπο ($18*10^6$ $μ^3$/έτος). Στο Στάδιο III (1956-2000) οι ανθρώπινες δραστηριότητες ελέγχουν πλήρως την εξέλιξη των δελταϊκών πεδίων προκαλώντας δραστική μείωση της στερεοπαροχής των ποταμών, επακόλουθη διάβρωση του θαλάσσιου πυθμένα (με ρυθμό $2.5*10^6$ $μ^3$/έτος), και σημαντική υποχώρηση της ακτογραμμής.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: εξέλιξη ακτής, διάβρωση, όγκος ιζημάτων, ΓΣΠ, Αξιός Π., Αλιάκμονας Π., Θερμαϊκός Κόλπος

KEYWORDS: coastal evolution, erosion, sediment budget, GIS, R. Axios, R. Aliakmon, Thermaikos Gulf

INTRODUCTION

Coastal zones are sensitive buffer areas between the hinterland and the open sea. In the past decades increased needs for fresh water (drinking water, irrigation, hydroelectric power, etc.) have resulted to a dramatic reduction of freshwater supply to the coastal zone. Moreover, changes in land use for crop farming caused a worldwide double sedimentation rates in coastal waters (Milliman and Syvitski, 1992), whereas the construction of dams caused a substantial reduction in sediment supply, often resulting to erosion of the coastal river deposits (Milliman and Meade, 1983). The latter patterns are also observed in northern Greece, where interregional water is consumed in the upstream neighbouring countries (FYROM, Bulgaria) and/or retained behind dams (Skoulikidis et al., 1998; Poulos and Chronis 1997). In this perspective, it was

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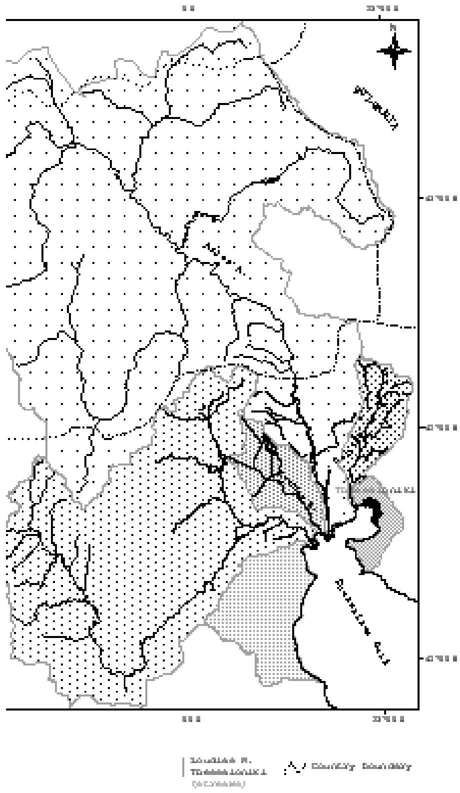
recognized that coastal zone problems should be addressed in combination with an assessment of the human-induced practices in the watershed.



The deltaic system of the Thermaikos Gulf and its evolution was previously investigated by Evmorphopoulos (1961) and Kotoulas (1984) whilst, more recently, Albanakis et al. (1993) have studied the mechanisms and the evolution of the Axios River delta, during the 20th century. Besides, Poulos et al. (1994) have studied the evolution of the Thessaloniki deltaic plain, whilst Stiros (2001) has provided an assessment of the observed subsidence rates for the period 1960-1999. The recent sedimentary processes in the Thermaikos Gulf have been studied by Chronis (1986), while Georgas and Perissoratis (1992) provided a socio-economic approach regarding the types of human activities in the area.

The gulf of Thermaikos, situated in the NW Aegean Sea (Fig. 1), receives freshwater from the Axios, Aliakmon, Loudias and Gallikos Rivers, which drain an area of ~35,000 km^2. Mean annual flow discharge from historical records was estimated at 276 m^3/s. However, recent measurements (Karageorgis and Anagnostou, 2001) revealed a substantial decrease of freshwater supply, estimated at 130 m^3/s, followed by extremely reduced sediment fluxes (Poulos et al., 2000) and subsequent retreat of the deltaic system.

