Natural Processes Versus Human Impacts During the Last Century: A Case Study of the Aliakmon River Delta

Michael Styllas

Abstract The Aliakmon River flows down from the northwestern mountains of Greece and is one of the largest fluvial systems in the Greek territory. Basin climate and geology favour the high rates of sediment production and transport and, consequently, the formation of an extensive (9.2% of basin area) bird-foot Holocene delta. Three phases (A, B and C) of human impacts over the past 90 years have caused pronounced changes on the natural evolution of the delta. During Phases A and B, a 50% increase of deltaic sedimentation rates in relation to Holocene pre-anthropogenic rates and an enrichment of deltaic deposits with heavy minerals occurred. Phase C, characterised by damming, increasing agricultural and industrial activities and population growth, resulted in 90% decrease in sedimentation rates compared to Phase B, a regulated hydrological regime with high electrical conductivity and nutrient concentrations of surface water, enhanced erosion of river channel and deltaic deposits and degradation of habitats along the lower Aliakmon River delta. Future climate scenarios and increasing environmental pressures are not compatible with current water use strategy and, given the vulnerability of the system (reservoirs and delta) to projected climate trends, stress for a new strategic natural resource management plan.

Keywords Aliakmon River, Deltaic sedimentation, Human impact, Natural resource management, Water quality

Contents

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1 Introduction

River deltas are linked to the evolution of many civilisations since the Stone Age. In many cases, coastlines have been formed by the interaction between fluvial and marine processes, while deltaic plains are the areas where agriculture was initially established. Since the early Bronze Age, when Sumerian, Babylonian and Assyrian empires evolved in the lower Tigris–Euphrates River, river deltas have been reclaimed and modified by humans. A detailed understanding of the local biogeochemical processes driving deltaic formation and evolution is essential in assessing the extent and magnitude of human impacts as well as in order to provide estimates of natural resource availability and proper future planning.

The Aliakmon River, which is the second largest fluvial system exclusively laying in Greece, exhibits a strategic status in terms of water resource and deltaic plain management. It is a mountainous river originating in northwestern Greece, discharging water and sediment into the Thermaikos Gulf (Fig. 1). Since the 1930s, different types of human impacts have disturbed its deltaic natural evolution, thus turning the lower Aliakmon River from natural to a human-controlled system with adverse consequences on water and sediment regimes.

The natural evolution of the Aliakmon River delta during the last century is presented here through estimates of selected quality and quantity parameters for water and sediment. A number of anthropogenic modifications on the watershed and delta for the past 90 years are cited. Natural (unregulated) fluvial water and sediment discharge estimates are derived through numerical modelling, as data sequences do not extend prior to 1925, when the river is considered to be undisturbed. On the contrary, the effects of anthropogenic pressures on water and sediment budgets are described by means of sample analyses, as the river lacks a monitoring network. Comparison of specific parameters between natural and disturbed periods provides useful conclusions about the present-day functionality of the lower course

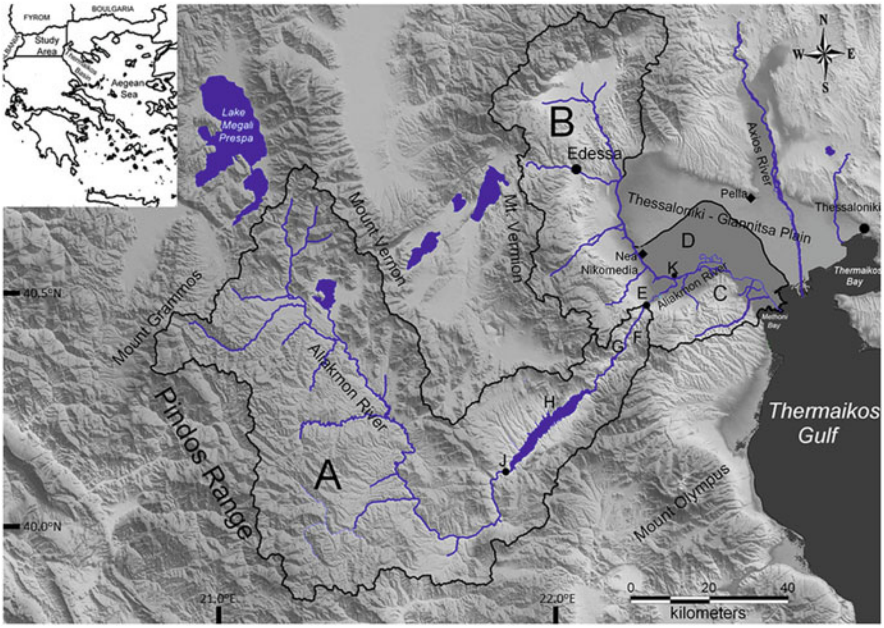

Fig. 1 General setting of the study area with all geographical elements cited in the study. A: Aliakmon River watershed with major subbasins (total area, 6,100 km^2). B: Peripheral Canal watershed with major subbasins (added to Aliakmon River basin in the 1930s, following Phase A of human interventions; total area, 2,223 km^2). C: Pieria subbasins (contribute water and sediment to Aliakmon River delta during the Holocene; total area, 453 km^2). D: Aliakmon River Holocene delta (defined from satellite elevation and topographical data and geomorphological land observations; total area, 567 km^2). Total drainage area of A, B, C and D sums to 9,343 km^2, the present-day surface area of Aliakmon River basin. E: Aliakmon River Holocene delta apex (the river's exit to the valley). F: Asomata reservoir. G: Sfikia reservoir. H: Polyfyto reservoir. J: Agios Ilarionas dam. K: Junction of Aliakmon River with Peripheral Canal. The Neolithic settlement of Nea Nikomedeia and the capital of Macedonian Empire Pella are also shown

of the Aliakmon River delta. The present study aims in providing a comprehensive review of the current environmental status and also of the environmental threats of Aliakmon River delta under climate change scenarios. The work presented here is considered as the basis that will comprise a useful tool for the political initiatives and future planning of Greece's most important fluvial system.

