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ASSESSING THE ANTHROPOGENIC IMPACTS ON THE FLUVIAL WATER AND SEDIMENT FLUXES INTO THE THERMAIKOS GULF, NORTHERN GREECE

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Abstract

The impacts of anthropogenic activities on the water and sediment fluxes in coastal areas have caused significant economic and environmental damages over the last century. The development of large-scale water abstraction and sediment retention infrastructures has facilitated phenomena such as coastal erosion, frequent eutrophication events and sea water anoxia. The present work investigates the alterations that have been observed over the last 50 years in the area of Thermaikos Gulf, Northern Greece, with emphasis on water overexploitation impacts on the coastal system. For this purpose two different water management scenarios have been set up; one prior and one after the significant human interventions in the Thermaikos Gulf catchment (includes Aliakmonas and Axios river catchments). The hydrodynamic model 'MIKE SHE', and the RUSLE sediment erosion model have been used in order to quantify and assess the human impacts on the water and suspended sediment discharges into the Inner Thermaikos Gulf, according to the aforementioned scenarios. The results indicated that both water and sediment discharges have severely diminished, with reductions reaching approximately 51 and 90% for the Axios River as well as 39 and 76% for the Aliakmon River, respectively. Agricultural and hydropower production activities with the associated dams are the main actors of these impacts. As a result, the natural system has started responding with subsidence and coastal erosion, frequent eutrophication events and sea water anoxic conditions. Inevitably, this leads to economic losses for other users of the local ecosystem services, such as aquaculture farmers, fishermen and tourists.

Key words: coastal zone, fluvial suspended sediment, impact assessment, integrated management, river discharge

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1. Introduction

The coastal ecosystems are under tremendous human pressure, whilst policy action has not been able to respond properly to the resultant negative impacts. This is indicated by the frequently observed eutrophication effects in many coastal waters (Moncheva et al., 2001; Nikolaidis et al., 2006) and the degradation of deltaic areas (salinization) combined with the loss of wetlands due to subsidence and erosion processes (Kapsimalis et al., 2005; Psimoulis et al., 2007; Stiros, 2001). Thus, integrated environmental assessments are a key step for the optimal management of coastal systems (Antunes and Santos, 1999; Cicin-Sain et al., 1995; Talaue-McManus et al., 2003).

Hence, a management and decision-making approach which treats the coastal zone as an integrally functioning system has to be used to overcome these problems. Accurate and timely prognostic information should be derived and improved ways of communicating research information to decision-makers and the public should be developed. The transition to a more sustainable society is an enormous

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challenge for modern society, but one with benefits from its initiation. Sustainability cannot be forced upon a society nor can it be achieved without the will and understanding of the public (Hopkins, 2007). In this context, various research projects, such as SPICOSA (EU FP 6 project: Science and Policy Integration for Coastal Systems Assessment), propose an approach that intends to support consultative decision-making processes aimed at improving the sustainability of coastal environment management, by making a better use of science and technology for the benefit of the society and the environment (Hopkins, 2007).

The objective of this work is to use scientific data in an integrated way in order to assess the impacts of current and past water and land use management practices on the coastal zone of Thermaikos Gulf in Northern Greece. Such a long-term impact assessment study in the sensitive and partially protected coastal area of Thermaikos Gulf is missing even though it is necessary for the development of an integrated management strategy for the future (as required by the Water Framework Directive -WFD, 2000/60/EC). The limited available data and the past anthropocentric approaches in the area's water management led to the progressive degradation of the coastal area ecological quality. Thus, for estimating these impacts, two scenarios regarding freshwater and suspended sediment discharges at the river mouths have been investigated; one without significant human interventions (natural flows, relatively undisturbed conditions) and another one with the existing human activities. The results from these scenarios have been compared to each other in order to assess the associated impacts of human interventions on fluvial water and sediment discharges into the coastal zone of the Inner Thermaikos Gulf. This approach offers a holistic picture of the impacts from the current management practices in the entire catchment including the coastal zone and can provide the scientific basis for improvements in the relevant decision-making processes.

2. Study system description

The study area is composed by (a) the coastal and marine areas of the Inner Thermaikos Gulf and (b) the catchment of the Thermaikos Gulf in Northern Greece (where intense agriculture, hydroelectric power generation, industrial and urban activities exist). In particular, the area under investigation includes the Axios and Aliakmon river catchments that are the major contributors of freshwater and suspended sediment material to the coastal zone of the Inner Thermaikos Gulf.

The Thermaikos Gulf is situated in the northwestern part of the Aegean Sea (Fig. 1) close to the city of Thessaloniki (second largest city of Greece). The bottom relief is smooth due to the continuous fluvial sediment input (mainly from the Axios and Aliakmon rivers). Water depth in the Inner Thermaikos Gulf reaches up to 40 m (Karageorgis and Anagnostou, 2001) and, generally, a wide continental shelf is formed.