The present contribution aims at the assessment of human activities in the catchment area of the rivers flowing in the Thermaikos Gulf, in relation to coastline changes, river delta evolution and sub-bottom morphology transformations. The present study, in contrast to the above mentioned, tries to quantify volumetrically the changes either along the coastline and/or on the seabed, over the last 150 years, utilizing Geographical Information Systems (GIS) techniques.

MATERIALS AND METHODS

Taking advantage of the rapid GIS development as a valuable tool for accurate chartographic analysis (Cooper and McLaughlin, 1998; Rooney and Smith, 1999) we homogenized in a digital format the five bathymetric maps from 1850, 1916, 1947 and 1956 provided by the UK Hydrographic Chart Office (Fig. 2), as well as a resent chart published by the Hydrographical Service of the Greek Navy in 2000. All maps were projected at the Greek Geodetic Reference System of 1987. Data manipulations and analysis have been carried out using the ArcView GIS (version 3.2), while volumetric changes of the study area were calculated using the SURFER (for WINDOWS) software package.

The comparison between the old maps is very difficult and requires careful confrontation of various errors, including vertical and horizontal datum inconsistencies, absence or use of dissimilar georeference systems, and computer gridding errors. To minimize these errors, standard reference points as churches, capes, lighthouses, were selected and used for an intercomparison of bathymetric levels on all the maps. In addition, a range of ±0.5 m of sea floor change was designated as a moderate degree of error in bathymetric comparisons and characterized as a zone of no significant change (List et al., 1997).

RESULTS AND DISCUSSION

The reconstruction of the historical evolution (Fig. 3), reveals major changes in the sediment budget of the inner Thernaikos Gulf and a variety of spatial trends of erosion or accretion during the last 150 years.

From 1850 to 1916 (Stage I), the gulf received terrigenous sediments of $430*10^6$ m^3 covering an area of $120*10^6$ m^2, from which the largest part were accumulated in front of the Axios and Aliakmon Rivers (Table 1). The active river mouth of the Axios River was variable. In particular, before the 1890s the main river channel was situated in Cape Kavoura to the northwest of Cape Megalo Emvolo, while later on and until 1934, the river changed its route and flowed near Kalochori, facing Cape Mikro Emvolo.

Sediment deposited recently in the Kavoura area, formed a prodeltaic progressive wedge having an area of $25*10^6$ m^2, maximum thickness of 22 m and volume of $85*10^6$ m^3. In the Palaiomana area, the new prodeltaic deposits covered an area of $23*10^6$ m^2, with a maximum thickness of 16 m and volume of $60*10^6$ m^3. In the area lying in between the aforementioned river mouths, deposits of great magnitude have not been observed, implying that the existed secondary streams were active only during flood events. During the same period, the R. Aliakmon exhibited meandering delta, in a stage of rapid progradation, accumulating some $340*10^6$ m^3 of sediment and filling the bay of Methoni (Table 2).

Comparing the depositional load of the two rivers, it is deduced that the R. Axios had carried substantially less material than the R. Aliakmon. This pattern is interpreted as the result of two factors: (1) the differences in lithology of the two catchments, as the R. Axios drains mostly ophiolite and metamorphic rocks (denudation resistant), whereas the R. Aliakmon drains clastic formations that are more susceptible to weathering processes; and (2) the complexity of the R. Axios hydrographic network (large number of primary and secondary branches, and meanders), combined with gentle slope of the delta plain, which resulted in the entrapment of clastic material and the reduction of coarse-grained sediment flux towards the gulf (Albanakis et al., 1993).