2 Thermaikos Basin

2.1 Geological Evolution and Sedimentary Depositional Regime

The Thermaikos basin is strongly related with the geological evolution of Aliakmon River basin. The thickness of Cenozoic deposits in the Thessaloniki–Giannitsa plain and the Thermaikos Gulf is 3,000 m [1]. Within the Thermaikos basin, the existence of molasses and lignite layers indicates the changing nature of depositional environments during the first cycle of basin subsidence, which is dated between Upper Oligocene and Lower Miocene [2]. The early Neogene phase of the Thermaikos basin subsidence is related to the opening of the Aegean back-arc basin that resulted from the southward retreat of the Hellenic subduction zone [3]. From Middle to Upper Miocene, the Thermaikos basin entered a period of sea-level regression that was characterised by extensive formation of red oxidised soil layers. A second phase of tectonic subsidence and deposition of lacustrine and shallow-marine sediments began in Early Pliocene. Continuous faulting along basin margins associated with the dextral motion of the western end of North Anatolian Fault [4] resulted to the deposition of volcanic tuffs of trachyandesite (felsic) composition [2].

Between Pliocene and Pleistocene, the basin entered another period of sea-level regression due to intense uplift that resulted in thermal spring activity and deposition of travertines along the basin margins. During the Pleistocene and the Holocene, sediment transport regime from the marginal rivers towards Thermaikos basin was mainly defined from eustatic and isostatic movements.

2.2 Oceanographic Setting

The Thermaikos Gulf (Fig. 1) is a semi-enclosed embayment at the NW part of the Aegean Sea. The oceanography of the gulf is characterised by low-energy wind, wave and tide regimes. Prevailing winds generally blow from north-northwestern directions, their velocities exceeding 15 m/s less than 1% of the year [5]. During the winter, northerly wind outbreaks of gale force (with velocities of 20 m/s) known as ‘Vardaris’ are funnelled to the gulf mainly through the river valley of the Axios River, resulting in abrupt surface water temperature lowering and cyclonic circulation pattern along the western coast of the gulf. Northern winds tend to be weaker and less frequent during the summer months [6].

Mean annual significant wave height is less than 0.5 m, and significant wave heights exceeding 3 m have been recorded at a frequency of 1%. Tidal range across the gulf varies between 30 cm at mean spring tides and 5 cm at mean neap tides [5]. In this relatively calm and tideless environment, the formation of the Aliakmon delta has been largely determined by the interaction between water/sediment discharge and wave action, the wave power not exceeding 30 W/m^2 with maxima observed between mid-spring and mid-autumn [7] coinciding with the period of low water and sediment discharge of the Aliakmon River.

3 Aliakmon River Watershed and Delta: Physical Characteristics

3.1 Basin Geology

The Aliakmon River originates on the northeastern side of the Pindus Range in continental Greece. The river's basin has a wave-shaped form and a surface area of 6,100 km^2 at the exit to the plain of Thessaloniki–Giannitsa (Fig. 1, E). The highest altitude of Aliakmon River watershed is located on the summit of Grammos Mountain (2,520 m.a.s.l.). Average drainage basin elevation is 836 m.a.s.l. with 32% of the total basin area being confined between 600 and 800 m.a.s.l., while average relief ratio is $1.7\ 10^{-2}$ [8].

The Aliakmon River length is 310 km along which the river drains four geotectonic zones, each of them corresponding to a different paleogeographical setting. Processes, such as uplift, erosion and intrabasin deposition during two major cycles (2.1), have created a variable basin lithological composition: felsic rocks 14.5%, mafic rocks 9.2%, volcanic rocks 0%, carbonates 15.7%, flysch–molasse 29.6% and Neogene and Quaternary sediments 31% [9].

The first erosion–deposition cycle took place during the Tertiary (Upper Oligocene and Lower Miocene) and resulted in excessive intrabasin and down-valley deposition of Neogene terrestrial, fluvial and lacustrine deposits. The second cycle of erosion is placed along the Pliocene–Pleistocene boundary and resulted in the incision of the Aliakmon gorge and the formation of the river's deltaic plain that was gradually silted up during the Quaternary.

3.2 Basin Climate

The Aliakmon River basin climate is characterised as 'continental' along its main watershed becoming 'Mediterranean' towards the deltaic plain [7]. Annual average values of main hydrological parameters demonstrate a west-east gradient. Higher values to the west result from the orographic effect of Pindus Range to the wet fronts arriving from the Adriatic Sea, gradually decreasing towards the eastern part of the watershed.

Data collected between 1963 and 1999 in the Agios Ilarionas dam (Fig. 1, J), a location representing 82% (5,005 km^2) of basin area (Fig. 1, A), provide annual average values of precipitation 764 mm, air temperature 12.2°C, evaporation and transpiration 435.4 mm (representing 56.2% of precipitation) and total runoff 339.4 mm/y representing the remaining 43.8% of total annual precipitation [10], while the entire watershed precipitation and temperature annual averages are 750 mm and 16.5°C, respectively [11].

3.3 River Discharge

Limited measurements at the river exit to the valley during 1930s indicate mean annual discharge values of 95 m^3/s [12], whereas hydrological model output estimates spanning a 40-year period (1960–2000) data reanalysis from the entire basin provide a better estimated mean annual discharge of 70.6 m^3/s [10], with minimum and maximum average monthly discharge values ranging between 21 and 137 m^3/s, respectively [11]. Measured discharge values at the river mouth during the 1997–1998 METROMED project [13] averaged 34 m^3/s, illustrating the effects of anthropogenic impacts on river Aliakmon's discharge. During periods characterised by rain on snow events, the Aliakmon River has exhibited discharge values higher than 3,200 m^3/s, resulting to frequent flooding of the lowlands since the ancient times [12].

