ECOHYDROLOGY & HYDROBIOLOGY

DOI: 10.2478/v10104-012-0010-6

Vol. 12
No. 2, 123-135
2012

Synthetic information

Restoration of a seashore eroded due to dam operation through beach nourishment

Georgios K. Sylaios*, Sotiria Anastasiou, Vassilios A. Tsihrintzis

Laboratory of Ecological Engineering and Technology, Department of Environmental Engineering, School of Engineeering Democritus University of Thrace;
* Corresponding author: Vas. Sofias 12, 67100 Xanthi, Greece, Tel: +30-25410-79398, e-mail: gsylaios@env.duth.gr

Abstract

Nestos River damming disrupted significantly the sedimentary equilibrium of Keramoti shoreline, intensifying the coastal erosion problem in the area. Coastal erosion, assessed through Landsat images, showed a net sediment deficit of 0.94 km^2 of land loss along this beach. An integrated study was undertaken aiming to detect submarine relict sand deposits available for beach nourishment, to estimate the total excavated and dry sediment volumes, to assess the post-nourishment longshore sand transport and to evaluate the related environmental implications. Results showed that available sediment volume extracted from the sandbank may range from 5×10^6 to 4.3×10^7 m^3, increasing beach width from 52 to 450 m, respectively. Post-nourishment longshore sediment transport volumes could reach 1.34×10^6 m^3 yr^{-1} at the exposed eastern part of the beach, diminishing rapidly to 2.91×10^5 m^3 yr^{-1} at its sheltered part, implying that beach restoration could last up to 33 years before sand is completely lost.

Key words: river damming environmental impacts, coastal erosion, beach nourishment, side scan sonar, North Aegean Sea.

1. Introduction

As water and energy are indispensable for human sustenance, their demand on global scale is expected to exponentially increase in the future, in accordance to population growth, food production needs and improved living standards (IEA 2006). At the global scale, the impoundment and abstraction of freshwater in river systems for the purposes of power generation and agricultural irrigation has provided huge economic benefits over the last 50 years (Millennium Ecosystem Assessment 2005). Worldwide, over 45 000 dams have been built in over 150 countries, and nearly half of the world's rivers are obstructed by large dams (World Commission on Dams 2000). Presently, dams generate almost 19% of the world's electricity supply and irrigate over 30% of the 271 million hectares irrigated worldwide (Bergkamp *et al.* 2000). At the global scale, river damming increases the average residence time of river waters by a factor of 3, i.e., from 16 days to 47 days (Covich 1993), augmenting the "standing stock" of free flowing river water by 700% (Vörösmarty *et al.* 1997).

Even though large dams seem to offer tremendous economic benefits, their environmental and social costs have been poorly accounted for, so that the wider long-term profitability of these structures remains elusive (World Commission on Dams 2000). On the one hand, the construction of large dams reduces the threat of devastation from extreme floods. However, on the other hand, large dams change watershed hydrology and impact the biosphere, creating a completely different hydrologic, sediment and ecologic regime with more severe alterations at the downstream part of the watershed, affecting the main river channel and delta, and the broader coastal zone and coastal ecosystem (Postel, Richter 2003; Ligon *et al.* 1995; Poff, Hart 2002; Grant *et al.* 2003).

One of the major environmental implications at the downstream part of the watershed, associated with river damming, is the reduction of sediment loads at the deltaic and coastal zone areas, resulting in the alteration of coastal sedimentary budget and the occurrence of coastal erosion (Graf 2006; Kummu, Varis 2007; Walling 2008). Thus, beach stabilization measures are necessary in several erosion-prone areas.

Beach stabilization measures can be divided into two broad categories: rigid and non-rigid (U.S. Army Corps of Engineers 1984), with the former involving the emplacement of seawalls, breakwaters, jetties and groins, and the latter beach nourishment and dune restoration actions (Leatherman 1996). Beach nourishment has recently become a more popular solution to beach erosion problems, mostly because this approach has the lesser environmental impact on the overall ecology and aesthetics of the area, compared to the others. Beach nourishment is defined as 'the process of mechanically or hydraulically placing sand directly on an eroding shore to restore it, and subsequently maintain, an adequate protective or desired recreational beach' (U.S. Army Corps of Engineers 1984). Beach nourishment gives rise to smaller changes in the dynamics of both sediment and water, thus, a natural equilibrium may be sooner and easier reached, staying in effect for a longer time (Peterson *et al.* 2000). The soft interface of the sandy beach is preserved for recreational uses, while storm protection can be gained provided that adequate sand quantities are available. Possible problems involve the higher costs derived by the need for replenishment every few years, together with the dredging and placement of sand procedures.

Almost 15 years after the construction and operation of the two large hydropower dams (Thissavros and Platanovrisi, located 70 km upstream of river mouth), and approximately 50 years after the operation of the irrigation dam and system at Toxotes (located 25 km upstream of river mouth), the environmental consequences at the deltaic and coastal area of Nestos River (Northern Greece) are evident. The application of specific eco-hydrologic concepts in the coastal area is presented here, which aims to mitigate the imposed environmental effects.

These impacts are particularly important for the valued ecological resources of the area, as Nestos River Delta and its adjacent wetlands system is included in the Ramsar Convention as an internationally important wetland complex (Gerakis, Kalburtji 1998). Nestos River Delta hosts a great variety of priority habitats and species, some of which are the most important in the Mediterranean zone, as the *Poseidonia oceanica* beds at the coastal zone, coastal lagoons and salt marshes with *Salicornia europea* and *Sarcocornetea fruticosa*, the Mediterranean salt meadows *Juncetalia maritimae* and *Limonietalia* and finally the coastal white dunes with *Ammophila arenaria* (Gerakis 1992). Moreover, erosion impact on lagoon barrier spits has occasionally led to seaside over-wash and breaching, especially due to southern storm waves, increasing the salinity of the system and disrupting its natural ecological functioning (Xeidakis *et al.* 2010a).

To mitigate the erosion effects, a beach nourishment study for Keramoti shoreline was undertaken aiming to identify areas of offshore relict sand deposits of adequate volume, and determine the potential beach nourishment length that could be reached for various dredging levels. Relict sands are non-diagenized sedimentary deposits mostly located along the continental shelf at variable depths (Nonnis *et al.* 2011). Their basic characteristic is that they contain most probably large amounts of sediments that are similar, in terms of grain size and geotechnical characteristics, to the current beach sediments. The use of relict sand deposits in beach nourishment projects could be economically advantageous, especially when large sediment volumes are being used. The removal of these sediments, especially when occurring at high depths, does not interfere with coastal dynamics and the associated wave and currents regime (La Porta *et al.* 2009). However, relict sand dredging may have significant physical and biological effects on the marine environment, disturbing macro-zoobenthic assemblages and increasing local turbidity, thus affecting adversely the sensitive Mediterranean habitats (Simonini *et al.* 2007).

The present paper presents the methodology followed a) to explore relict sand deposits offshore of Keramoti shoreline (Nestos River Delta), b) to assess beach fill volumes in relation to relict sand deposit dredging depth, c) to estimate the post-nourishment beach morphometric change, in terms of beach widening and profile analysis, and d) to address the environmental and ecological effects related to relict sand dredging. It is the first time that a similar work has been undertaken in Greece.