Stage II (1916-1956) comprises of a sub-period with natural coastal evolution and a second one characterized by increasing human interventions on the deltaic plain. Thus, between 1916 and 1934 the delta evolution was natural and the mouth of R. Axios was in the Palaiomana area, whilst continuous siltation threatened navigation in/out to the port of Thessaloniki. The apparent hazard forced the first plans to rearrange the route of R. Axios and divert the river mouth to its previous location near Cape Kavoura. The constructions commenced in 1930 and finished in 1934. Accompanying works were conducted in the deltaic plain, including the exsiccation of Yiannitsa Lake and the Loudias swamp (1933-1935), the construction of the Loudias drainage channel and a network of irrigation channels; these were completed in the 1960s. Since then, a bird foot delta has been developed, due to high sediment load and absence of intensive wave activity in the inner Thermaikos Gulf (Albanakis et al., 1993). Between 1934 and 1956, the R. Axios delta was developed further to the south, while erosion took place in the Cape Kavoura area (Fig. 3). Eroded sediments were partially accumulated in the new delta, whereas another portion of them was transported towards the deeper waters of the Gulf. The isolated branches of the R. Axios in Palaiomana were relatively inactive and functioned only episodically during floods. The R. Aliakmon prograded to the NE and developed also a bird-foot delta.

This period is characterized by substantial sediment deposition in the inner Thermaikos Gulf that is estimated to be in the order of $900*10^6$ m^3 (Table 1). Although sediments were deposited throughout the sea floor, the highest accretion rates occurred in front of the active river mouths. At the Palaiomana mouth, $140*10^6$ m^3 of sediments have settled on an area of $30*10^6$ m^2 with a maximum thickness of 21 m (Table 2). Large part of these sediments had been deposited before the artificial diversion of the main river channel. In reverse, at the Kavoura mouth, a high sedimentation period initiated in 1934.

This overall increase in sediment supply is mainly attributed to the R. Axios realignment and straitening of its lower route, which caused elevated flow velocities and possible erosion of older terrestrial deposits. Similarly, artificially cut-off of meanders in the R. Aliakmon delta plain also increased its sediment supply.

High sediment discharge during this period is also related to the absence of dams along the river channels, with the exception of a small reservoir (capacity $3,6*10^6$ m^3) built in 1938 in a tributary of R. Axios (R. Treska) (Konstantinidis, 1989).

Evmorphopoulos (1961) using topographic methods calculated that the average rate of sediment load that entered Thermaikos Gulf in the period between 1850 and 1952, was $16*10^6$ m^3/yr. Similarly, Kotoulas (1984) estimated the annual sediment discharge or the rivers at $16,4*10^6$ m^3/yr, which is almost the same with the first one. Our calculations provided by the comparison of the bathymetric maps of 1850 and 1956 give an net sediment gain of about $1.350*10^6$ m^3, i.e., an annual accumulation rate of $12,8*10^6$ m^3/yr. The difference between our estimation (deposits in the gulf) and the Evmorpholoulos and Kotoulas' estimations (incoming load from the rivers) is about $3.5*10^6$ m^3/yr, which could be attributed to direct escape of the fine-grained and dissolved load from the river mouths to outer Thermaikos Gulf. Thus, an amount of 80% of the total terrestrial supply was trapped in the gulf and particularly in front of the main river mouths; and the rest of 20% was shifted seaward in suspension.

Stage III (1956-2000) reflects the intensification of human interventions and outlines a period of substantial alterations of the natural processes due to increased freshwater needs. Two irrigation dams were constructed along the R. Axios (Prochoma) and the R. Aliakmon (near Verroia) in 1958, followed by the development of an extensive irrigation network in the Thessaloniki Plain. Eleven dams were constructed (Psilivikos and Psilovikos, 1997) further along the route of the R. Axios (within its catchment belonging to FYROM) with a total capacity of $803*10^6$ m^3; this resulted in the considerable reduction of freshwater entering Greece. To face this problem, a connection was built between the R. Aliakmon and the R. Axios, in order to supply the Prochoma reservoir. Afterwards, three more hydroelectric dams were constructed along the R. Aliakmon: Polyphytos (1974), Sfikia (1975) and Asomatoi (1989). The entrapment basically of the total bed load and most of the suspended material within the reservoirs resulted to a drastic reduction of deltaic progradation, the salinisation of the deltaic areas, deterioration of the wetlands and sea water invasion during high tides (astronomical + meteorological). Coastal protection measures were undertaken until 1966, comprising the construction of 22 km of sea walls (height +2.5 m). Parts of the sea walls were subsequently destroyed by the combined action of rapid subsidence (in some places ~10 cm/yr) due to decomposition of organic matter and compaction of fine-grained material accompanied by syn-sedimentary deformation (Stiros, 2001); the later processes were enhanced by the extended and often illegal overpumping of the deltaic aquifers. In addition, coastal erosion was caused by the abstraction (not always after appropriate license) of aggregates (sand and gravel) from the lower route of the rivers that reduces rivers' bedload transport and, subsequently, the process of deltaic infilling and progradation.