Spectral analyses of monthly precipitation and discharge suggest that river discharge annual distribution peaks occur during the winter months (December–March) in contrast to double peaks of precipitation maxima occurring during October–December and April–June, respectively (Fig. 2). This discrepancy is explained by the high infiltration rates that result from basin lithology (75% of Aliakmon basin formations are either soft sediments or carbonates), from sparse vegetation and basin climate, with dry summers characterised by high evaporation rates (56% of total

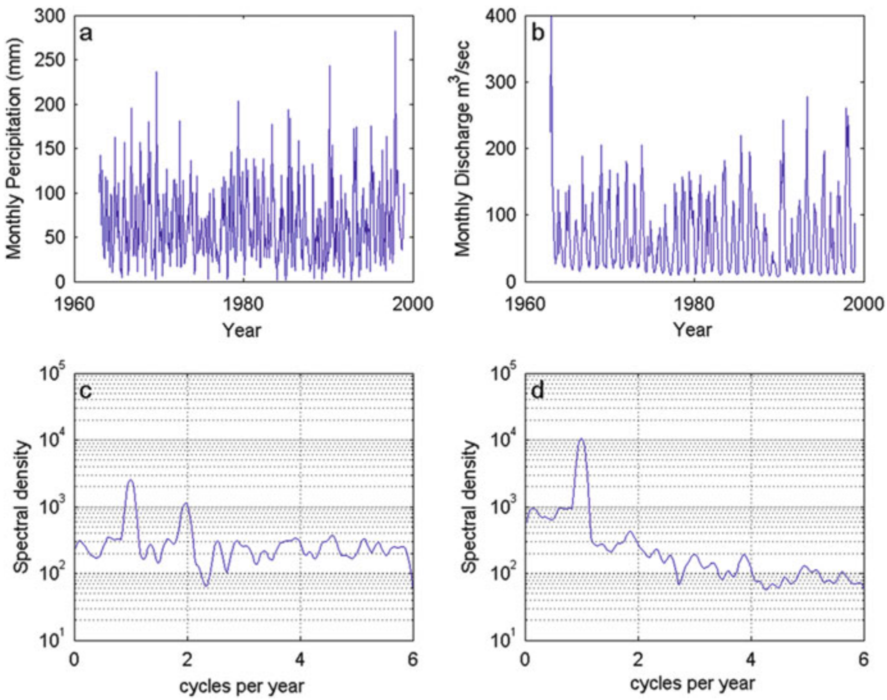

Fig. 2 Time series of (**a**) precipitation and (**b**) discharge monthly average values of Aliakmon River at Agios Ilarionas (Fig. 1, J) gauging station and (**c**, **d**) their associated spectra

precipitation) and thick unsaturated soils (high denudation). Such hydrological conditions require large amounts of precipitated water to provide adequate surface runoff during the autumn rain period, resulting to delay of the high discharge period. Increased discharge values are observed at the end of the autumn rain period (December) peaking during early spring (March), the maxima explained by snowmelting, rain on snow events and saturated soils.

The chemistry of Aliakmon River surface water is determined by basin climate and basin lithology as both factors control the type of weathering. The geochemical signal of river water is dominated by calcium (Ca^{2+} 38.5 mg/l), magnesium (Mg^{2+} 31.3 mg/l), silica (SiO_2 11.4 mg/l) and chloride (Cl^- 5.6 mg/l) contents. While the main portion of major ions is related to weathering of recent (Neogene and Quaternary) sediments, magnesium and silica are also derived from mafic rock weathering [9, 14].

3.4 Deltaic Stratigraphy

In sequence stratigraphic terms, the Holocene delta of Aliakmon River is divided into three systems tracts: (1) LST, a low-stand systems tract of variable thickness, composed of fluvial gravels and sands (alluvial fan) of the Late Pleistocene, as well as from red oxidised clays (alluvial plain); (2) TST, a relatively thin (2–8 m) transgressive systems tract composed of fluvial channel sands, overlain by a thin transgressive sand bed of coastal origin, characterised by fining upward (FU) grain-size trends that indicate a phase of sea-level transgression; and (3) HST, high-stand systems tracts (5–35 m), constituted by a variety of stratigraphic units, stacking patterns and depositional environments (fluvial channel, levee channel, coastal lagoon, marsh, delta front and floodplain); characterised by coarsening upward (CU) sequences, representing both aggradational (sea-level rise rate = sedimentation rate) and progradational (sea-level rise rate < sedimentation rate) facies; and dominated by the presence of three distinct progradational wedges associated with climatic (high sedimentation rates) and/or eustatic (still stands, tectonic uplift) oscillations [15].

The estimated volume of Holocene deltaic deposits derived from the underground mapping of TST and HST from drill profiles by using a measured (100 samples) average-specific weight value of $\gamma = 1.49$ g/cm^3 is 26.3×10^9 m^3.

3.5 Deltaic Sedimentation

For the purposes of the current study, natural deltaic sedimentation rates have been estimated by the following methods: (1) From application of an empirical power law function on annual water and sediment discharge data measured by the Greek Public Power Corporation at the Agios Ilarionas dam (Fig. 1, J) and extended by linear interpolation to cover the entire drainage basin (Fig. 1, A + C + D). The results suggest average annual estimates at the present-day river mouth of 6.75×10^6 t/y.

