ABSTRACT

This paper presents the results of geomorphological investigations carried out on the Pinios River delta, which is a Late Holocene arcuate type delta, located in the southern Thermaikos Gulf (Central Greece). Digital elevation model (DEM) analysis and the study of maps of the last two centuries, accompanied by field survey and aerial photo interpretation have led to the production of a geomorphological map at 1:15,000 scale which outlines the features of the deltaic plain and coastal zone. The evolution and the associated morphology of the delta are the result of the complex interplay of fluvial sedimentation, wave activity and prevailing longshore currents. The dominant landforms of the delta are the numerous abandoned meandering channels, as the river has changed its course several times, and a series of sub-parallel linear sandy beach ridges (cheniers) occupy the lower delta plain. The shoreline of the delta is generally retreating due to marine processes, especially where former river mouths occur whereas the presently active mouth of the river and its immediate surrounds are prograding.

1. Introduction

Deltas are important geomorphic and sedimentary environments, acting as major sinks for fluvially derived sediments in the coastal zone, as important ecological systems, and as foci for urban and agricultural development. Deltaic systems are relatively complex systems and subject to a range of fluvial, climatic, tectonic and sea-level controls (Gaki-Papanastassiou, Cundy, & Maroukian, 2011).

A large part of the low lands of mainland Greece are composed of deltaic plains (Karymbalis & Gaki-Papanastassiou, 2008). The evolution of larger deltaic and coastal depositional systems in Greece has been relatively extensively studied (Ghilardi et al., 2008; Maroukian & Karymbalis, 2004; Papadopoulos, 2009; Piper, Kontopoulos, Anagnostou, Chronis, & Panagos, 1990; Piper & Panagos, 1981; Poulos & Chronis, 1997; Psilovikos, Vavlaki, & Laggalis, 1988; Vott, Schriever, Handl, & Brückner, 2007). The beginning of the evolution of nearly all Greek deltas is the same during the Last Glacial Maximum around 20,000 years ago, sea level fell to its lowest point, ca. 120 m below that of today. From ca. 14,000 BP onwards, sea level rose at an average speed of 1.5 cm/year, presumably reaching its present position (or close to it) around 6000–5500 BP (Lambeck, 1996). In the following 5500 or so years, the significant expansion of Greek deltas occurred since many of the former marine embayments silted up, mainly due to fluvial sedimentation (Bruckner, Vott, Schriever, & Handl, 2005; Gaki-Papanastassiou et al., 2011).

The present study aims at a better understanding of the prevailing processes which contributed to the geomorphic evolution and recent configuration of the Pinios River delta, located in the prefecture of Thessaly (Central Greece), during the Late Holocene. There is a lack of a comprehensive and detailed geomorphological mapping of the Pinios River delta, which is limited to some features depicted on a 1:50,000 geological map covering the broader area (IGME, 1987). Moreover, most of the coastal and fluvial features identified on the 1945 aerial photographs are now obscured by development. The geomorphological map of this study attempts to fill this gap, by providing information about the dominant landforms of the delta. The final product of the geomorphological survey and mapping is a detailed (at 1:15,000 scale) geomorphological map, depicting the main landforms of the delta.

2. Study area

The Pinios River delta is located on the western shore of the Thermaikos Gulf, north-west Aegean Sea, Thessaly (Central Greece) (Figure 1). It is an arcuate type delta of 69 km² with a mean gradient of 0.058% and a straight or gently curved shoreline. Deltas are typically classified according to the main control on deposition, which is usually either riverine sediment supply, waves or tides (Coleman & Wright, 1975; Galloway, 1975; Wright & Coleman, 1973). These controls have a large effect on the shape of the resulting delta. The very low tidal range (<20 cm), the rather linear...
shoreline and the geomorphological features encountered in the delta front zone (e.g. the presence of sandy beaches, cheniers and aeolian dunes) lead to the conclusion that the Pinios delta should be classified among those dominated by fluvial sediment supply, wave action and longshore drift (Bhattacharya & Giosan, 2003).

