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The role of sediments in the dynamics and preservation of the aquatic forest in the Nestos Delta (northern Greece)

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Abstract The River Nestos empties into the Aegean Sea creating its delta. An aquatic forest of exceptional natural beauty has developed on this delta, which is considered to be the largest in the Balkans. Today, this forest is endangered due to various reasons. However, the most recent and important one is a major decrease in the sediment quantity that discharges into the territory of both the delta and the forest, because of the construction of two large hydropower dams. The purpose of this paper is to investigate the sediment dynamics in the bed and delta of the River Nestos, before and after the construction of the dams, respectively. The research was carried out using satellite imagery and GIS modelling, demonstrating that declining water supply and sediment fluxes led to significant changes in the area (>200 ha) and shape of the delta, causing functional impairment and serious degradation of the aquatic forest.

Key words aquatic forest; delta; GIS model; satellite image; sediment dynamics

INTRODUCTION

Aquatic forests are highly dynamic ecosystems with great biodiversity, which means that they are rich in terms of flora, fauna and types of habitat, despite the fact that they are situated on “poor”, mainly sandy, soils. This extensive biological activity means aquatic forests share many similarities with tropical forests (Efthimiou, 2000). According to Dafis (1992), a characteristic feature of these forests is that they are considered to be stable ecosystems for as long as they remain unaffected by any human activity or intervention. However, should such an external disturbance occur, these ecosystems can collapse causing degradation to a state that may be irreversible. Furthermore, this will not occur in non-aquatic forests, which are naturally re-born after being repeatedly destroyed by fires, for instance. Aquatic forests are usually located on river deltas and on flood plains and occasionally on the shores of lakes.

The main factors causing degradation of these forests are either the upstream construction of hydropower and irrigation dams resulting in a significant reduction of river flow, or the excessive pumping of the groundwater aquifers of the deltas where these forests are situated (Szijj, 1997). In such cases degradation, or even their final devastation, stems from both the decrease in discharge and reduction in sediment load. Loss of water, sediment and sediment-associated nutrients, the reduced size of large floods and reduced exchanges of genetic material between the different species in the aquatic forests, all serve to compromise key functions of these forests and can lead to a change in species composition (Efthimiou, 2000). Over time, pristine aquatic forests can be reduced to a small number of trees arranged along the riverside, which are internationally characterized as gallery forests (Tsiouris, 1999).

The purpose of the present study is to investigate the condition and dynamic evolution of the aquatic forest on the River Nestos delta (the largest natural aquatic forest in the Balkan Peninsula), which is threatened because of the construction of two large hydropower dams upstream. The decreased discharge led to the dramatic degradation and decline of the forest, which had already been restricted to one third of its original area during the period 1922–1980. The study of the variation of the aquifers and of the sediment transport is achieved by analysing and comparing satellite images and by using stochastic models and piezometric maps.

STUDY AREA

The study area is the River Nestos delta. This river, whose sources are found on the Mount Rila in central Bulgaria, has a total basin area of 5752 km^2, 60% in Bulgaria and 40% in Greece. The formation of the Nestos Delta took place during the late Holocene. It occupies an area of 551 km^2, has a coastline of 29 km^2 and forms the natural coastline between Macedonia and Thrace (Fig. 1). The most significant ecosystem of the delta is the aquatic forest, which reached its maximum extent between 1900 and 1910 but is presently confined to one-twentieth of its original area.

The forest occupied an area of 127 km^2 in 1922, and an area of 72 km^2 in 1946, while only 27 km^2 were left in 1953. This reduction was due to the deforestation that took place in order to yield either small holdings for farmers or poplar tree cultivations. After its declaration as a protected area according to the Ramsar Convention, it was fenced and preserved in a fairly good ecophysiological status. However, in the summer of 1998, the opening up of the PPC (Public Power Corporation) dams caused the situation to deteriorate by threatening and thus putting in danger, the survival of the forest (Fig. 2).