(2) From estimates of Aliakmon Holocene delta (Fig. 1, D) accommodation space derived from drill data that penetrated the Pleistocene–Holocene boundary (Sect. 3.4). Drill data suggest average sedimentation rates of 2.5 m/ky in agreement with the findings of [8] that employed geophysical methods and estimated the bottomset and foreset deposition to be 0.5 and 3.0 m/ky, respectively. Such sediment accumulation rate values, together with the underground mapping of the Holocene (10 ky BP) lower boundary, marked by transgressive systems track deposits (Sect. 3.4), provide an average annual Holocene sedimentation rate of 6.52×10^6 t/y. (3) From estimates of the Holocene deltaic sequence thickness at the Aliakmon River mouth, derived from seismic profiling and quantification of shoreline and bathymetric changes from digitised hydrographic maps between 1850 and 1916, a period lacking substantial human impacts on watersheds and delta. This method provided natural sediment discharge values at the present-day mouth of 6.63×10^6 t/y [16]. All three methods are in general agreement suggesting that average natural sediment discharge of Aliakmon River at its present-day mouth is 6.6×10^6 t/y. The relatively high annual sediment yields of 462 t/km^2/y [8], combined with high flood discharge values (Sect. 3.3) and low wave energy (Sect. 2.2), have resulted to the formation of a bird-foot delta during the Holocene, still evident from high-resolution topographic data (Fig. 3).

The geochemical composition of Aliakmon River deltaic sediments is defined by weathering processes on the watershed and biochemical processes that follow sediment deposition in a variety of environments along the delta. On average, Aliakmon River deltaic sediments contain low organic matter concentrations (2.4%), while higher concentrations (5%) are observed within lagoonal and marsh environments [15].

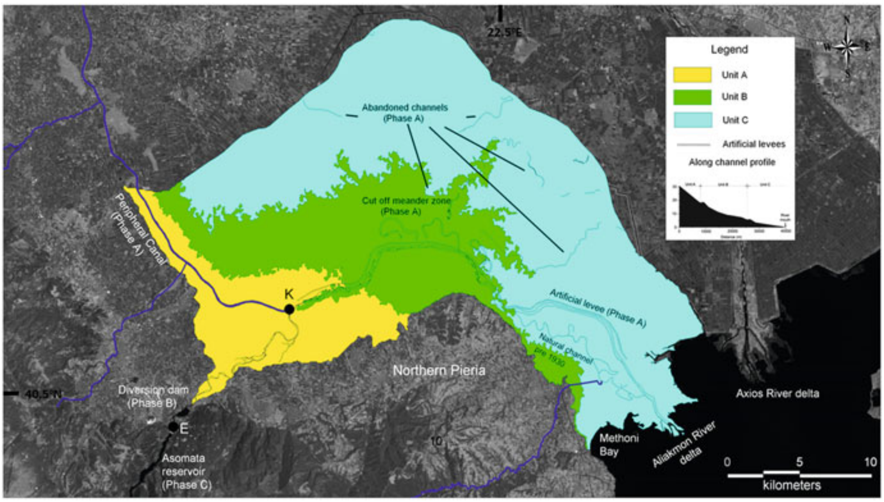

Fig. 3 Digital elevation data (SRTM 90) superimposed on satellite imagery (LANDSAT 97) illustrating the Holocene delta of Aliakmon River with its most prominent morphological features and human impacts. Extensive cut-off of the river's meander zone was realised in the 1930s for flood control. Abandoned channels, former lobes and the bird-foot shape of the Holocene delta are also evident

Calcium carbonate ($CaCO_3$) average concentration is 13% and reflects basin lithology and/or biological activity confined within delta marshes and back barrier lagoons, while observed down-core increase of $CaCO_3$ is attributed either to a decalcification process that results from a transient drop of pore water pH or to temporal decrease of biological activity.

Deltaic sediment sand fraction is rich in minerals containing silica (quartz 48.5%), calcium (epidote 13.8%, augite 2% and plagioclase 1.6%), magnesium (hornblende 5.8%) and potassium (muscovite 7.4%, feldspar 3.7%). Considerable amounts of underdetermined rock fragments (11.5%) and traces of biogenic silica (2.15%) are also present [1]. Clay mineralogy of river Aliakmon deltaic deposits is dominated by chlorite and kaolinite (up to 30%) that result from mechanical weathering of mafic rock formations, while smectite is more abundant in offshore (Thermaikos Gulf) locations [11].

3.6 Deltaic Evolution

The Aliakmon River delta plain has an area of 567 km^2. Holocene delta morphology derived from elevation and sedimentological data analyses is partitioned in three major units: The delta apex (12.5–30 m.a.s.l.) covering an area of 88.2 km^2 (15%) is registered as morphological Unit A and characterised by coarse-grained deposits (boulders, gravel and sand). Morphological Unit B is made up of sandy deposits of various origins (delta front, river channel, channel levee and floodplain) and covers an area of 151.8 km^2 (26%), its elevation bounded between 2.5 and 12.5 m.a.s.l., while morphological Unit C is characterised by fine-grained sediments, covers the majority (59%) of the Holocene delta surface (348 km^2) and is bounded between the 0 and 2.5 m.a.s.l. elevation contours (Fig. 3).

The subaqueous part (delta front and prodelta) of Aliakmon River modern delta interfingers with the prodeltas of the closely located Axios River and other minor rivers (Gallikos, Loudias), extending almost 50 km to the southeast and characterised by smooth gradients. Altogether, this complex system covers an area of 51,000 km^2 of the Thermaikos Gulf continental shelf, down to a depth of 200 m.b.s.l. [17].