The formation of the Pinios delta is the result of the combination of suitable conditions for delta formation during the late Holocene. Climate conditions within the drainage basin (high mean annual precipitation especially between November and February) along with the catchment geology (presence of highly erodible formations) and relief (relatively steep slopes in the upper reaches) are characteristics favorable for weathering and erosion in the area of the catchment. Large amounts of sediments supplied by erosion are transported down the valley of the river to the coast. Thus, the presence of the delta depends largely on the conditions within the Pinios River drainage basin.

In addition, the characteristics of the receiving basin (low tidal range, waves and longshore currents not strong enough to remove all, or at least most, of the sediments deposited by the river and relatively gentle slope of the sea floor around the river mouth) have permitted long-term sediment accumulation and the formation of the delta.

Although Pinios has not suffered severe human interventions (like artificial distributary channel alignment or diversion or dam construction in the upper reaches of the drainage basin) that have affected the natural evolution of the delta, cultivated and residential areas have increased 80% over recent decades. Hence, the main land-use in the deltaic plain is agriculture and buildings along the shoreline.

2.1. Drainage basin

The drainage basin of the Pinios River has an area of 10,704 km² flowing into the Thermaikos Gulf.
(Figure 1). Lithologically, it consists of 25.8% clastic sedimentary rocks, 21.4% metamorphic rocks, 7.1% calcareous sedimentary rocks, 5.5% igneous rocks and 40.2% of unconsolidated fluvial and lacustrine sediments (Main Map) (IGME, 1983).

Despite the relatively small size of the catchment areas, many Greek rivers have well-developed deltas. Comparing the ratio between the area of the delta plain and that of the drainage basin of the Pinios River (0.7) with the mean ratio value of seven Greek deltas (7.3), it can be concluded that the extension of the Pinios River delta is limited in relation to the area of the drainage basin (Poulos & Chronis, 1997). A large amount of riverine sediments have been trapped upstream within the extensive alluvial plain of the river due to the presence of the narrow, resistant, gorge of Tembi, located between the delta and the alluvial plain, acting as a temporary base level for the whole drainage basin of the Pinios River. This is the main reason for the limited extent of the delta in relation to the area of the drainage basin (Karymbalis & Gaki-Papanastassiou, 2008).

Mean annual precipitation ranges from 400 mm near the delta to nearly 1600 mm in the highlands, whereas mean annual temperature is about 17°C. Mean annual river discharge is 81 m³/s ranging between 11 and 176 m³/sec (Table of the Main Map). The high water period lasts from December until April. Annual suspended sediment load amounts to 0.6×10³ t/km² while the annual yield of dissolved load is 0.15×10³ t/km² (Poulos, Chronis, Collins, & Papageorgiou, 1987). Wave heights and direction moves northwards (Balopoulos, Chronis, Lykousis, & Papageorgiou, 2000). Prevailing N-NW winds move water south along the coastline while in the case of S-SW winds surface water moves northwards (Balopoulos, Chronis, Lykousis, & Papageorgiou, 1987). Wave heights and direction depend on the existing wind regime. Waves related to southerly winds are considered to be the most important in terms of magnitude. Thus, high waves of long wave-length are to be expected only from southerly directions. In contrast, winds blowing from the north are more frequent and despite the smaller fetches they generate surface gravity waves influencing the general water surface circulation of the gulf. The Pinios delta is exposed to long wave fetches subjecting the deltaic coastline to a monthly wave power of 70–1454 w/m² (Poulos et al., 2000). Current speeds are of the order of 5–20 cm/s near the water surface and up to 9 cm/s near the seabed.