2. Materials and methods

2.1. Study site description

Nestos/Mesta River is one of the 71 internationally shared river catchments of Europe draining an area of 5479 km^2, of which 2768 km^2 (or 49.34% of the total basin) belong to Bulgaria, while 2843 km^2 (or 50.66% of the total basin) is located in Greece (Ganoulis *et al.* 2008). In the early 1990s, two large hydropower dams (Thyssavros and Platanovrisi) were constructed in the Greek part of Nestos river course (170 m and 95 m in height, respectively), altering the hydrology, hydrochemistry and hydromorphology of the river (Sylaios *et al.* 2010). The river had a pre-damming mean annual discharge of 39 $m^3 s^{-1}$, reduced presently to 17 $m^3 s^{-1}$, as recorded downstream of the dams, in direct dependence on power energy demand (Koutroumanidis *et al.* 2009).

Nestos River mouth and coastline belong to the East Macedonia – Thrace coastline, being part of the Thracian Sea continental shelf. The area represents the eastern outmost of Kavala Gulf, the second in size semi-enclosed water body of the Thracian Sea and the North Aegean continental shelf. The coastline area situated to the west of Nestos River mouth, where a series of coastal lagoons and the sandy headland of Keramoti develop, appears as the zone with the highest present and future erosion vulnerability (Fig. 1).

The erosion rate of the area varies considerably in the alongshore direction, ranging between a few centimetres up to 25 m per year (Xeidakis, Delimani 1999). Such phenomenon has been attributed to the entrenchment of Nestos River course along its delta and the construction of an extensive irrigation system during the early 1950s (Xeidakis, Delimani 1999). This intervention increased the velocity of water flow at the mouth and reinforced the offshore spread of sediments, contributing mostly to shoreline accretion (by approximately 76%) and to a lesser degree to erosion (Xeidakis *et al.* 2010b). In parallel, the two large dams constructed in Nestos River during the early 1990s have significantly decreased the terrestrial sediment transport through the river to the coast, thus increasing the coastal erosion risk. This reduction has been estimated to approximately 60% of the historic sediment supply to the delta, with most sediments being entrapped in these two reservoirs (Hrissanthou 1999). Recent estimates increase the rate of sediment yield reduction due to dam construction to 84% (Andredaki *et al.* 2008). Aerial image comparison before and after dam construction revealed that only 39% of the delta and the adjacent coastline have been accreted while the remaining 61% has been eroded (Xediakis *et al.* 2010b). Finally, the location of the study area along the northern coastline of the Aegean Sea, with a long fetch of the order of hundreds of kilometres, favours the development and progress of southern swells, contributing to the cross-shore sediment transport. The presence of Keramoti – Thassos Passage, enhances coastal velocities, producing current speeds up to 1.2 m s^{-1}, resulting in further erosion through alongshore sediment transport. On the other hand, the presence of Thassos Island causes alongshore variation in the erosion intensity rates, due to alterations from the exposed, long-fetch, highly energetic coastline parts to low-fetch and 'sheltered' parts. Coastal erosion has been also affected by the construction of small ports and other similar structures which alter the sediment transport along the coastline.

Landsat imagery provided evidence for coastline erosion in the study area. As shown in Fig. 2, Keramoti coastline has suffered from significant

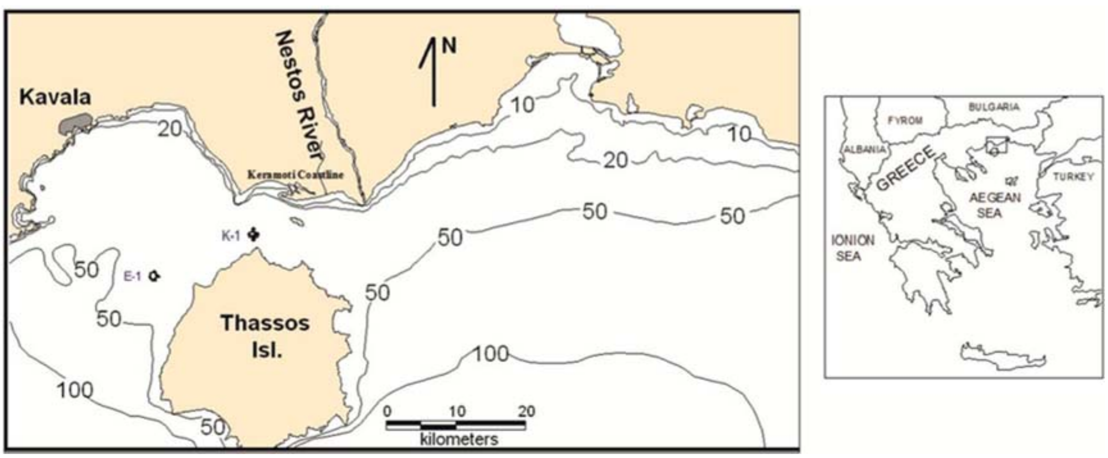

Fig. 1. Location map of the study area.

erosion, for the period 1982-2001. Significant erosion is observed in the first 2 km of the coastline western of Nestos River mouth, with a diminishing erosion trend up to the next 12 km of the coastline. In Keramoti Bay, the sandbar evolving westwards appears as a deposition area, receiving significant parts of the eroded material transported westwards by the alongshore currents. Significant erosion is also observed at the westward end of Keramoti Bay, about 4 km from the end of the studied coastline. Based on these images, Tsihrintzis *et al*. (2008) estimated for the examined coastline length of 21.22 km, over the 1982-2001 period, a total erosion area of 1.16 km^2 and an accretion area of 0.22 km^2, indicating the net sediment deficit.

2.2. Broader geological setting

Over the recent geological evolution, the coastline along the Thracian Sea continental shelf progressively retired approximately 16 000 years ago, and the sedimentation of coarse-grained terrestrial deposits (shingles, gravels and sands) took place, transported to the area by local rivers and torrents (van Andel, Lianos 1984). The sea level was stabilized approximately 7000 years ago, allowing marine sedimentation to commence, leading to the settlement of fine-grained sediments (clays, silts, fine sands), distributed in the area under the action of coastal currents and waves (Ruddiman, Duplessey 1985). By this process, small channels and riparian watercourses were covered by sediments, while the alluvial deposits of River Nestos covered its old watercourse, shifting the river eastwards. Surface sediments are dominated by sands and silty sands, occurring extensively at the western coast of Thassos Island and the vicinity of Nestos River mouth. These sediments form relict sand deposits having similar geotechnical characteristics to the sediments of presently eroded Keramoti beach. Stratigraphic examination in the area was limited; however, two 20 m deep boreholes (E-1 and K-1, Fig. 1), indicate a sequence of silty sands, fine silty sands and sandy silts. Sedimentary succession also presents the absence of coarse-grained layers, i.e., gravels and pebbles, deposited near the sea bottom surface.