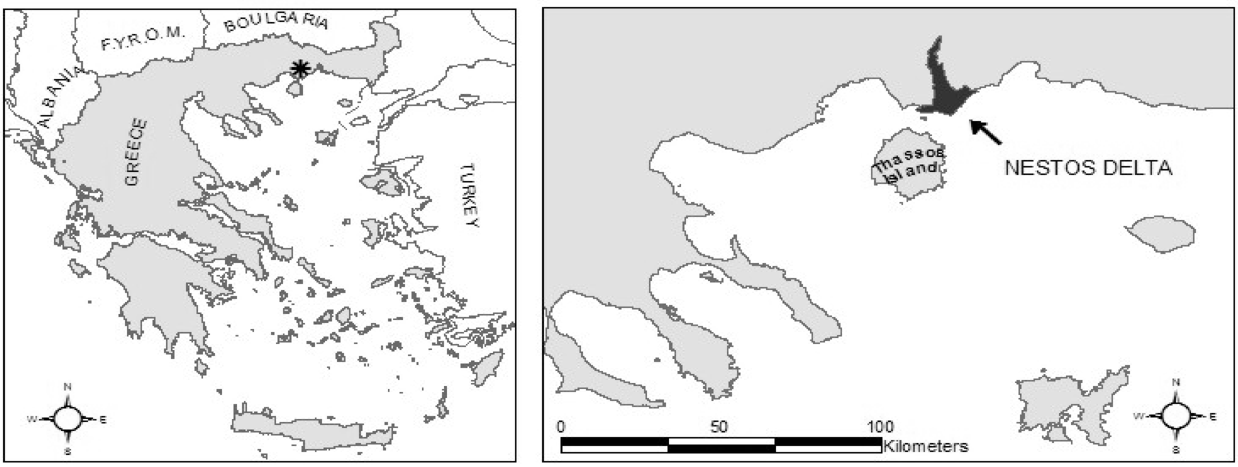

Fig. 1 Location map of study area.

Fig. 2 Comparative images of the aquatic forest before and after the construction of the PPC dams.

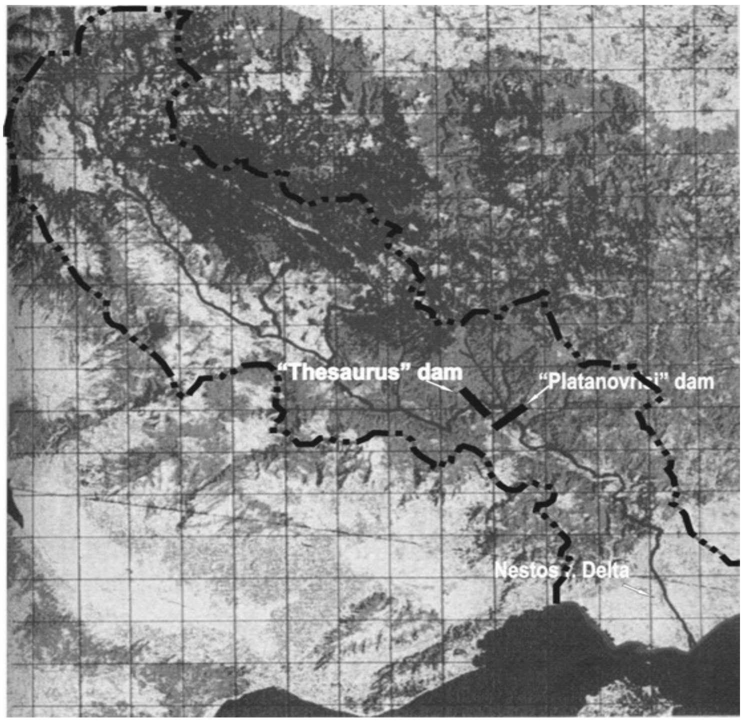

Fig. 3 Drainage basin of the River Nestos and the location of the two dams.

HYDROPOWER DAMS

The two hydropower dams constructed on the flow of the River Nestos are shown in Fig. 3. The upper dam at Thesaurus is at an altitude of 175 m, has a total reservoir volume of 705×10^6 m^3 and a surface area of 22.5 km^2. The lower Platanovrisis dam located 12 km downstream of Thesaurus at 95 m altitude, has a total reservoir volume of 84×10^6 m^3 and a reservoir area of 3.3 km^2. The construction of these two dams lasted from 1990 till 1998, while the preparation works (deforestation, woodcutting, land reclamation, scraping of gradients, excavations, opening up of diversion tunnels) preceded this during the period 1985–1990 (Fig. 4).