3. Materials and methods

The geomorphological mapping of the Pinios River delta was carried out in three phases (Figure 2). During the first phase all necessary remote sensing and topographic survey data were collected including: topographic diagrams covering the delta plain (1:5000, obtained from the Hellenic Military Geographical Service), a 1972 1:50,000 scale analogue topographic map (Hellenic Military Geographical Service), old topographic maps from the previous century, a 1987 1:50,000 scale geological map (Institute of Geology and Mineral Exploration of Greece) and two series of aerial photographs (~1:42,000 and 1:33,000) taken in 1945 and 1995, respectively, obtained from the Hellenic Military Geographical Service. Data were organized into a geographic information system (GIS) spatial geodatabase using Esri ArcGIS 10. The projection system was the Hellenic Geodetic Reference System 1987 (HGRS’87). These maps and aerial photos were the source for the creation of the primary thematic layers (with point-to-point on screen digitizing) which include coastline, contour lines (with 4 m contour interval for the deltaic plain), isolaths, elevation points, channel networks, geological formations and tectonic elements. The geological formations layer was used as intersection with flat surfaces. GIS procedures produced secondary layers which include a raster digital elevation model (DEM) of the delta, a hill-shade map, a slope-aspect map, a range map and a map of morphological discontinuities of slopes. The basic input data for the production of the DEM were contours with a good density (4 m contour interval, as well as 1 m in some relatively flat regions) together with elevation points and the drainage network from the 1:5000 scale maps. The TOPOGRID algorithm in ArcGIS 10 was used to generate a 2 × 2 cell size DEM of the delta. Aerial photos and Google Earth images were used for visual inspection and interpretation along with DEM analysis as a first step in order to produce morphological sketches of the study area in the form of paper field maps at the scale of 1:5000, suitable for field survey. Additionally, land surface parameters such as slope, gradient, aspect, curvature and roughness have been calculated and used in the production of the morphological sketch of the study area depicting spatial patterns that contributed to the preliminary delimitation of elementary features. These derivatives were useful for mapping fluvial, coastal and aeolian landforms. For instance slope angle (rate of change in altitude) was used in order to determine abandoned channels, point bar ridges, beach ridges and crevasse splays. Aspect (circular variable describing the direction of azimuth) proved helpful for the identification of different beach ridge sets. Curvature was used for mapping alluvial fans and crevasse splays as their aprons correlate well with negative values of concavity.
Since the increasing impact of human interference diminishes the quality of newer images for geomorphological mapping, older images (especially the aerial photos taken in 1945) proved to be more effective in mapping some types of landforms such as abandoned distributary channels, point bar ridges, crevasse splays and beach ridges (Figure 3). The lithological and structural features around the delta have been derived from the 1:50,000 scale geological map (sheet Rapsani) of the Greek Institute of Geology and Mineral Exploration (1987), validated and implemented by means of field observations.

The interpretation of the morphological sketches was digitally stored as vector data comprised of points, lines and polygons in the form of layers. Three main sets of landforms have been identified and mapped: (i) fluvial, (ii) coastal and (iii) aeolian. Some of the large-scale landforms (such as abandoned distributary channels and...
meanders, point bar ridges, crevasse splays and beach ridges) as well as the 2013 shoreline were initially digitalized directly in Google Earth where they were saved as KML files. These were then converted to shape-files using the Department of Natural Resources Garmin application (http://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html) and organized into thematic layers according to the type of each landform. Manual interpretation of patterns within the landscape in conjunction with the contextual information was important in order to identify and outline individual landforms.

Field control was necessary to avoid mistakes made from maps drawn from the DEM analysis and aerial photos and Google Earth image interpretation. During the field survey the entire deltaic area was examined following the traditional protocol of geomorphological mapping, verifying all the features and landforms identified during the previous phase. Furthermore, a handheld Topcon GMS-2 differential global positioning system (DGPS) was used in order to mark waypoints for the precise location of landforms. The accuracy of the DGPS used is considered to be suitable for 1:5000 scale field survey.

During the final, post-field survey, mapping phase the existing GIS database was integrated with the GPS data and a comparison of field and remote sensing mapping data took place in order to validate the initial landscape map unit and proceed to the production of the final geomorphological map of the delta. The validation included the correct classification and inclusion of all landforms that actually exist as well as their location accuracy within the deltaic plain and along the delta coastline.

4. Results

The hilly area north and east of the delta consists of terrestrial and lacustrine deposits of Neogene age including marls, breccia-conglomerates and terra rossa, whereas the mountainous area south of the delta is composed of amphibolites, schists and crystalline limestones of Mesozoic age (IGME, 1987). The delta plain is bordered by the active WNW–ESE trending normal fault of Omolio to the south (Caputo, 1990). Along the north and south limbs of the delta torrential streams, which discharge into the delta plain, have created small and steep alluvial fans.