2.3. Seafloor mapping methodology

Seafloor mapping included the use of swath sonar (side-scan and bathymetric) systems, towed by and mounted on the research vessel, respectively. The Simrad ES60 high-resolution single-beam bathymetry measurement system, interfaced with the OLEX 3D software were used to obtain the updated broad-scale physical characterization of the surface sediments covering the study area. The system utilizes a narrow-beam (3°), 200-kHz transducer, able to produce a continuous analogue record of the bottom, and transmits approximately 5 digital depth values per second. Within OLEX 3D software, the time-tagged position and depth data were merged to create continuous depth records along the actual survey track. These records were viewed in real-time to ensure adequate coverage of the survey area.

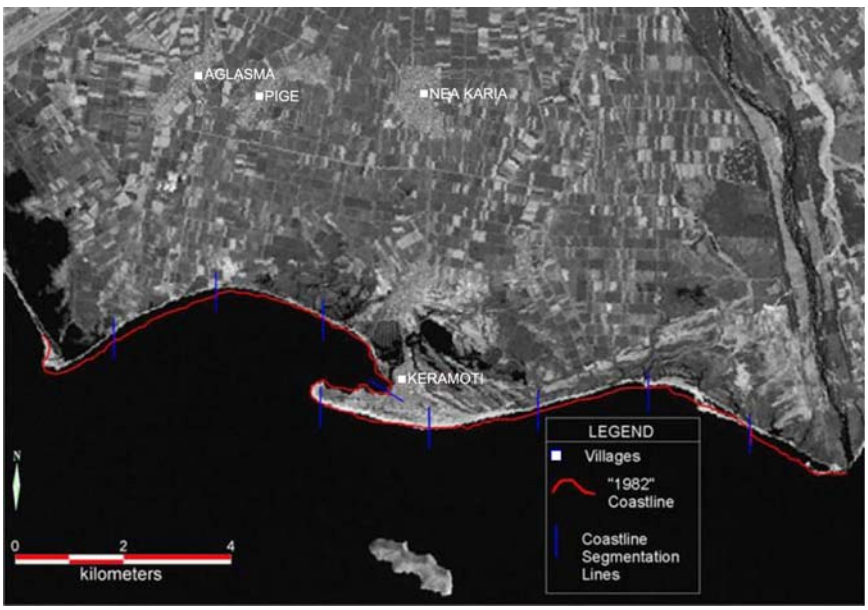

Fig. 2. LandSat imagery for the study area obtained in 2001, illustrating the digitized 1982 coastline (red line).

The broad-scale surface sediments characterization was performed using a high resolution C-Max CM2 Side Scan Sonar, providing digital side-scan sonar imagery. The system allowed the user to operate it under dual acoustic signal frequencies, at 325 KHz and 100 KHz. Therefore, lateral resolution depended on acoustic signal frequency, defined as 78 mm (at 325 KHz) and 156 mm (at 100 KHz). Similarly, the range of the signal from towfish in the port and starboard direction varied according to the selected frequency, from 150 m (at 325 KHz) and 500 m (at 100 KHz). The beam angle at the horizontal level ranged from 0.3° to 1°, depending on operational frequency (at 325 KHz and 100 KHz, respectively).

Overall, an area of 42.34 km^2 was surveyed by both systems at the southern part of Nestos River mouth (Fig. 3). Most of the surveys were conducted using the low frequency beam, and only 4.4 km^2, representing the area of recorded sand deposits, were surveyed using the high frequency beam. In parallel, 14 surface sediment samples were collected along the side scan sonar survey lines using a KC Denmark van Veen stainless steel grab (20 × 20 cm), aiming to compare the side scan sonar imagery results with the sediments from several points (Fig. 3). Samples were stored in plastic bags on board at 0°C temperature and at the laboratory at -28°C. Wet sieving was used for the textural analysis of sediment samples (% of sand, silt and clay).

2.4. Beach nourishment width and volume estimations

Determination of the alongshore nourished beach length and the beach fill volume are particularly important for beach nourishment operations (Jackson *et al.* 2010). The length of beach fill influences the rate of sediment loss after project completion, as the newly nourished shoreline equilibrates to the wave regime, while cross-shore volume per unit length determines the design form of the nourished beach, estimating the berm elevation and width and the closure depth of the system (Dean 2002).

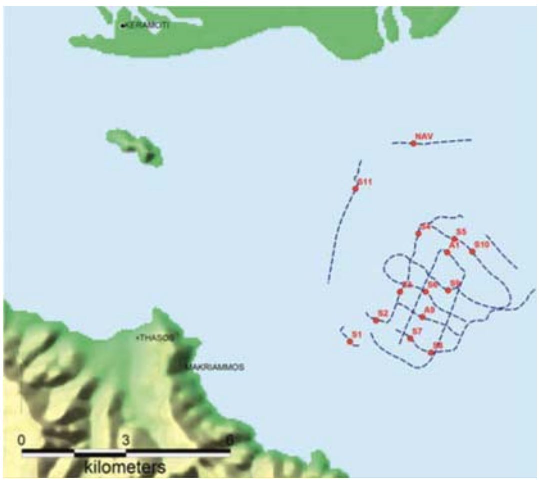

Fig. 3. Sea bottom coverage using bathymetric and side scan sonar systems. Points represent van Veen surface sediment samples.

The sediment volume excavated from the sandbank at various depths was determined through a detailed GIS model of sea bottom, based on bathymetric and side scan sonar records. Based on these calculations, the nourished dry beach width Δy_0 [m] and the nourished volume density per unit of beach length V [m^3 m^{-1}] were estimated following Dean (2002):

$$\Delta y_0 = \frac{V}{(h_* + B)} \quad (1)$$

where h_* is the so-called “depth of closure” or “depth of effective motion” [m], i.e., the seaward limit of the effective seasonal profile fluctuations, and B is the berm height (= 0.8 m for Keramoti shoreline). The approximation for the depth of closure was determined based on the incident wave characteristics (Dean 2002):

$$h_* = 2.28\,H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \quad (2)$$

in which T_e [s] is the wave period associated with the effective significant wave height H_e [m], defined as that which is exceeded only 0.14% of the time. H_e may be approximated using the annual mean significant wave height $\bar{H}$ [m] and the standard deviation in wave height σ_H [m], as follows (Dean 2002):

$$H_e = \bar{H} + 5.6\,\sigma_H \quad (3)$$

Beach widening through nourishment has been developed by utilizing equilibrium profile concepts. The volume placed per unit of shoreline length, V_1 [m^3 m^{-1}], associated with a shoreline advancement of Δy_0 is given by (Dean 2002):

$$\frac{V_1}{BW_*} = \frac{\Delta y_0}{W_*} + \frac{3}{5}\left(\frac{h_*}{B}\right)\left\{\left[\frac{\Delta y_0}{W_*} + \left(\frac{A_N}{A_F}\right)^{3/2}\right]^{5/3} - \left(\frac{A_N}{A_F}\right)^{3/2}\right\} \quad (4)$$

where B is the berm height [m] of the beach profile (= 0.8 m for Keramoti beach), h_* is the closure depth [m], W_* is the offshore distance associated to the closure depth [m], Δy_0 is the dry beach width increase due to nourishment [m], and parameters A_N and A_F [$m^{1/3}$] are profile scale parameters (‘N’ refers to the native beach profile and ‘F’ to the filled beach profile) connecting profile depth and horizontal distance by $h_{N,F} = A_{N,F}\, y^{2/3}$.