Finally, since 1956, the inner Thermaikos Gulf has entered an erosional period having overall sediment losses of about $110*10^6$ m^3 (Table 1). Small amounts of sediment have been accumulated just in front of the river mouths. Thus, R. Axios sediment load has been deposited mainly seawards to its central tributary at a rate of $1.4*10^6$ m^3/yr, while the R. Aliakmon sediment load was estimated at $0.8*10^6$ m^3/yr (Table 2). Of course, a significant amount of suspended particulate matter and dissolved load escape the inner gulf towards the outer shelf (Karageorgis and Anagnostou, 2001).

Table 1. Estimations of morphological changes in the inner Thermaikos Gulf. (A) areas of net gain (> +0,5 m), no significant change (-0,5 - +0,5 m) and net loss < -0,5 m); and (B) volumetric changes and the average accretion/erosion rates during various intervals.

Estimates / Period	1850-1916	1916-1956	1956-2000	1850-1956	1850-2000
A. Cut-Fill areas of the inner Thermaikos Gulf					
Net gain ($*10^6$ m^2)	120	270	60	270	60
Unchanged ($*10^6$ m^2)	180	70	150	60	150
Net loss($*10^6$ m^2)	80	40	170	50	170
B. Sediment budget					
Deposition ($*10^6$ m^3)	560	1.020	200	1450	1.350
Erosion ($*10^6$ m^3)	130	120	300	120	120
Net sediment supply ($*10^6$ m^3)	430	900	-100	1330	1.230
Accretion/erosion rate ($*10^6$ m^3/yr)	6,5	18	-2,5	12,6	8

Table 2. Etimations of morphological changes in front of the active river mouths. (A) Maximum thickness; (B) fill areas; and (C) volume of deposits.

Estimates / Period	1850-1916	1916-1956	1956-2000	1850-1956	1850-2000
A. Maximun thickness of the pesently constructed sedimentary prism					
Axios Kavoura (m)	22	20	16	23	23
Axios Palaiomana (m)	16	21	5	23	22
Aliakmon Mouth (m)	20	22	10	24	26
B. Fill areas in front of the active river mouths					
Axios Kavoura ($*10^6$ m^2)	25	39	18	40	40
Axios Palaiomana ($*10^6$ m^2)	23	30	7	30	30
Aliakmon Mouth ($*10^6$ m^2)	55	59	24	60	60
C. Sediment budget in front of the active river mouth					
Axios Kavoura ($*10^6$ m^3)	85	220	60	284	300
Axios Palaiomana ($*10^6$ m^3)	60	140	10	193	160
Aliakmon Mouth ($*10^6$ m^3)	340	270	35	609	610

CONCLUSIONS

The recent evolution of the inner Thermaikos Gulf is closely associated with the human interventions in two main (Axios and Aliakmon) and two small (Gallikos and Loudias) rivers as well as some ephemeral streams. Over the last 150 years three evolutionary stages were determined by the comparison of five bathymetric charts.

In the period from 1850-1916 (Stage I), the system was naturally operated with an average accretion rate of $6.5*10^6$ m^3/yr. Progradation of the delta complex took place at the active river mouths. The Axios River discharged its sediment load into two locations (Kavoura and Palaiomana), whereas R. Aliakmon discharged to the north of Methoni.

The following Stage II (1916-1956) was characterized by increasing human activity, with artificial diversion and realignment of the main river channels (1934) and draining of the Yiannitsa Lake and Loudias swamp (1935). These reclamation projects caused a considerable increase of the accretion rate in the gulf, which attained $18*10^6$ m^3/yr. Axios and Aliakmon River mouths took a bird-foot form and a rapid progradation of their deltas was recorded.