The geomorphological survey led to the identification and mapping of three main sets of landforms and deposits: (i) fluvial, (ii) coastal and (iii) aeolian.

4.1. Fluvial landforms

Numerous abandoned distributaries were recognized across the delta plain. Most of these palaeochannels, which are clearly visible in the 1945 aerial photographs, are no longer identifiable in the landscape (Figure 3). Thus, aerial photographs of 1945 have been particularly useful for identifying and mapping these landforms. Apart from the linear segments of abandoned distributary channels across the flood plain of the delta, there are several abandoned meanders (Figure 4). The interior areas of most meander bends exhibit meander scroll terrain patterns consisting of numerous, sub-parallel, curvilinear ridges separated by topographic swales. These features were formed as stream channels meandered across the delta by the emplacement of point bar deposits which had built up on the inside of the meander bends. Several example areas of such terrain were identified and are shown on the Main Map as curved, sub-parallel dashed lines.

The use of historical maps and aerial photos allowed us to identify only recent changes in the river course. Two major former river mouths, associated with channel avulsion, have been identified north of the present active mouth, whereas there are two more south of it. The most recently abandoned river course is a meandering channel south of the present active one. This channel, which is depicted in 1881, 1910, 1924 and 1935 topographic maps, separates into two simultaneously active distributaries leading to Armira and Stomio, about 3 and 5 km south of the present active mouth of the river, respectively (Main Map). It was partially abandoned naturally in 1955 when the river migrated northwards. The avulsion point is located 8.6 km upstream from the former river mouth. Hence, a change from active channel deposition in the southern delta to active deposition in the central delta occurred after 1955. Comparative visual inspection of the 1945 and 1995 aerial photographs shows that the new course of the active distributary channel follows a previously abandoned course of the river. Another abandoned meandering channel, visible in 1910, 1924 and 1935 maps discharging into the sea 1.2 km north of the present active channel, occurs and for a long time appears to act as a secondary distributary. A much older group consisting of both linear and meandering palaeochannels is located at the northern part of the delta leading to Paliomana, 3.7 km north-west of the present mouth. It should be noted here that avulsion and evolution of new distributary channels is a relatively frequent natural phenomenon, at least for the last 135 years, compared to other deltas on the Greek coast (Karymbalis & Gaki-Papanastassiou, 2008; Maroukian & Karymbalis, 2004). For most of the Greek deltas, recent changes in river course are mainly associated with direct and indirect human interference, which include artificial diversion and confinement of distributaries as well as dam construction at the upper reaches of the catchments.
Two recent crevasse splays, located in the central part of the delta plain, are clearly visible on 1945 aerial photos. These fluvial sedimentary deposits apparently were developed before 1945 when the oldest aerial photographs used in this study were taken. They were formed when the natural levees broke as water levels in the distributary channel rose above them. The breach of the natural levees resulted in rapid flooding and sediment deposition in the delta floodplain. The first, more extensive, crevasse splay covers an area of 1 km² and is located 5.2 km upstream from the presently active river mouth. The breach that formed this crevasse splay led to fluvial sediment deposition in a similar pattern to an alluvial fan deposit. The surface of the fan-like deposit is intersected by numerous crevasse channels. The other, fan-shaped, crevasse splay is situated 13 km upstream from the pre-1935 river mouth. It is a much smaller sedimentary body, covering an area of 0.26 km².

Figure 4. Abandoned and active channel in the delta plain of the Pinios River. The photo is taken from the northwestern flank of the delta.

Figure 5. Beach ridge and swale topography at the lower Pinios River delta plain.
4.2. Coastal landforms

The particle size distribution of surficial sediments along the delta shoreline is relatively uniform (fine to medium sands) with slightly coarser sand size material located around the older (abandoned) channel mouths.