The stratigraphy and morphology of the Aliakmon River delta are indicative of a mountainous river, characterised by high sediment transport rates and a rapid growing delta. The delta's central lobe rapid progradation that followed the stabilisation of sea level during mid-Holocene is partly responsible for the siltation and abandonment of the ancient harbour of Pella (Fig. 1) at 2,350 y BP [18]. Late Holocene stages of deltaic evolution still evident in aerial and satellite photos and topographic maps are characterised by delta progradation, flooding, lobe switching, frequent abandonment of active channels, high sinuosity meandering and avulsion of the main channel to the southeast, a result of the interplay between climatic, oceanographic and tectonic forcing. Further studies are required to define the later evolution stages of Aliakmon River delta.

4 Human Impacts on the Aliakmon River

Human presence along the western part of Aliakmon river delta dates back to the early Neolithic, in a settlement close to the present-day village of Nea Nikomedeia [19]. The excavated Neolithic settlement is considered as the oldest farming village in Greece [20]. Except farming, other interventions on the natural evolution of the Aliakmon River had not been realised until the beginning of the twentieth century. Major political events in 1922 resulted to the migration of more than 150,000 Greek refugees from Asia Minor to Northern Greece, forcing the Greek government to reclaim the plain of Thessaloniki–Giannitsa by means of hydraulic works along the channels of the main rivers, both for social health condition improvement and for the initiation of systematic agriculture in the area. Based on their timing, expanse and type, human impacts along the Aliakmon River watershed and delta are divided into three major phases.

4.1 *Phase A (1925–1934)*

The primary goal of the 'Reclamation Project of Thessaloniki–Giannitsa Plain' was the drainage of swamps and lakes through canalisation of rivers and streams draining the eastern (Mount Vermion) part and discharged directly onto the plain. These rivers were canalised along their lower courses as their water and sediment loads were diverted into a trapezoidal concrete drainage channel, the Peripheral Canal (Fig. 3), which was constructed between 1925 and 1930. The Peripheral Canal joins the Aliakmon River approximately 40 km upstream of its present-day mouth (Figs. 1 and 3, K). Along with drainage of floodplains, artificial levees were constructed to prevent flooding, thus protecting the newly established agricultural areas. In the case of the Aliakmon River, an artificial levee 38.5 km long and 6 m high was constructed along the left (north) bank of the channel and resulted to the cut-off of the river's meander zone (Fig. 3).

In contrast to the Aliakmon channel length reduction, the addition of the Peripheral Canal basin resulted to a drainage area increase of 2,223 km^2 but of different lithological composition (felsic rocks 4.9%, mafic rocks 12.3%, volcanic rocks 9.6%, carbonates 34.5%, flysch–molasse 8.1%, Neogene and Quaternary sediments 23.7%) most notably marked by the presence of Almopia volcanics.

4.2 *Phase B (1934–1974)*

Following drainage and protection of delta plain from flooding, reclamation of the land and initiation of systematic agriculture, the need for an irrigation network became apparent. Even though small-scale interventions never stopped after the termination of Phase A, it was not until the mid-1950s that the second phase of human impacts was more evident in the area. Hydraulic works included the construction of a diversion dam and water reservoir at the exit of the Aliakmon River gorge (Fig. 3) as well as of an extensive irrigation network (started in 1963 and completed in 1988) along the river's deltaic plain. The irrigation network expands beyond the boundaries of the Aliakmon River Holocene delta spanning an area of 774 km^2, nearly 70% of which is supplied with water from Aliakmon River [21].

In addition to the irrigation network, numerous roads and artificial sea walls along the coastal zone were constructed. The construction of the latter took place due to the continuous subsidence of the drained areas, a result of prodelta fine-grained deposit compaction. Even though Phase B had no direct impact on deltaic sedimentation and water quality, it did raise water demand issues and the need for additional human interventions that affected the evolution of the Aliakmon delta.

4.3 Phase C (1974–Today)

The fact that 95% of Axios River watershed belongs to FYROM and the amount of water reaching Greece and its delta is regulated from the neighbouring country raised the issue of the construction of a succession of hydroelectric dams along the Aliakmon River. The Greek government decided to construct the first of the four reservoirs in Polyfyto (Fig. 1, H). Construction began in 1970 and operation of the hydroelectric power plant (HEP) in 1974. In addition to Polyfyto (reservoir capacity, 1.937×10^6 m^3) HEP, two more HEPs were completed in 1985, the HEPs of Sfikia (Fig. 1, G; reservoir capacity, 103×10^6 m^3) and Asomata (Fig. 1, F; reservoir capacity, 53×10^6 m^3), the three of them covering a total area of 81 km^2 [22]. At present, the fourth HEP of Agios Ilarionas (reservoir capacity, 520×10^6 m^3) has started to operate, while the Greek Ministry of Environment, Energy and Climate Change and the Public Power Corporation are opting to construct additional minor reservoirs for electrical power generation and irrigation needs.

The construction of dams divided the river into two parts: upper Aliakmon (upstream of the dams) and lower Aliakmon (downstream of the dams). Phase C was also characterised by significant increases of fertiliser and pesticide use and urban and industrial activities (fruit and vegetable canning units) along the Peripheral Canal and by sand mining for highway construction, all leading to significant landscape and functionality changes of Aliakmon fluvial system.

5 From a Natural to a Human-Controlled System

The three phases of human impacts on river Aliakmon watershed and delta have had a direct impact on deltaic evolution. Despite the fact that Aliakmon is one of Greece's most important fluvial systems, it is lacking a thorough description of its present-day condition. The man-caused alterations of sedimentary and water regimes associated with these impacts stress for an accurate account of the human impact effects on the delta.