Since 1956, a second reclamation “cycle” including construction of irrigation reservoirs, hydroelectric dams, seawalls etc., caused a significant reduction of the water and sediment discharge. The erosion process dominated on the sea floor and pulled-out sediments with an average rate of $2,5*10^6$ m^3/yr.

In general, over the last 150 years, the gulf has gained a net sediment amount of $1.230*10^6$ m^3 (average accretion rate of $8*10^6$ m^3/yr), from which 85% of this load has accumulated around the active river mouth and 15% has been dispersed into the other areas of the gulf. R. Axios discharged $300*10^6$ m^3 of sediment of at the Kavoura area and $160*10^6$ m^3 at the Palaiomana area, while R. Aliakmon supplied its prodelta with $610*10^6$ m^3 of sediment. Although R. Axios seems to discharge lesser sediment than R. Aliakmon, the load of R. Axios contains more fine-grained particulate and dissolved material (Poulos and Chronis, 1997), which is transported to the inner gulf or the open sea in suspension.

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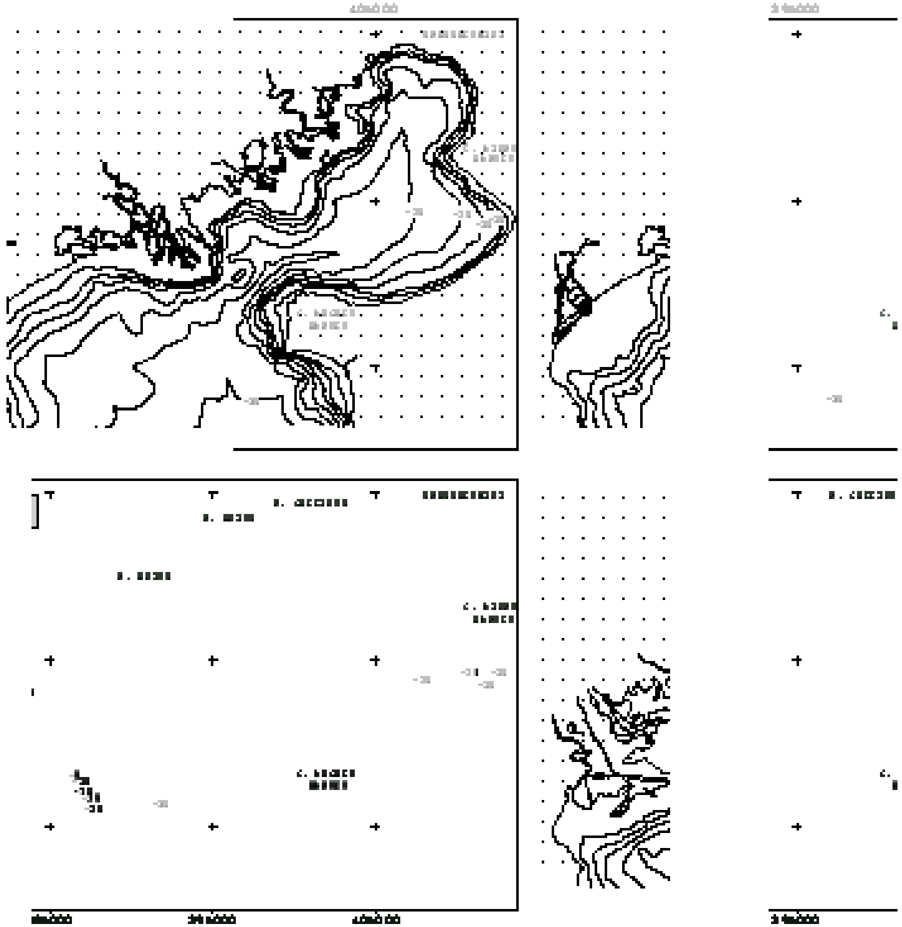

Figure 2. Digitized bathymetric maps from the UK Hydrographic Office (depths in meters).