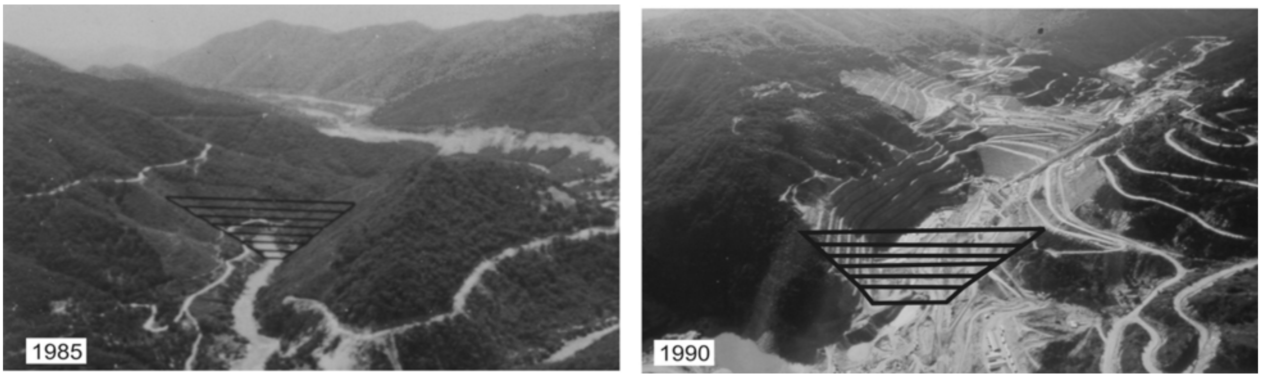

Fig. 4 Illustration of the Thesaurus dam site prior to (1985), and during (1990) construction of the dam.

METHODS AND RESULTS

The research assessed variations in sedimentation rates across the delta area before and after the construction of the dams. The status of the aquifers was also assessed from flow gauging stations and boreholes located in the channel bed. It was considered important to assess the sediment flux to validate the flux data reported by the PPC (1985) using a stochastic model, and also to explore the following hypotheses and questions by analysing satellite images:

(a) Was the inferred decrease of the sediment load in the delta region accompanied by an alteration of the delta area?
(b) Was there a change in the subsurface deposits and in which degree?
(c) Was there a modification of not only the area but also of the shape of the delta and in what way?
(d) What, if any, land cover changes have taken place in the coastal zone?

In the case that an affirmative answer is given to all of the above questions, it means that significant changes are manifesting even within a relatively small period of seven years. It may be anticipated that such changes will impact the balance of the aquatic forest and may provoke its final collapse.

Stochastic model data

Emmanouloudis & Filippidis (1999) used a GIS enabled 3D-version model (Gavrilovic, 1972) to verify the sediment load values that had been reported in the research of the PPC (1985). This stochastic model, combined with a GIS framework for data processing, was used to assess the evolution of steep torrent basins based on changing input data. The model was run on a randomly selected sub-basin 2 km upstream of the Platanovrisis Dam. According to Gavrilovic (1972), the equation providing the average annual degradation in a basin is: $W = Th\pi\sqrt{z^3}\,F$, where T is a coefficient of temperature given by $T = \sqrt{(to/10) + 0.1}$ with *to* being the average annual rainfall (mm); $\pi = 3.14$; F is basin area (km^2), z is the coefficient of erosion given by the ratio:

$z = xy(\varphi + J)$ with x, y and φ being the partial coefficients that depend on the vegetation, the geological base and the degree of erosion of the basin, respectively, whereas J is the average slope of the basin area expressed as the tangent of the slope.

The total annual suspended load in the small research basin was estimated to be w = 1699.2 m^3 km^{-2} $year^{-1}$. This corresponds to moderate degradation of the basin, where d = 0.7 mm. This result is very close to the average degradation value for the total Nestos basin that is reported in the PPC study and which is equal to d = 0.67 mm. This result suggests that the catchment yield estimation of the PPC study is valid. According to Kotoulas (1985), 65% of the transported load usually deposits in the delta regions of the rivers in northern Greece, whereas the rest is deposited in the form of intrabasin deposits. The sediment delivered to the delta region prior to the construction of the two dams was thus estimated at 2.5 Mm^3 $year^{-1}$.