2.5. Post-nourishment longshore sediment transport

After nourishment, sand material is expected to spread out along the shoreline, enriching with sand the adjacent beaches. Sand spreading determines the beach nourishment volumetric performance and is related to the longshore sediment transport Q. The longshore sediment transport is defined by the CERC formula (U.S. Army Corps of Engineers 1984) as:

$$Q = \mathrm{K}\left(\frac{\rho\sqrt{g}}{16\kappa^{1/2}(\rho_s-\rho)(1-n)}\right)H_b^{5/2}\sin(2\alpha_b) \quad (5)$$

where 'b' denotes breaking zone conditions, K is a dimensionless coefficient related to the beach mean sediment grain size (≈ 0.23), ρ_s is the quartz sand density (≈ 2 650 kg m^{-3}), ρ is the sea water density (≈ 1 025 kg m^{-3}), n is sediment porosity (≈ 0.4), κ is the breaker index ratio (≈ 0.8), H_b is the breaking significant wave height, and α_b the azimuth of the incident waves orthogonals.

Data on the wave characteristics along the breaking zone of Keramoti shoreline were supplied by a nearshore third-generation wave model (SWAN) applied at pre- and post-nourishment conditions (Anastasiou, Sylaios 2012). These data consisted of the breaking wave height and direction for the dominant incident waves.

3. Results and discussion

3.1. Sea bottom classification

Sounding analysis was achieved mainly visually, and secondarily, using computational tools to test the safety of the extracted conclusions. The final aim of this analysis was the development of a sea bottom classification map, grouping areas of sounding mosaic showing similar acoustic character. Among the soundings of the present study, four main acoustic types were recognized (Table I). Acoustic type recognition was made based on criteria such as the acoustic reverberation, textural characteristics and other structural elements observed on a broader scale. During sounding analysis, approximately 1/3 of their band width of the signal was ignored, as this signal was strongly influenced by its multiple reflections on sea bottom and sea surface. The ratio between the first and second signal reflection was used as a differentiation criterion for the various sea bed types, according to the methodology of Roxanne echosounder.

Figure 4 presents the classification map of the various acoustic types recorded in the area of interest. The bottom sediment sampling points using the van Veen bottom sampler also appear in this map. Figure 5 illustrates the comparison of the side scan sonar imagery and the collected sediment samples. The results of the side scan imagery agree with that of sediment samples, illustrating coarse sand of biogenic origin.

3.2. OLEX scan results

Figure 6a presents sea bottom bathymetry of the studied area. The combined bathymetric and GPS datasets were imported on an ArcGIS system for further processing and manipulation (Fig. 6b). Three-dimensional views of the area's sea bottom were extracted from both systems revealing the presence of a sandbank (Fig. 6c).

3.3. Bottom sediment grain size analysis

Sediment samples were obtained from each sampling station over the examined sandbank aiming to determine the sediment characteristics of the area. Cumulative occurrence percentage curves for each sampling station were produced (Fig. 7). It occurs that the finer sediments appear in stations S4 and S7, with mean diameters D_{50} = 0.228 mm and D_{50} = 0.225 mm, respectively. These stations are located at the northern and southern boundaries of the sandbank, with sediments classified as fine-grained sand. Stations S10 and S8, located at the

Table I. Sea bottom types and their characteristics.

Sea bottom type	Characteristics	Comments
A	Acoustic reverberation: relatively high; Texture: high entropy, high homogeneity.	Hard sediment with micro-structures; possibly coarse to medium grained sand.
B	Acoustic reverberation: intermediate; Texture: low entropy, high homogeneity.	Finer sediments enriched with cohesive clay, sands and biogenic residues.
C	Acoustic reverberation: relatively low; Texture: high entropy, low homogeneity.	Sharp relief with laminar elements. Possibly clay and signs from trawling activity. The material is plastic and fine-grained.
D	Acoustic reverberation: intermediate; Texture: low entropy high homogeneity.	Presence of circular hunches of intense reverberation. Similar characteristics to acoustic type 'B' with the presence of biogenic material.

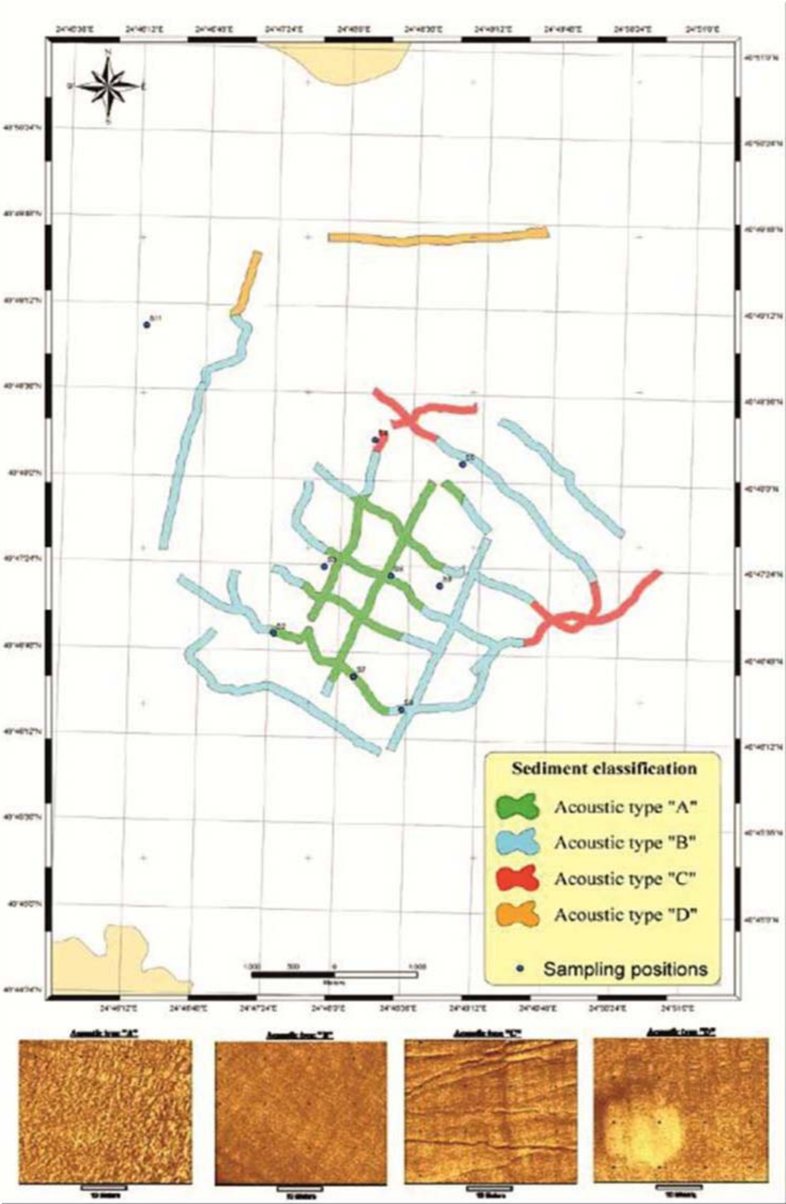

Fig. 4. Classification map of the various acoustic types recorded in the area of interest.