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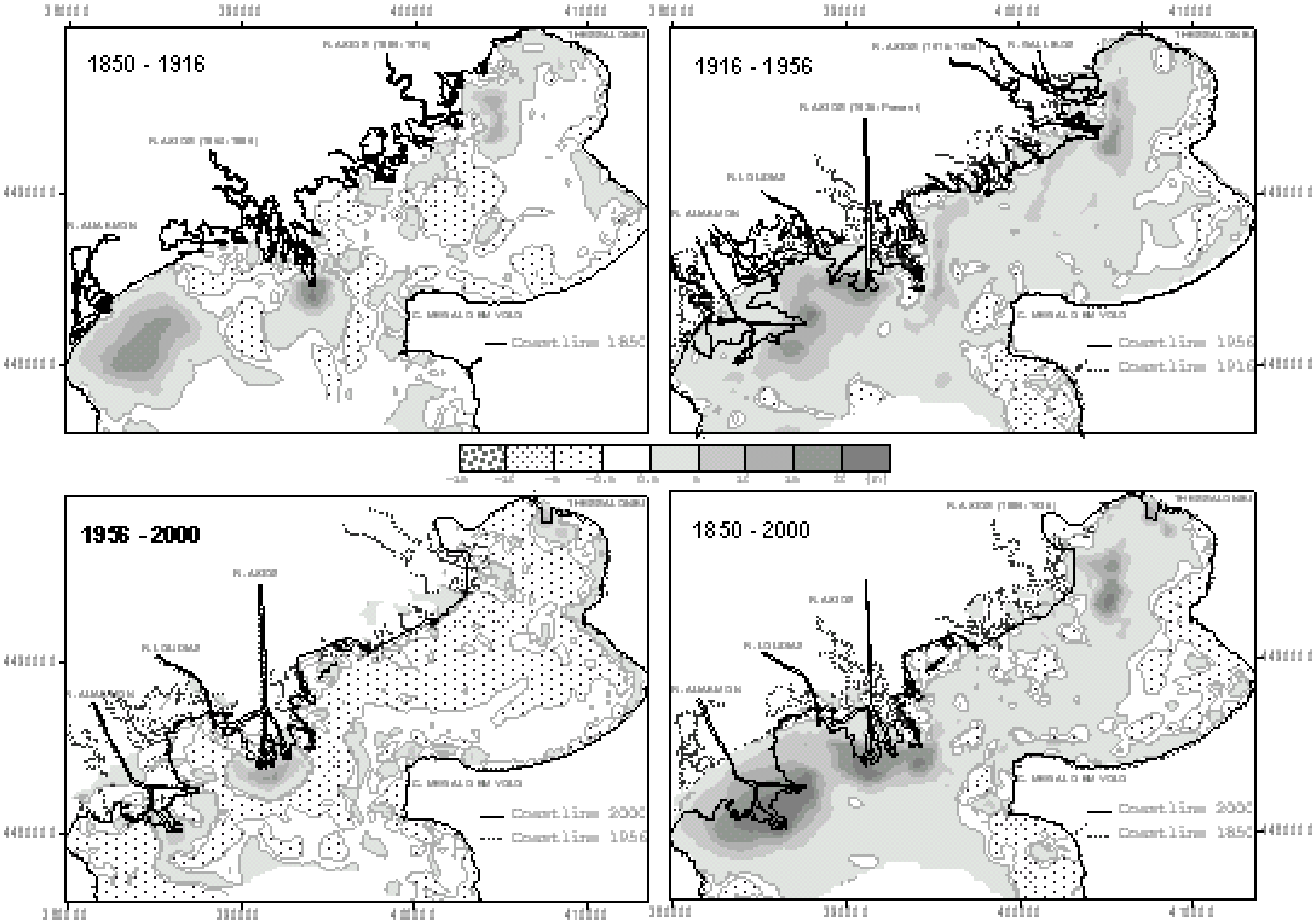

Figure 3. Morphological evolution of the inner Thermaikos Gulf in time steps.