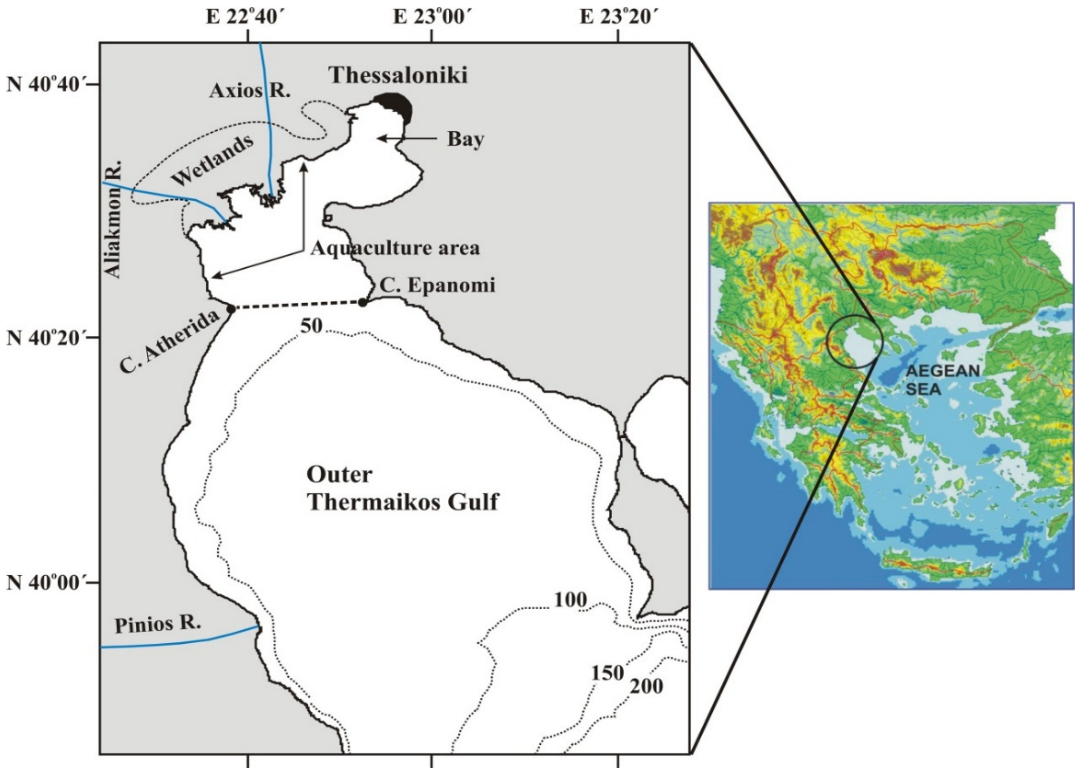

Fig. 1. The Inner Thermaikos Gulf and its main coastal characteristics as well as its location in the broader region