According to Kotoulas (1988), in those cases where artificial reservoirs having a capacity over a 500 Mm^3 and a reservoir area that exceeds the 20 km^2, are built, then nearly 5/6ths of the transported suspended load is detained by the reservoir, while the remaining 1/6th is transported downstream. Finally, taking into consideration that the distance between the two dams and the beginning of the delta is approximately 50 km, it becomes apparent that not even the above-mentioned quantity makes it down to the delta region, but a far lesser quantity, which is nearly equal to 400 000 m^3 (Kotoulas, 1985).

Remote sensing data

The geographic characteristics of the study area were extracted through high-resolution remote sensing data obtained from Digital Globe. An area of 27 km^2 was captured from the Quick Bird imaging system during December 2003. Digital Globe provided a multispectral image product and the data were delivered in 16-bit format at a spatial resolution of approximately 0.6 m over four bands: blue, red, green and near infrared. The imagery was geometrically and spectrally corrected in the laboratory, and an orthorectification process was applied in order to provide the highest degree of geometric accuracy. The 1998 image was a Landsat image taken in November 1998, just two months after the commissioning of the dams. Figure 5 illustrates the changes in the land use of the delta region during the period 1998–2005, obtained by comparison of the two satellite images and summarized in Table 1.

Water discharge data

During the period 1965–1985, and according to the PPC assessments, the mean annual discharge was 1363 Mm^3 s^{-1} at the Platanovrisis Dam site. The compensation flow was established at 180 Mm^3. Thus, the flow reaching the Nestos Delta is eight times less than that of the pre-dam period. Comparative piezometric maps of the delta region (Fig. 6) confirm that the water table dropped by about 11 m in the delta region during the period 1988–2005. This decline is due to the decrease in the water discharge and to the increased number of drillings in the delta region especially during the last decade.