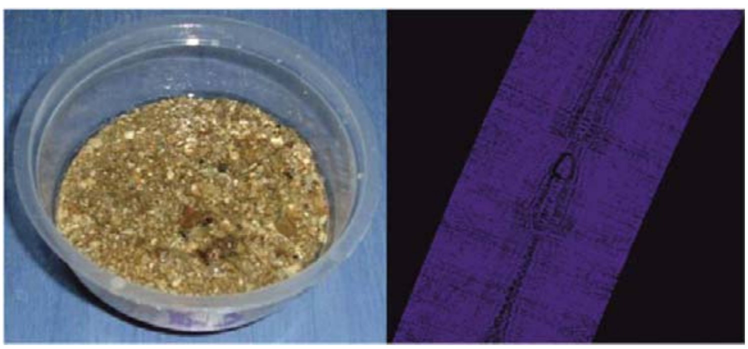

Fig. 5. Side scan imagery and sediment sample image for sampling point S2.

north-eastern shallower part of the sandbank, have coarser sediments with mean diameter D_{50} = 0.5 mm and D_{50} = 0.445 mm (medium-grained sand). Stations S4 and S11 have the lower standard deviation of 0.248 mm and 0.223 mm, respectively, and therefore, they are considered as the most homogeneous sediment samples of the area. Similarly, stations S5 and S10 depict the highest kurtosis values (K = 1.467 and 1.443, respectively), indicating that these samples show the highest deviation from the normal grain size distribution, while S7 has almost normal grain size distribution (K = 0.994).

3.4. Beach profile analysis

In order to estimate the beach nourishment volume per unit length and the nourished beach width, the sediment volume excavated from the sandbank at several depths was calculated. The results are shown in Fig. 8. The sediment volume excavated from the sandbank could range between 5×10^6 m^3 for excavation up to 26 m depth and 4.3×10^7 m^3 for excavation up to 30 m depth.

Wave data from the study area, collected by an upward-facing ADCP deployed near the project area at a depth of 22 m for years 2007 and 2008 (Sylaios *et al.* 2008), provided the following values: $\bar{H}$ = 0.73 m, σ_H = 0.15 m and T_e = 6.7 s. Following eq. (3), it results that the effective significant wave height H_e is 1.57 m, while substituting this value to eq. (2) it occurs that the closure depth of the area h_* is 3.2 m.

Beach profile analysis for Keramoti shoreline indicated that the profile scale parameters A_N for the native beach profile and A_F for the filled beach profile obtain the values 0.035 m$^{1/3}$ and 0.14 m$^{1/3}$, respectively. Since the ratio $A_F / A_N > 1$, the native and nourished profiles are intersecting, having the general form shown in Figure 9.

Several scenarios were considered according to the selected dredging depth of the sandbank, as shown in Table II. For a total shoreline length of 21.2 km, the volume per unit length, the nourished dry beach width Δy_0, the dry sediment volume placed per unit of shoreline length V_1 and the total dry volume nourished were calculated by solving eq. (1) and (4). Results show that for excavation up to 26 m depth, the sediment volume excavated will be 5×10^6 m^3, which could be used to increase the beach width at the surface by 52 m, corresponding to a nourishment rate of 63.6 m^3 per meter of shoreline length, and increasing its dry volume by 1.35×10^6 m^3. In case the whole sandbank was dredged (excavation up to 30 m depth), a volume of 4.3×10^7 m^3 of sediments will be excavated, which could increase beach width by almost 450 m, or beach volume by 1140 m^3 per shoreline meter, corresponding to 2.4×10^7 m^3 of dry sediments. Based on the sediment losses estimated by the Landsat images, it occurs that approximately 30% of the eroded Kearmoti beach could be restored under scenario 1.

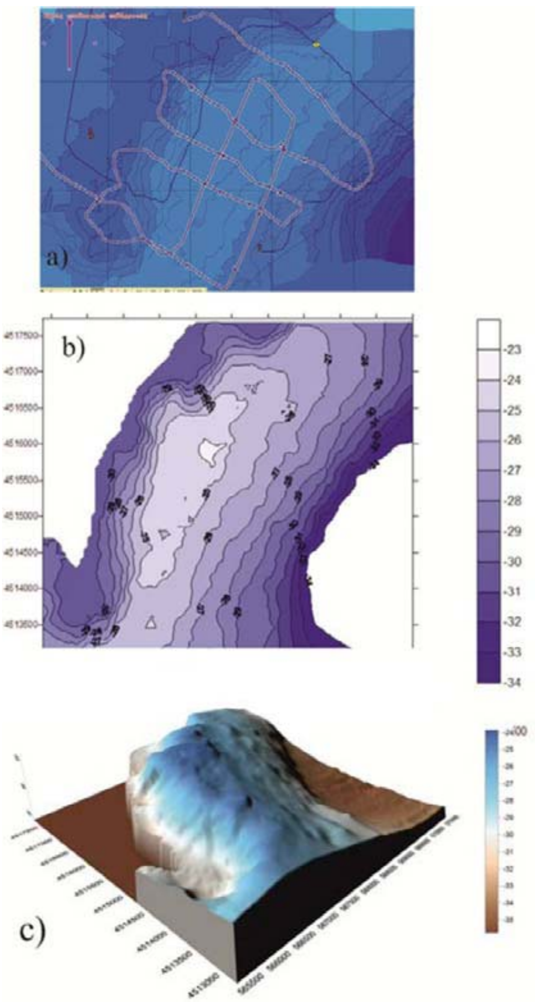

Fig. 6. a) Contours of sea bottom bathymetry and survey lines in the area of interest, b) Contours of sea bottom bathymetry produced using ArcGIS, and c) three-dimensional view of the sandbank.

3.5. Post-nourishment sand transport

SWAN model results of incident wave heights and directions for the most dominant waves reaching the shoreline of interest are shown in Figure 10. The impact of Thassos Island sheltering is rather obvious diminishing the significant wave heights by 47% as moving from Nestos River mouth to Keramoti sand spit. Incident wave angles increase slowly from 111° at Nestos River mouth to 135° at Keramoti sand spit (anti-clockwise from x-positive (easting) axis). Based on SWAN model results, the calculated longshore sediment transport (using eq. 5) obtains negative values, implying that sediment is moving westwards. At the highly exposed part of the shoreline, near Nestos River delta, longshore sediment transport reaches 0.042 $m^3\ s^{-1}$ (or $3.66 \times 10^3\ m^3\ d^{-1}$ or $1.34 \times 10^6\ m^3\ yr^{-1}$), diminishing rapidly westwards to 0.009 $m^3\ s^{-1}$ (or $7.97 \times 10^2\ m^3\ d^{-1}$ or $2.91 \times 10^5\ m^3\ yr^{-1}$). Based on these model results, for sandbank excavation up to 26 m depth, the nourished sediment will be transported alongshore within 1.8 years, while if the whole sandbank is dredged, nourished sediment is expected to need approximately 33 years before it is completely spread out.