The low-lying coastal section of the lower Pinios River delta plain consists of a series of straight to gently curved sub-parallel linear abandoned sandy beach ridges (cheniers), signifying recent (in historical times) progradation of the delta (Figure 5). The Pinios River delta, as a wave-influenced delta, is characterized by beach ridge and swale topography where sand is supplied by the major distributaries. Preservation of such ridge and swale complexes results in homogeneous sands formed by accretion of beach and shoreface deposits on either side of the river mouth. The abandoned beach ridges (cheniers) were recognized via topographical changes and changes in vegetation. They were mapped in detail and classified into six groups according to their orientation since there are no available data about their absolute age. The prograding beach ridges are developed on both sides of the present river mouth as well as in the inter-distributary areas of the delta plain. The ridge sets of the north delta plain are roughly NW–SE aligned (from N114° to N150°). On the other hand, the sets of the south delta tend to align in roughly NNE–SSW (N5°–N20°) and N–S directions (from N170°–N175° to N190°–N205°). Beach ridge patterns illustrate the response of wave gradients and longshore currents to changing deltaic shoreline configurations, sediment loads and distributary channel shifting.

A recent sandy backshore berm ridge is formed south of the post-1955 active river mouth (Figure 6). According to Otvos (2000) such berm ridges should not be considered beach ridges until separated from the shoreline by progradation. The period of high water discharge (December–March) coincides with that of high wave power. Hence, the fluvial sediment input is being reworked by waves and associated southward longshore currents to form this new berm ridge.

The comparable analysis of the digitized shorelines of 1945, 1995 and 2013 shows that about 10 km, corresponding to 50% of the Pinios delta coastline, is currently undergoing erosion. This change in coastline position is the result of redistribution of sediment from former river mouths, producing straightening. The area of the abandoned mouth to the south (north of Stomio) has retreated about 180 m over the 40-year period between 1955 and 1995 (corresponding to a maximum mean erosion rate of −4 m/year). This rate was reduced to −3 m/year over the next 17 years. Due to the presence of the previous active river mouth, the alluvial deposits were concentrated at one location along the coast, which led to the build up of a sediment lobe. Today three lobes are identifiable in the submarine morphology facing the deactivated former mouths (Main Map). As soon as the river abandoned its mouth, the sediment deposition ceased. The process of the straightening of the coastline then commenced, which resulted in a rapid regression of the coast around the abandoned mouth. In contrast, the area around the presently active mouth of the river has prograded for about 440 m from 1955 to 2013 (mean rate: +7.5 m/year) when the river shifted to its present position. For the same period of time, the coastline along the delta south of the present mouth advanced through the formation of a sandy backshore berm ridge. In Greece the most distinctive coastline changes are related to river deltas and include progradation of active river mouths and retreat of abandoned lobes (Karymbalis et al., 2012). Extremely high mean erosion rates of up to more than −20 m/year are very rare and characterize the Acheloos and Nestos deltas (Piper & Panagos, 1981; Psilovikos et al., 1988). Usually erosion rates of deltaic coastlines are less than −4 m/year. By contrast, active river mouths are areas of rapid accretion with progradation rates up to more than +7 m/year with the exception of the Acheloos delta, where mean pragradation rates of more than +40 m/year have been reported (Piper & Panagos, 1981). Consequently, mean rates of shoreline changes estimated for the Pinios delta are comparable to other deltas on the Greek coast.

A process that is expected to influence the Pinios delta, like most of the low-lying coastal areas, is the anticipated rapid sea-level rise (Karymbalis & Gaki-Papanastassiou, 2008; Maroukian & Karymbalis, 2004; ). The recent IPCC (2014) reports suggest that sea level will rise from 25 to 95 cm by the year 2100. In the case of deltaic deposits, an additional land subsidence due to sediment compaction should be taken into account (Parcharidis, Kourkouli, Karymbalis, Foumelis, & Karathanassi, 2013). The future sea-level rise may enhance the retreat of the Pinios delta coastline leading to the loss of delta plain, except in the actively aggrading channel areas and their immediate surrounds. The area lying below the 0.5 m contour line, which will face severe problems, covers 6.5 km² (corresponds to 9.5% of the total area of the delta). An extensive part of this low-lying area is occupied by economically important cultivation (2.0 km²), residential areas (3.0 km²), and beach sands and coastal marshes (1.5 km²).