5.1 Effects on Water Regime

Isolation of lower Aliakmon from its headwaters and water regulation caused by damming, together with an increase of population and industrial activities in the vicinity of Peripheral Canal, had a significant impact on the Aliakmon River flow regime and ecological quality. The upper part of the river transports water, sediment and pollutants (domestic effluents and fertilisers) into the Polyfyto reservoir. The estimated annual organic load of the lake is 2,000 tonnes (BOD units), approximately 80% of which is transported by the Aliakmon River [23]. The Sfikia and Asomata reservoirs receive water from the Polyfyto reservoir but are largely unaffected and free of any sources of pollution, as indicated from the application of ecological monitoring (benthic macroinvertebrate abundance, BMWP taxa and values of biotic scores) at downstream locations from the Asomata reservoir [24].

The lower part of the Aliakmon River, below the reservoir of Asomata, flows through its Holocene channel belt bounded by an artificial levee along its left bank (Sect. 4.1). Released water discharge is considerably lower than natural, as indicated by the comparison of modelled and released discharge data at the Asomata reservoir between 1986 and 1999 (Fig. 4a), together with a shift of the high discharge period from spring to summer (Fig. 4b). On a daily basis, the Aliakmon River flow had been largely controlled by the operational needs of Asomata HEP and irrigation needs, hydrologically expressed as daily freshwater pulses [6]. This phenomenon ceased in 2008 with the construction of an additional reservoir downstream of Asomata HEP, which regulates a steady flow for the Aliakmon River with minimal discharge of 4.5 m^3/s (Aliakmon River Hydro Group – PPC, personal communication).

Aliakmon River water geochemical composition close to its present-day mouth [25] differs from the river's upper part (Sect. 3.3). Calcium concentrations are higher by a factor of 2 (Ca^{2+} 66 mg/l), an increase explained by the fact that the watershed between the Polyfyto and Asomata reservoirs is composed of carbonate rocks. Magnesium concentrations are similar to the upper part (Mg^{2+} 29 mg/l), while increased chloride concentrations result from polluted water (urban sewage) transferred to the lower Aliakmon River through the Polyfyto reservoir (Cl^- 34 mg/l at the exit of Asomata reservoir) and Peripheral Canal (Cl^- 40 mg/l close to the river mouth). As a result, electrical conductivity of the Aliakmon River surface water along its lower course exceeds the EU-suggested levels (250 mS) for drinking water (EU Council Directive for Drinking Water 80/778/EC).

The intersection of Aliakmon River with Peripheral Canal (Figs. 1 and 3, K) comprises a significant point of water quality degradation. Water of 'poor' quality from Peripheral Canal [24], which receives substantial loads of effluents and other compounds from urban (sewage and detergents), agricultural (fertilisers and pesticides) and industrial (fruit and vegetable cannery) sources, is transported to the

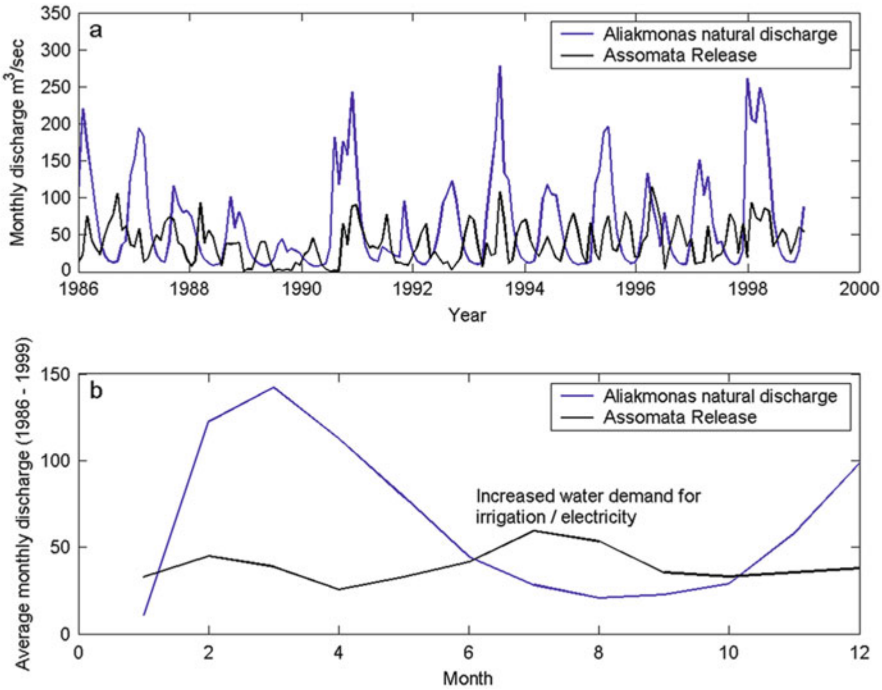

Fig. 4 The effects of human impact on the Aliakmon River hydrological cycle. (**a**) Reduced discharge at the river's exit to the delta plain (Asomata HEP). (**b**) Temporal displacement of the river's high discharge period, a result of irrigation and electricity demand

Aliakmon River. During low-flow season (September 1995), the Peripheral Canal nutrient (NO_2-N, NO_3-N and PO_4-N) concentrations exceeded EU levels. A strong seasonal signal of the Aliakmon River water quality deterioration close to its mouth is evident during summer and autumn months, associated with the intensification of agricultural and industrial activities as well as the abstraction of water for irrigation [24].

In the absence of a monitoring network, nutrient long-term trends, as derived from sparse data mainly referring to the autumn (low discharge) season, indicate a remarkable increase in total nitrates and phosphates and a subsequent degradation of the river's water quality through time. During Phase B (1969), a sampling field campaign highlighted the 'excellent' quality of Aliakmon and Axios Rivers' surface waters [1]. Seventeen years later (1985), the Aristotle University of Thessaloniki (Civil Engineering Department) conducted a study concerning the 'Water Quality of Thermaikos Bay' and pointed out potential eutrophication issues for Aliakmon River surface waters as total nitrate concentrations were considerably high (Table 1). Twenty years later, the sampling during 2005 indicated total nitrate and phosphorus concentrations to be considerably higher [25] than the previous decade.