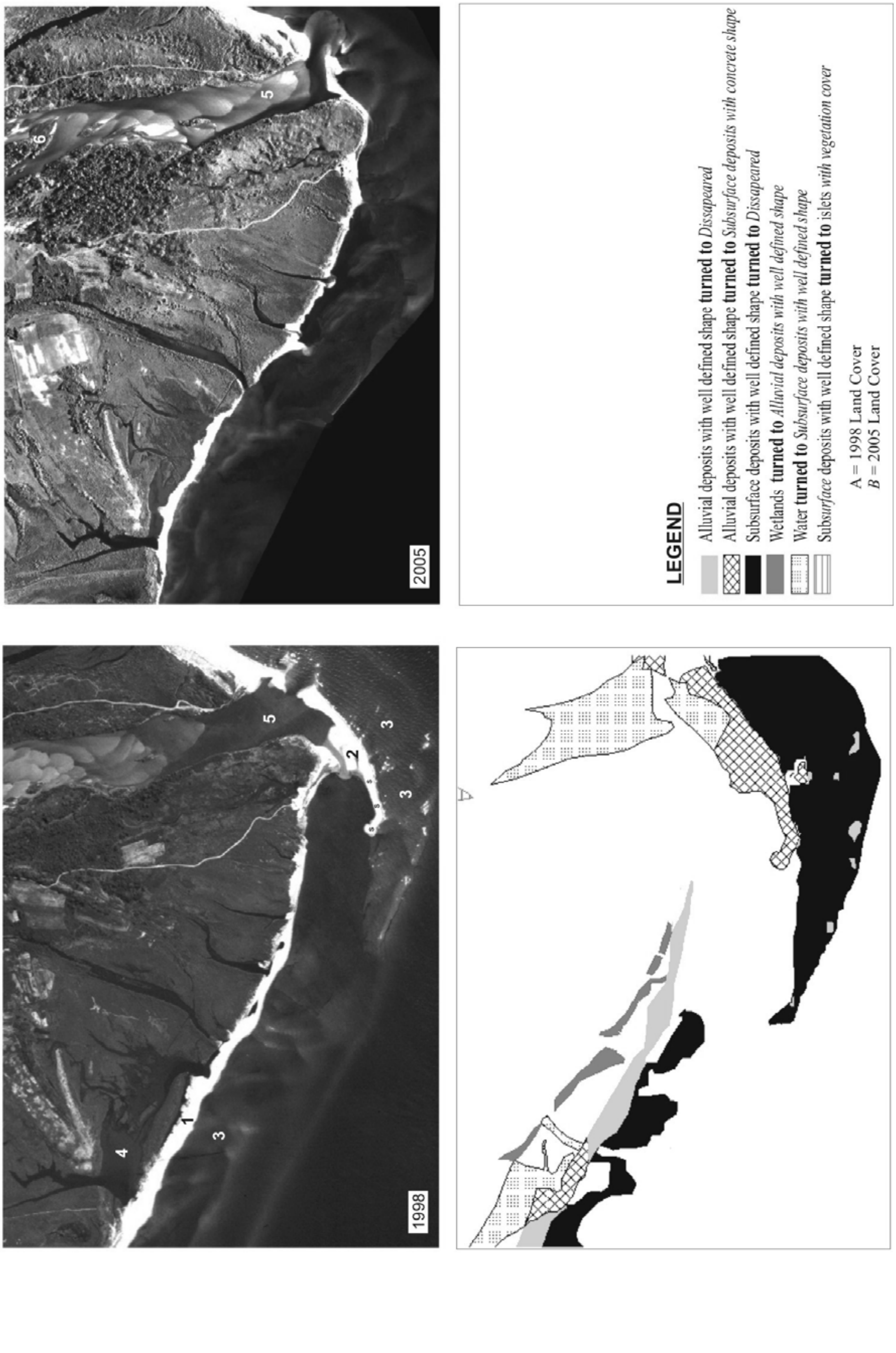

Fig. 5 Comparison of the two satellite images and the relative map.

Table 1 Changes in land use of the delta region during the period 1998–2005.

Land cover (1998)	Land cover (2005)	Area (ha)	Area (%)
Water	Subsurface deposits with well-defined shape	9.80	4.71
Alluvial deposits with well-defined shape	Disappeared	11.82	5.68
Alluvial deposits with well-defined shape	Subsurface deposits with well-defined shape	12.63	6.07
Wetlands	Alluvial deposits with well-defined shape	15.18	7.30
Subsurface deposits with well-defined shape	Disappeared	148.93	71.60
Subsurface deposits with well-defined shape	Islets with vegetation cover	9.65	4.64
Total		208	100

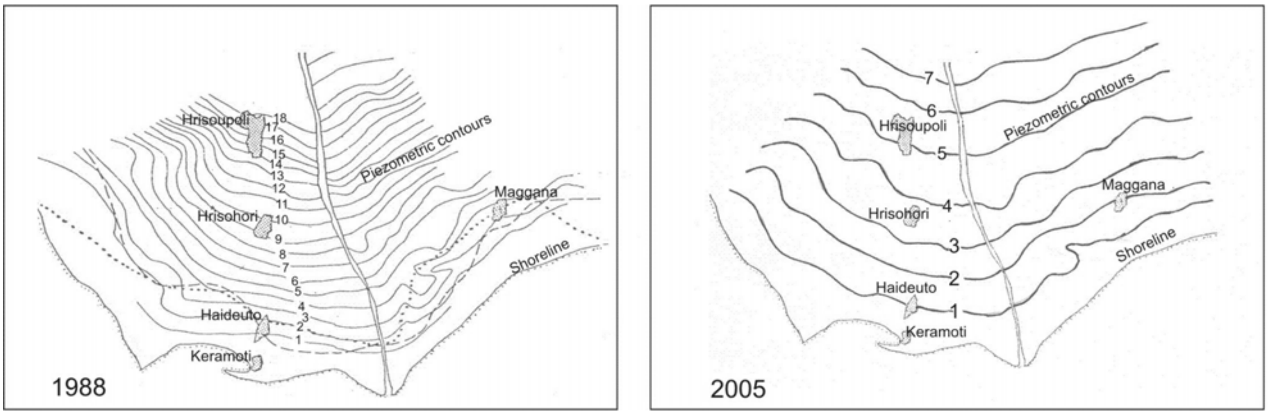

Fig. 6 Piezometric maps of the delta region.