3.6. Environmental and ecological concerns

The environmental and ecological concerns of beach nourishment using relict sand submarine deposits have been summarised by Nicoletti *et al.* (2006). In this section we discuss them in the context of the studied sandbank and its dredging for

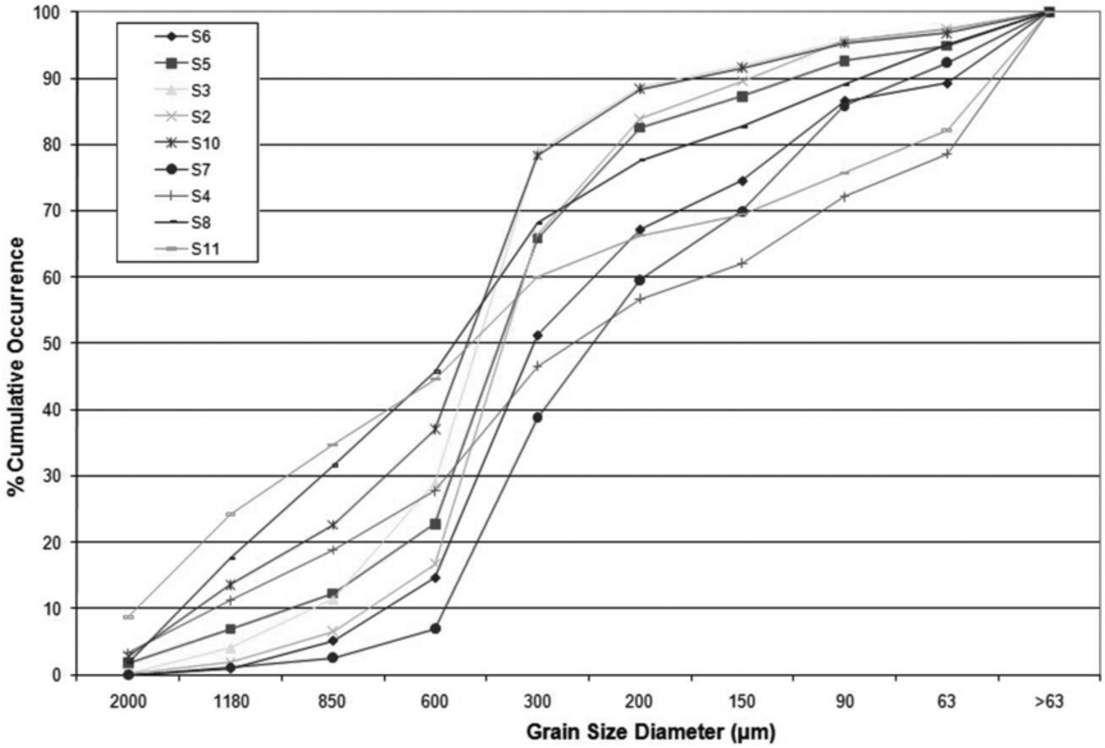

Fig. 7. Curves of cumulative occurrence of grain size distribution for all bottom samples.

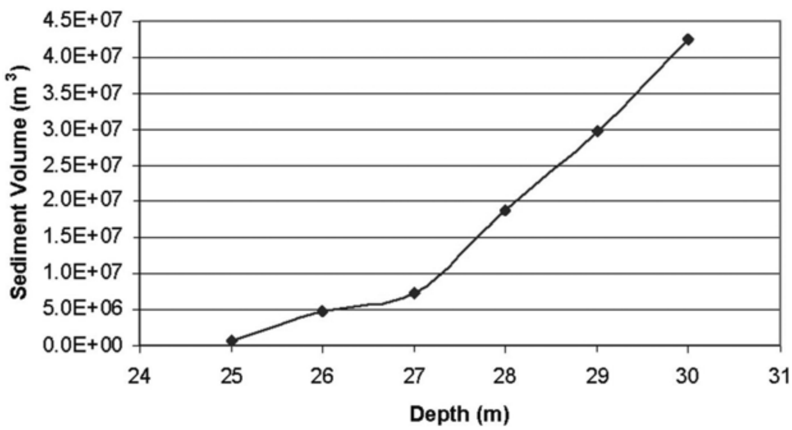

Fig. 8. Estimation of sediment volume excavated from seabed for beach nourishment.

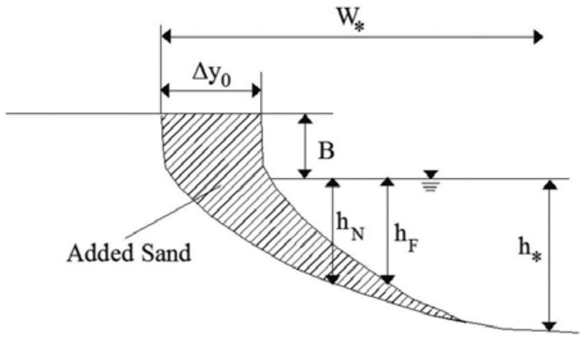

Fig. 9. Intersecting native and nourished beach profiles.

Table II. Estimations of beach nourishment width, volume per shoreline length and total dry sediment volume.

Maximum dredging depth (m)	Dredged sediment volume (m^3)	Volume per unit length (m^3 m^{-1})	Nourishment beach width, Δy_0 (m)	Nourished volume per shoreline length (m^3 m^{-1})	Nourished dry sediment volume (m^3)
26	5.0E+06	2.4E+02	52.4	63.62	1.35E+06
27	7.5E+06	3.5E+02	78.6	105.52	2.24E+06
28	1.8E+07	8.5E+02	188.8	334.23	7.09E+06
29	3.0E+07	1.4E+03	314.7	680.91	1.44E+07
30	4.3E+07	2.0E+03	451.1	1142.80	2.42E+07