Table 1 Long-term nutrient concentrations (mg/l) at the Aliakmon River delta

Date	NO_2-N	NO_3-N	PO_4-P
October 1985[a]	0.02	6.18	0.30
October 2005[b]	0.006	7.92	1.82

[a]After AUTH, Civil Engineering Department (1987)
[b]After Ilias et al. [25]

Increase in nitrate results from agricultural runoff and waste waters, as 1985 and 2005 values exceed EU values (NO_3-N 5.6 mg/l) for drinking water (EU Council Directive for Drinking Water 80/778/EC). Phosphorus was 6–12 times higher than previous (1985, 1995) measurements, an increase probably attributed to fertilisers, increase of industrial units along the Peripheral Canal and increase of population as urban (household) pollution contributes large amounts of phosphorous into surface water bodies.

Periods of high agricultural and industrial activity (summer–autumn) coincide with periods of low discharge and are characterised by very low water quality [24, 25] with immediate impacts on delta flora (degradation of riparian vegetation) and fauna (reduction of aquatic life habitats). As a consequence, the human-controlled lower threshold of 4.5 m^3/s appears inadequate to maintain the river's purification capacity, so locations close to the river mouth exceed EU levels for conductivity, nitrates and phosphates. Poor environmental quality at the Aliakmon River mouth is expected to have an immediate impact on local fishery and mussel farming units when 80% of Greece's mussel production units are located off the mouths of the Axios and Aliakmon Rivers. Moreover, according to the Aliakmon Hydropower Group, the four major HEPs on the Aliakmon River upper course account for an average of 4% of the total generated electric power in Greece, while their reservoirs have a total capacity of 1.937×10^9 m^3, the equivalent of the river's annual natural discharge.

The main concern for the Aliakmon River delta rises from the ever-increasing demand for water consumption. The Aliakmon River is the main water contributor for the city of Thessaloniki with average annual water volume of 88.3×10^6 m^3. Annual irrigation needs of more than 750 km^2 of land across the plain of Thessaloniki–Giannitsa require 520×10^6 m^3 of water. The Polyfyto reservoir contributes annually 35×10^6 m^3 to irrigation needs in locations upstream of the reservoir, yet another 65×10^6 m^3 is used for cooling four thermoelectric power plants located in close proximity to the reservoir. In addition, the Aliakmon River lower part contributes water for industrial needs with 32×10^6 m^3 annually, while 14×10^6 m^3 is the river's minimal annual discharge, less than 2% of the volume consumed for all other (irrigation, industrial, drinking, etc.) needs combined. In the near future, the Aliakmon River is planned to cover the irrigation needs of its right bank (south) agricultural area (340 km^2), to provide water to the Pella irrigation network (50 km^2), while the annual water transfer to the city of Thessaloniki calls for a rise up to 220×10^6 m^3.

Despite sparse sampling and non-existing monitoring that prohibit quantitative conclusions to be drawn, the evidence presented here undoubtedly shows that Phase C has caused a significant deterioration of the Aliakmon River delta surface water quality and a considerable reduction of water discharge.

5.2 *Effects on Sedimentary Regime*

The primary impact of damming on deltaic regions is the reduction of sediment load to the river mouth and coastline erosion. During Phases A, B and C, the Aliakmon River delta underwent major hydrological (Sect. 5.1) and sedimentological changes. Phase A resulted in the reduction of channel length by 20 km. The addition of the Peripheral Canal basin, together with channel straightening and the construction of artificial levee, increased sediment transport to the delta. The Peripheral Canal natural sedimentation rates are estimated between 2.32 and 3.14 $\times$ 10^6 t/y [10], while additional in-channel load due to increased sediment transport capacity of the straightened (higher flow velocities) and steeper (higher hydraulic gradient) channel is expected to have reached the Aliakmon River mouth during Phases A and B. As a consequence, delta progradation proceeded with faster (60 m/y for channel levees) than normal rates [26] and led to the development of a new bird-foot delta (Fig. 5a, b). Average annual

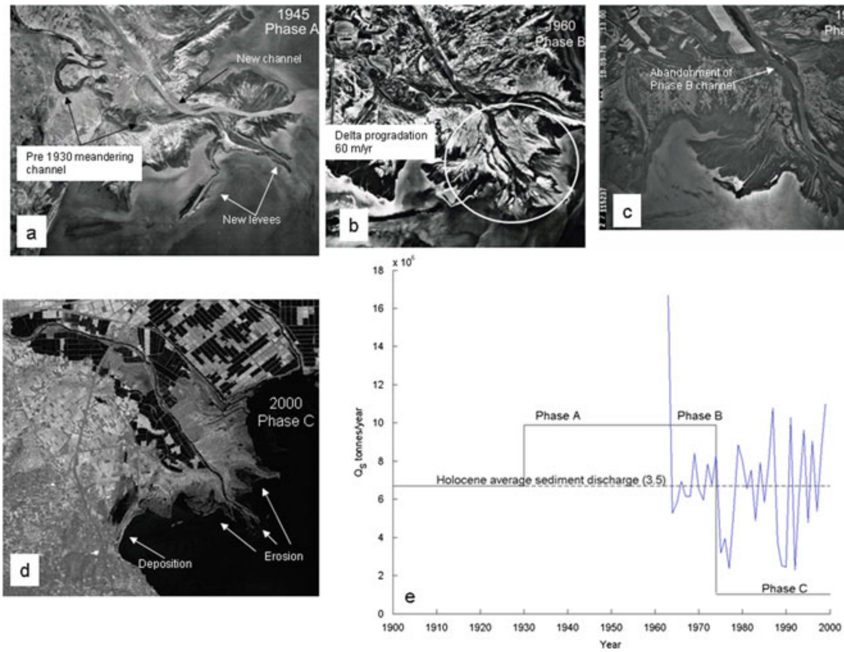

Fig. 5 General review of human-induced changes on Aliakmon River Holocene delta's morphology and sedimentary regime during Phases A, B and C. (**a**) 1945 aerial photo. (**b**) 1960 aerial photo. (**c**) 1979 aerial photo. (**d**) 2000 LANDSAT satellite image. (**e**) Natural (*blue line*) versus human-induced (*black line*) average sediment discharge values at Aliakmon River mouth