4.3. Aeolian landforms

A 2 km long narrow strip of sand dunes (not exceeding 1.5 m high) are present behind the beach of Nei Pori indicating that the northern part of the delta is dominated by aeolian processes (Figure 7). These embryo dunes are partially stabilized by vegetation while the
natural geomorphology immediately behind the dune field is obscured due to anthropogenic modification.

4.4. Land-use change

Comparative analysis of the aerial photomosaic, created from the 1945 aerial photographs, and the recent Google Earth image of the delta show significant changes in land-use over the last 68 years. The coastline between Paralia Koulouras and Platamonas is used for tourism-related activities and recreation. In the early 1950s, the only settlements along the coast were at Platamonas in the north and Stomio in the south. In recent decades these regions have expanded considerably as they have become important resort areas for local and foreign tourists. The most important resort settlement today is Nei Pori. It is estimated that the population of the coastal zone triples in the summer.

The character of this low-lying part of the north delta plain has significantly changed from land occupied by natural grasslands, and agricultural activities to an urbanized one. It is estimated that residential area has increased by 170%. Furthermore, there has been a sparse cottage-housing development along the coastline of the south delta between the active river mouth and Alexandrini (a small village consisting of more than 150 cottages) during the last two decades. The distribution of residential areas shows that more than 85% of this land is located along a zone (straight line distance <1 km) parallel to the coastline. In contrast, the upper delta plain was left for extensive rural activities. Cultivated areas of the Pinios River delta have increased by about 70%. Reclamation work reaches as far as 1 km inland (especially at the south part of the delta plain) having converted inter-distributary areas and part of the coastal forest to arable land.
These land-use changes have had a large impact on the deltaic landscape. Landforms of fluvial (point bars, abandoned distributary channels and crevasse splays), coastal (beach ridges) and aeolian (coastal dunes) origin have disappeared under housing development over the last few decades. Additionally fluvial landforms in the upper delta plain have been obscured by agricultural activity, which has steadily increased.

5. Conclusions

The results of the geomorphological survey carried out on the Pinios River delta have been illustrated with special reference to the 1:15,000 geomorphological map, which has been produced. The latter is accompanied by a map of the Thermaikos Gulf, a lithological map of the Pinios River catchment, and a table including the main characteristics of the Pinios River system regarding the catchment, the alluvial valley, the delta plain and the receiving basin (Thermaikos Gulf). Particular emphasis has been devoted to the identification and mapping of the palaeochannels and associated former river mouths, beach ridges (cheniers) and recent shoreline shifting.

The survey of historical maps and aerial photos has allowed the identification of several palaeo-distributaries which outline changes in the river course and migration of the active mouth of the river. The recent major change in the course of the Pinios River occurred in 1955 through a northward avulsion of the main active distributary channel. The main geomorphological characteristic of the lower delta plain are a series of abandoned, sub-parallel, linear sandy beach ridges (cheniers), which were mapped in detail and classified into six groups according to their orientation. The delta plain of the Pinios River was advanced by the gradual accretion of these beach ridge sets. The reconstruction of the recent (after 1945) evolution of the shoreline showed that about 10 km, corresponding to 50% of the modern delta coastline, is undergoing active marine erosion. The only area where the delta aggrades today is the presently active mouth of the river and its immediate surrounds, where a mean annual progradation rate of about +7.5 m/year is observed for the time period between 1955 and 2013. For the same time period, a mean retreat rate of -3.5 m/year is estimated north of Stomio where the most recently abandoned mouth is being reworked by marine processes since 1955. Coastline changes are mainly associated with wave reworking and redistribution of abandoned lobes of sediment. An increase in mean sea level of more than 0.5 m, related to the predicted total increase of 2–3°C of the mean global air temperature, might enhance the erosion of the delta, with important economic repercussions. It is estimated that the area which lies below 0.5 m is approximately 6.5 km² and is occupied by economically important agricultural land and tourism activities.

Software

Esri ArcGIS 10 was used to digitize the data collected during field survey and aerial photo interpretation. The final layout of the geomorphological and lithological map was assembled using Corel Draw 15.

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