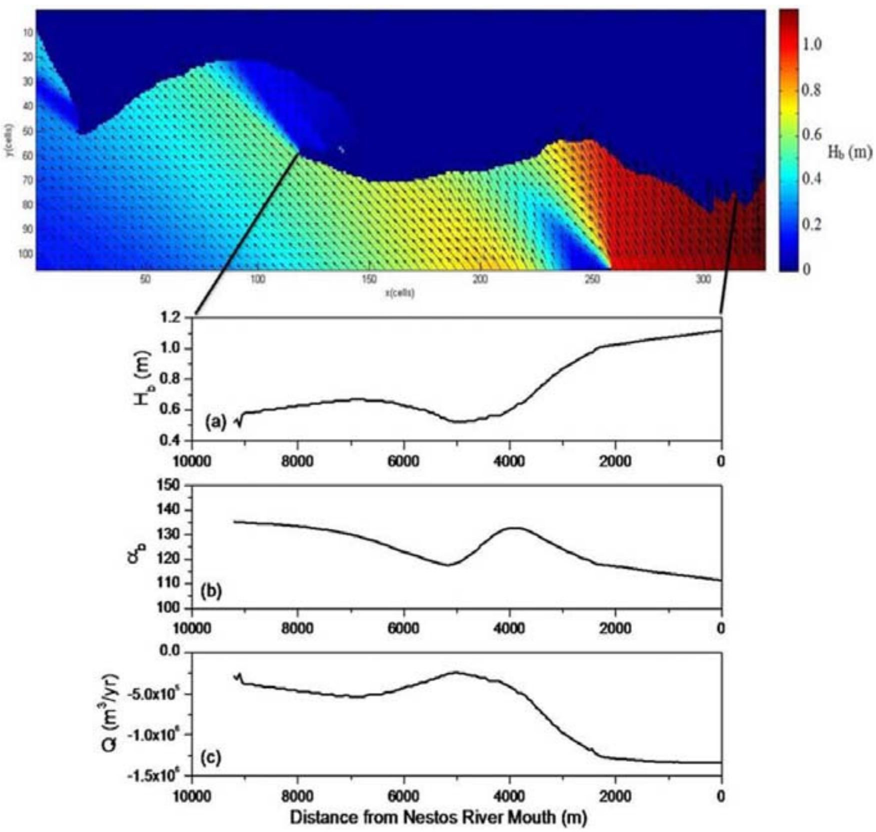

Fig. 10. SWAN model results showing incident wave heights and angles (upper panel) and longshore distribution of (a) breaking wave height (m), (b) breaking wave angle (o) measured from the x-positive (east) axis in an anti-clockwise manner, and (c) longshore sediment transport (m^3 yr^{-1}) at Keramoti shoreline (lower panel).

Keramoti shoreline nourishment. Environmental impacts affect the dredging area, the transport zone and the nourishment area. In the dredging area, effects concentrate on alterations in the sea bottom characteristics and morphodynamics, changes in the water column properties (e.g., turbidity and SPM content) and effects on sea organisms as benthos, nekton and sensitive habitats.

Bathymetric changes in the dredging area consist of depressions while morphological alterations affect the texture of superficial sediments. These effects are minimized if anchor dredging is selected as the method of sediments' removal and the dredging area is limited in space. This could be the case for the relict sand deposit identified southern of Nestos Delta area, as it presents a prevailing vertical development and it is relatively limited in space. Hydrodynamics in the area will not be significantly altered, as bottom currents are generally low (~0.05 m s^{-1}) in the studied area. Water column effects are associated to the produced turbidity plume released in the water column. The finest sediments are expected to form a superficial plume while higher grain sizes will contribute to the benthic plume. Due to the limited bottom circulation the benthic plume will have only local effects. The surface plume will be limited as water depth is relatively high. It is expected to be transported by the prevailing winds, thus increasing surface turbidity levels in a zone of 0.5 to 1 km from the dredging site. In any case, water column effects are temporal, site-specific and seasonal.

Soft bottom benthic organisms will be mostly affected by relict sand dredging activities, as a result of their partial or complete removal. Dredging is expected to destroy the microbial film of the substratum, being an important food source for benthic organisms. In our case, the vegetal component of benthic communities is close to zero, as light represents the limiting factor. High bacterial abundances, phaeopigment and chlorophyll-a concentrations have been detected by Polymenakou *et al*. (2007), at the surface sediments of the studied area. These groups appear in assemblage with benthic small crustaceans, shrimps (Tsagarakis *et al*. 2010) and demersal fish species as *S. cabrilla*, *L. cavillone*, *D. annularis* and *M. barbatus* (Kallianiotis *et al*. 2004).

The environmental alterations expected in the transport zone are quite limited in space and time. In the nourishment zone relevant effects involve benthic and fish assemblages in the proximity to the beach. However, most of these species are burrowing or temporarily migrant species, having a tendency to adapt in a stressed environment.

Conclusions

A complete bathymetric, acoustic and sedimentology study was performed to identify the presence of submarine relict sands that could be used for the potential beach nourishment of the eroded coastline in Keramoti area, in the vicinity of Nestos River mouth, Northern Greece. The study area was located southern of Nestos River deltaic zone, the main sediment supplier in the area, especially before river damming in 1996.

A submarine sandbank consisting of a relict sand deposit was identified near the eroded beach, with grain size characteristics similar to the shoreline under restoration. Results illustrated that the sediment volume excavated could vary from 5.0×10^6 m^3 (for excavation up to 26 m depth) to 4.3×10^7 m^3 for dredging up to of 30 m depth. These scenarios correspond to a nourished beach width ranging from 52 to 450 m, respectively. Post-nourishment longshore sediment transport estimations revealed that sediment reduction could vary from 1.34×10^6 m^3 yr^{-1} at the exposed deltaic part to 2.91×10^5 m^3 yr^{-1} at the sheltered western coastline. Such rates indicate that the nourished beach could sustain its sand for duration of up to 33 years, in case the whole sandbank was dredged, illustrating the effectiveness of this approach for beach restoration. The consideration of environmental effects related to the beach nourishment of Keramoti coastline showed that sea bottom dredging activities and the produced turbidity plumes may affect the benthic assemblages of the sandbank, such as small crustaceans, shrimps and demersal fishes.

Acknowledgements

This work was partially funded by the EU Interreg IIIC Program, Project "BeachMed-e". Part of this work has also been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: Heraclitus II. Investing in knowledge society through the European Social Fund.

References

Anastasiou, S., Sylaios, G. 2012. *Description of wave climate characteristics and hydrodynamic circulation in the Nestos River Delta area – Application, validation and coupling of wave and hydrodynamic models*. Proceedings of the 10th Panhellenic Symposium on Oceanography and Fisheries, Athens, 7-11/5/2012.

Andreadaki, M., Hrissanthou, V., Kotsovinos, N. 2008. *Calculation of sediment reduction at the outlet of Nestos river basin due to the dams.* IV International Symposium on Transboundary Waters Management, Thessaloniki, 15–18/10/2008.

Bergkamp, G., McCartney, M., Dugan, P., McNeely, J., Acreman, M. 2000. *Dams, ecosystem functions and environmental restoration. Thematic reviews II.1.*

World Commission of Dams, Cape Town, www.dams.org.

Covich, A.P. 1993. Water and ecosystems. In: Gleick, P.H. [Ed.] *Water in Crisis*. Oxford University Press, New York, 40-55.

Dean, R.G. 2002. *Beach Nourishment: Theory and Practice*. World Scientific Publishing, 390 p.

Ganoulis, J., Skoulikaris, H., Monget, J.M. 2008. *Involving stakeholders in transboundary water resource management: The Mesta/Nestos 'HELP' basin*. International Symposium 'HELP in Action: Local Solutions to Global Water Problems – Lessons from the South', Emperor's Palace, Johannesburg, South Africa, 4-9 November 2007.

Gerakis, P.A. 1992. *Conservation and management of Greek wetlands.* Proceedings of a Workshop of Greek Wetlands. The IUCN Wetlands Program, Thessaloniki, Greece, 17/4/1989, 497 p.

Gerakis, A., Kalburtzi, K. 1998. Agricultural activities affecting the functions and values of Ramsar wetland sites of Greece. *Agricultural Ecosystems Environment* **70** (2-3), 119-128.