sediment discharge at the mouth of the Aliakmon River, between 1916 and 1956 (Phases A and B), has been estimated [16] at 9.9 × 10^6 t/y (Fig. 5e), a value in agreement with the sum of estimated natural rates of the Aliakmon River (Sect. 3.5) and Peripheral Canal.

Furthermore, the Peripheral Canal drainage basin contribution has altered the mineral composition of deltaic deposits with an observed enrichment in heavy minerals. Measured values at the river mouth indicate high concentrations of Mn, Ni, Co and Cr [27], most likely derived from the weathering of lateritic deposits within the Peripheral Canal basin (northeastern Vermion) [28]. In contrast, mineral compositions of deltaic deposits from sediment cores provided no evidence of heavy mineral transport from the upper Aliakmon River (3.5). Deltaic sediments are characterised by low concentrations of Cu, Pb and Zn [7], a phenomenon linked to the lack of heavy industrial activities along its lower course.

Damming during Phase C caused a 90% reduction of deltaic sedimentation (estimated load 1.03 × 10^6 t/y), compared to Phase B. More recent (1995–2000) estimates of sediment discharge of the Aliakmon River mouth suggest even lower values of 0.1 × 10^6 t/y [29]. Consequently, human-induced changes on the sedimentary regime had an immediate impact on the shoreline evolution of the Aliakmon delta, with erosion of the northern part and subsequent siltation of the Methoni Bay (Fig. 5d).

In addition to human-induced alterations of the Aliakmon River sediment transport regime, Phase C caused a pronounced change of channel and deltaic sediment grain-size distributions. Enrichment of deltaic deposits with finer sediments resulted from the reduction of coarse (fine gravel and sand) sediment availability and transport capacity (low discharge).

6 Conclusions

The natural evolution of the Aliakmon River delta has been affected by human activities since the Palaeolithic. During the past 90 years, there has been an intensification of anthropogenic pressures on the river's watershed and delta along three major phases. The former Phases A (1925–1934) and B (1934–1974) of human impacts included a series of hydraulic works that aimed at flood interception, the drainage of swamps and low-lying areas and the construction of an extensive irrigation network. These works were necessary, initially for the hygiene of the newly located immigrant populations and, to a further extent, for the economic development of the area through initiation of systematic agriculture. During these phases, the Aliakmon River delta experienced a 50% sediment transport increase in relation to Holocene pre-anthropogenic rates, an enrichment of deltaic deposits with heavy minerals and higher than normal delta progradation rates. Water quality during this period was 'excellent' as population along the entire watershed was significantly lower, agriculture was confined in smaller than present areas along the delta and the area was lacking industrial units; a few units contributed to limited sources of surface water pollution.

Phase C marked the beginning of a heavily impacted period for the Aliakmon River delta. Damming along the rivers' upper course, population growth along its lower part, use of fertilisers and pesticides for agricultural activities and establishment of food and fruit cannery industrial units, coupled with the ever-increasing demand for electrical power and water, have resulted in a human-controlled system characterised by intense environmental pressures.

More specifically, during Phase C, the Aliakmon River delta experienced a reduction of water discharge towards the river mouth, an alteration of its hydrological regime, a deterioration of its water quality characteristics and a 90% reduction of sediment transport rates compared to Phase B. Reduced water discharge and the interception of sediment transport from the river's upper reaches have resulted to enrichment of river channel and delta front deposits with finer sediments. Fine sediments trap pollutants, enhancing river and seabed pollution, and are easily eroded by waves and longshore currents. As a result, the Aliakmon River delta is currently undergoing erosion and the shoreline is retreating (Fig. 5d). Immobilised material from the Aliakmon River mouth and delta through the prevailing cyclonic circulation is deposited in the Methoni Bay and other locations south of the river mouth, enhancing siltation and degradation of proximal to delta beaches, on which major touristic units have developed during Phase C. Also, the ever-increasing need for water, for urban, industrial and agricultural use, along with increasing pollutants and decreased water discharge in the vicinity of the Aliakmon River, has left very little space for proper regulation of the ecological quality of lower Aliakmon and the deltaic region. Water abstraction poses as a major threat to coastal aquifers, through salinisation.

The future evolution of the entire Aliakmon River fluvial system is not restricted to its lower course and delta but is of great importance to the broader region of Northern Greece. More than two million people directly involved on primary and secondary production and touristic sectors depend in many ways on the Aliakmon River water and sediment resources. Various scenarios of future climate change have demonstrated the vulnerability of the Aliakmon River human-controlled system to even minor hydrological changes. Currently, as Greece is making significant efforts to overcome the ongoing economic crisis, there appears a unique chance for the country to look back to its own natural resources in a financially realistic and environmentally sustainable way. By taking into account the findings of this review, the call for a new realistic strategic plan concerning the future evolution of the Aliakmon River delta, based on a long-term monitoring study, should be put into effect to prevent the continuous degradation of this fragile and otherwise protected (RAMSAR, NATURA 2000) area and to open a new chapter in the economy of Northern Greece.

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