DISCUSSION AND CONCLUSIONS

The analysis undertaken suggests that construction of the dams has reduced the sediment flux to 1/6th of the pre-dam period and reduced the water discharge by a factor of 8. As mentioned, these assessments are approximate and cannot securely lead to scenarios concerning the evolution and modification of the delta. As a result of this, we analysed the satellite images to examine for changes to the delta shape and area, and to both the surface and subsurface levels, during the period 1998–2005, and so to answer all four questions raised in the introduction.

The following categories of change were identified:

1. First 11.8 ha of surface alluvial deposits visible in the 1998 image, were not observed in the 2005 image.
2. An estimated 12.6 ha of surface alluvial deposits with distinct limits in the 1998 image, have altered to subsurface alluvium in the 2005 image.
3. The third category comprises an area of 148.9 ha of clearly recognizable subsurface deposits in the 1998 image, but which have vague limits in the 2005 image.
4. The fourth category includes an area of 15.18 ha, containing regions covered by

wetlands in 1998, which have become alluvial deposits with distinct boundaries in 2005.

5. The fifth category comprises an area of 9.80 ha of a region of the Nestos channel at the point where the river discharges into the sea. In the 1998 image, the shaded surfaces of this category were covered by water but in the 2005 image, the formally subsurface deposits have been exposed (Fig. 5).
6. Finally, the sixth category includes an area of 9.65 ha of subsurface deposits of Nestos channel sediment all around the delta body in the 1998 image, which have transformed to islets with vegetation cover in the 2005 image.

It was concluded that, following the commissioning of the dams, there has been a striking reduction of sediment delivery to the delta leading to the gradual fragmentation of the surface sediments (category 1) as a result of the continuous action of the waves that sweep the region (Emmanouloudis, 2000). This fragmentation is especially intense on the west half of the delta apex, where the wave action also appears to be impacting on the thickness of the deltaic sediments. Moreover, it seems to be localized only on the surface sediments and not on the subsurface deposits which remain visible to fairly visible in the greater part of their area (categories 2 and 3). It should be noted that, due to the great difference in the temperature between the cold water of the Nestos River and the shallow, warm seawater at the discharging point, there is rapid sinking of the sediments in the sea area. This also explains why the appearance and spreading of the subsurface deposits is so intense in this delta.

The shrinkage and movement of the delta towards its interior in the way described, and the simultaneous decrease in the aquifers, have caused the alteration mentioned in category 4, where areas covered by wetlands in 1998, ceased to be covered by water in 2005. This alteration, i.e. the gradual disappearance of the wetlands due to shrinkage of the delta, and the simultaneous decrease in the aquifers, is a rather frequent phenomenon in deltas that are both exposed to the direct effect of sea waves and are adjacent to cultivated areas (Pethick, 1984; Clark, 1995). Finally, the variations observed in categories 5 and 6 are due to the noticeable fall of the river level, as a consequence of its reduced supply. On the one hand, this leads to the more conspicuous distinction of the subsurface deposits as it is shown in the 2005 image (category 5), compared to the 1998 image (especially at the discharging point), and on the other hand, to the appearance of islets with vegetation cover in the region upstream of the discharging point (2005 image, category 6). Surface and subsurface deposits having vague limits appear in the place of the newly revealed islets in the 1998 image.

As a conclusion to the above, it has been established that in a period of only seven years, significant modifications have taken place in the extent and the shape of the Nestos Delta. Sediments covering an area of nearly 25 ha were fragmented, while other sediments covering an area of nearly 150 ha were fragmented on their surface part. In other words, all of the four questions, identified initially, have an affirmative answer.

When an entire delta experiences a reduction in water discharge and sediment load, it is logical to expect an ecosystem, such as this aquatic forest, to experience a shock, which will probably lead to its decline and collapse as was witnessed in the aquatic forest of the Appolonia River Delta (Emmanouloudis & Tsoukas, 2004). The solution to saving not only this but any aquatic forest in danger is simple and it is accompanied by simple water and environmental management measures.

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