Graf, W.L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology* **79**, 336-360.

Grant, G.E., Schmidt, J.C., Lewis, S.L. 2003. A geological framework for interpreting downstream effects of dams on rivers. In: O'Connor, J.E., Grant, G.E. [Eds] *A Peculiar River*. American Geophysical Union, Washington, DC, pp. 209–219.

Hrissanthou, V. 1999. *Erosion, Transport and Sedimentation in the Nestos River Basin*. Proceedings of International Conference on Hydrology & Geochemistry. Processes of Large Scale River Basins, Manaus, Brazil, 15-19/11/1999.

IEA, International Energy Agency 2006. *Hydropower good practices: Environmental mitigation measures and benefits*. Annex VIII, New Energy Foundation, Japan, 27 p.

Jackson, N.L., Nordstrom, K.F., Saini, S., Smith, D.R. 2010. Effects of nourishment on the form and function of an estuarine beach. *Ecological Engineering* **36**, 1709-1718.

Kallianiotis, A., Vidoris, P., Sylaios, G. 2004. Fish species assemblages and geographical sub-areas in the North Aegean Sea, Greece. *Fisheries Research* **68**, 171-187.

Koutroumanidis, Th., Sylaios, G., Zafeiriou, E., Tsihrintzis, V.A. 2009. Genetic modeling for the optimal forecasting of hydrologic time-series: Application in Nestos River. *J. Hydrol.* **368**, 156-164.

Kummu, M., Varis, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* **85**, 275-293.

La Porta, B., Targusi, M., Lattanzi, L., La Valle, P., Paganelli, D., Nicoletti, L. 2009. Relict sand dredging for beach nourishment in the central Tyrrhenian Sea (Italy): effects on benthic assemblages. *Marine Ecology* **30**, 97-104.

Leatherman, S.P. 1996. Shoreline stabilization approaches in response to sea level rise: U.S. experience and implications for Pacific Island and Asian Nations. *Water, Air and Soil Pollution* **92**, 149-157.

Ligon, F.K., Dietrich, W.E., Trush, W.J. 1995. Downstream ecological effects of dams. *Bioscience* **45**, 183-192.

Millennium Ecosystem Assessment 2005. *Inland water systems. Ecosystems and human well-being: Current state and trends*. Island Press, Washington DC.

Nicoletti, L., Paganelli, D., Gabellini, M. 2006. *Environmental aspects of relict sand dredging for beach nourishment: proposal for a monitoring protocol*. Quaderno ICRAM n.5, 155 p.

Nonnis, O., Paganelli, D., Proietti, R., Nicoletti, L. 2011. Physical effects related to relict sand dredging for beach nourishment in the Tyrrhenian sea: the Anzio case. *J. Coastal Res. Sp. Iss.* **64**, 1380-1384.

Peterson, C.H., Hickerson, D.H.M., Johnson, G.G. 2000. Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *J. Coastal Res.* **16**(2), 368-378.

Poff, N.L., Hart, D.D. 2002. How dams vary and why it matters for the emerging science of dam removal. *Bioscience* **52**, 659–668.

Polymenakou, P.N., Fragkioudaki, G., Tselepides, A. 2007. Bacterial and organic matter distribution in the sediments of the Thracian Sea (NE Aegean Sea). *Continental Shelf Research* **27**, 2187-2197.

Postel, S., Richter, B. 2003. *Rivers for Life: Managing Water for People and Nature*. Island Press, Washington DC.

Ruddiman, W.F., Duplesey, J.C. 1985. Conference on the last glaciation: time and mechanism, *Quaternary Res.* **23**, 1-17.

Simonini, R., Ansaloni, I., Bonini, P., Grandi, V., Graziosi, F., Iotti, M., Massamba-N'Siala, G., Mauri, M., Montanari, G., Preti, M., De Nigris, N., Prevedelli, D. 2007. Recolonization and recovery dynamics of the macrozoobenthos after sand extraction in relict sand bottoms of the Northern Adriatic Sea. *Marine Environmental Research* **64**, 574-589.

Sylaios, G., Akratos, C., Pisinaras, V., Kamidis, N., Tsihrintzis, V.A. 2008. *"TRITON": A monitoring station for wave climate, hydrodynamics and turbidity offshore of Nestos River mouth, N. Greece*. Proceedings of the IX International Conference on "Protection and Restoration of the Environment". Kefalonia, Greece.

Sylaios, G., Kamidis, N., Tsihrintzis, V.A. 2010. Impact of river damming on the coastal stratification-mixing processes: The cases of Strymon and Nestos Rivers, Greece. *Desalination* **250**(1), 302-312.

Tsagarakis, K., Coll, M., Giannoulaki, M., Somarakis, S., Papaconstantinou, C., Machias, A. 2010. Food-web traits of the North Aegean Sea ecosystem (Eastern Mediterranean) and comparison with other Mediterranean ecosystems. *Estuarine, Coastal & Shelf Science* **88**, 233-248.

Tsihrintzis, V.A., Sylaios, G., Akratos, C., Pisinaras, V. 2008. *Beach nourishment studies along the East-Macedonia and Thrace coastline*. Proceedings of the IX International Conference on "Protection and Restoration of the Environment". Kefalonia, Greece.

U.S. Army Corps of Engineers 1984. *Shore Protection Manual.* U.S. Army Corps of Engineers, Vicksburg, Mississippi.

van Andel, T.J.H., Lianos, N. 1984. High resolution seismic reflection profiles for the reconstruction of postglacial transgressive shorelines: An example from Greece, *Quaternary Res.* **22**, 31-45.

Vörösmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., Lough, J.A. 1997. The storage and aging of continental runoff in large reservoir systems of the world. *Ambio* **26,** 210-219.

Walling, D.E. 2008. The changing sediment loads of the world rivers. Annals of Warsaw University of Life Sciences – SGGW. *Land Reclamation* **39**, 3-20.

World Commission on Dams 2000. *Dams and development. A new framework for decision making*. Earthscan Publications Ltd., London, UK, 356 p.

Xeidakis, G.S., Delimani, P. 1999. Coastal erosion problems in the Northern Aegean Coastline: The case of Nestos River Delta and the adjacent coastlines. In: Brebbia, C.A. [Ed.] *Coastal Environment, Environmental Problems in Coastal Regions IV*. WIT Press, pp. 151-159.

Xeidakis, G.S., Georgoulas, A., Kotsovinos, N., Delimani, P., Varragouli, E. 2010a. *Environmental degradation of the coastal zone of the west part of Nestos River Delta, N. Greece*. Bulletin of the Geological Society of Greece, Proceedings of the 12th International Congress, Patras, May 2010.

Xeidakis, G.S., Georgoulas, A., Kotsovinos, N., Varragouli, E. 2010b. Human interventions and degradation of the coastal zone of Nestos River Delta, North Aegean Sea, N. Greece. In: Williams, A.L., Pinches, G.M., Chin, C.Y., McMorran, T.J., Massey, C.I. [Eds] *Geologically Active: Proceedings of the 11th IAEG Congress*. Auckland, New Zealand, 5-10 September 2010, pp. 797-804.