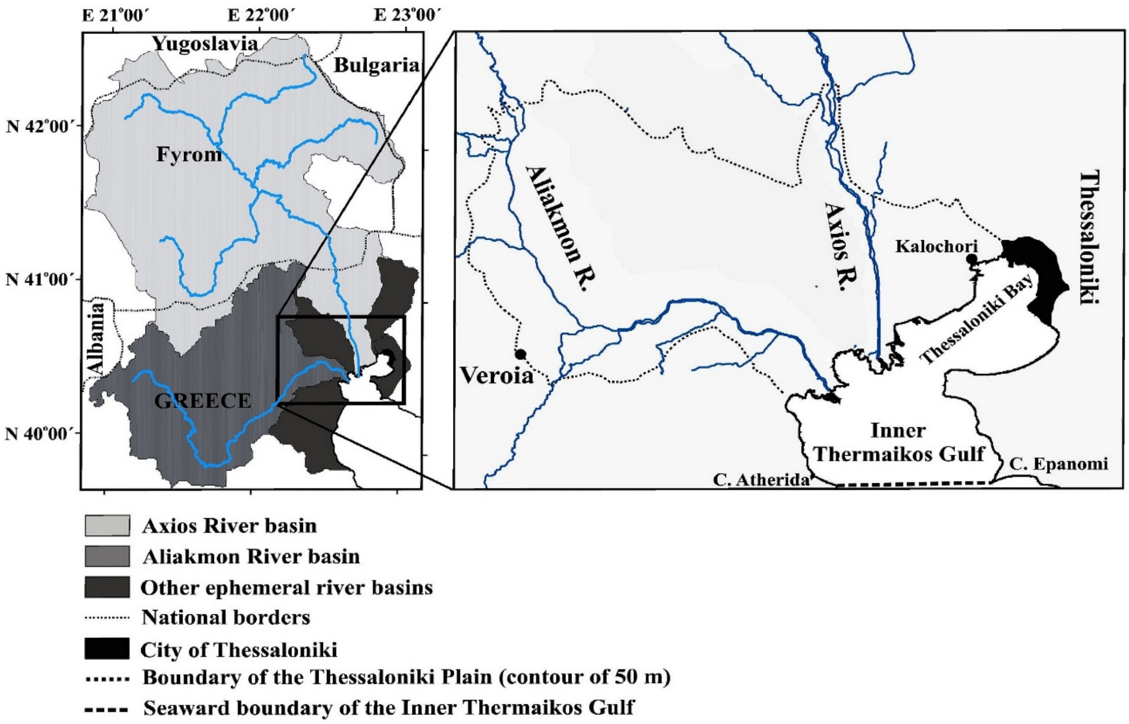

Fig. 2. The Thermaikos Gulf catchment

The watershed of the Thermaikos Gulf watershed (Fig. 2) covers a region of about 40,000 km^2 and has a human population of about 3,500,000 inhabitants (Karageorgis et al., 2005). The main rivers discharging into Thermaikos Gulf are Axios (388 km long) and Aliakmon (320 km long). The Axios River basin (Fig. 2) is located in the central Balkan Peninsula and drains 80% of Fyrom, 12% of Greece (the latter occupies the important data area) and small parts of Kosovo, Serbia and Bulgaria, with the river catchment covering an area of approximately 25,000 km^2. The Aliakmon River basin (Fig. 2) drains part of the north-western mainland of Greece extending to about 11,400 km^2, lying mainly at an elevation of more than 600 m. The climate varies between 'continental' in the northern part of the river basin and 'mediterranean' towards the coastal zone (Poulos and Collins, 2002). Mean annual air temperatures vary between 9 and 17.5 ^{0}C, while annual rainfall ranges from 400 to 1,300 mm. (Poulos and Collins, 2002).

Agricultural practices, hydroelectric power production, industrial activity and urbanization constitute the major forcing on fluvial water and sediment discharges into the Inner Thermaikos Gulf. These activities may be considered as the actors of a transformation process (i.e., quantitative modification of riverine water and suspended sediment fluxes into the sea) that have caused significant hydromorphologic alterations during the last century.

These changes have led to significant impacts on the area's ecological quality such as the loss of important wetlands in the deltaic area, coastal subsidence and erosion as well as occurrence of eutrophic sea water (Karageorgis et al., 2006). These impacts had severe consequences on some of the area's ecosystem services including the decrease in the productivity of mussel-culture farmers and fishermen, the reduction in the number of tourists, etc. (Karageorgis et al., 2006).

3. Methodology

3.1. Natural freshwater discharges

The potential monthly and annual natural water discharges of the Axios and Aliakmon rivers into Thermaikos Gulf were assessed, before and after the current human interventions on the riverine systems. To achieve this, hydrometeorological data of the period 1994-1999 were used, including annual, monthly and daily rainfall and air temperature values from a network of 16 meteorological stations (9 in the Axios and 7 in the Aliakmon catchment, Figs. 3 and 4). In addition, geological data derived from the respective maps of the investigated catchment areas were considered for estimating water infiltration, while CORINE Land Cover 2000 (European Environment Agency, 2005) maps (Figs. 5-6) in combination with bibliographic crop demand indices have been used to estimate the water consumption for irrigation in the current scenario. The main hydrogeological formations of the study area have been inferred by the geological maps and imported in the MIKE SHE hydrological model to estimate the infiltration potential. For this purpose, different hydraulic conductivity values for each hydrogeological type (high, medium, low permeability) have been assigned to the model according to values provided in the literature (Domenico and Schwartz, 1990).

For the estimation of surface runoff two different approaches have been used in order to compare and assess the consistency of the calculations. Firstly, the classical water balance equation (Ward and Robinson, 1990) with the soil moisture deficit concept incorporated (Thornthwaite, 1963) was used to identify the average annual and monthly water balance for the period 1981-2000 (Eq. 1):

$$P = AE + R + I + \Delta S\ (+ \Delta q) \qquad (1)$$

where P is the precipitation (mm), AE is the actual evapo-transpiration (mm), R is the runoff (mm), I is the infiltration (mm), ΔS is the change in storage (mm) and Δq represents the water abstractions for human activities.

Then, for the 2nd approach, the hydrodynamic 'MIKE SHE' distributed model was used (Abbott et al., 1986), in which all the available catchments' data, i.e., topography, geology, land use maps, precipitation and potential evapotranspiration (PET) was used. The grid cell size of the model was 1 km. The model output was the monthly and annual water balance of the study catchments and the calibration of the hydrodynamic model occurred in 2 ways; a) the water balance error to be close to zero (mass balance preservation principle) and b) the model water balance estimates to be comparable to the calculations of the classical water balance approach.

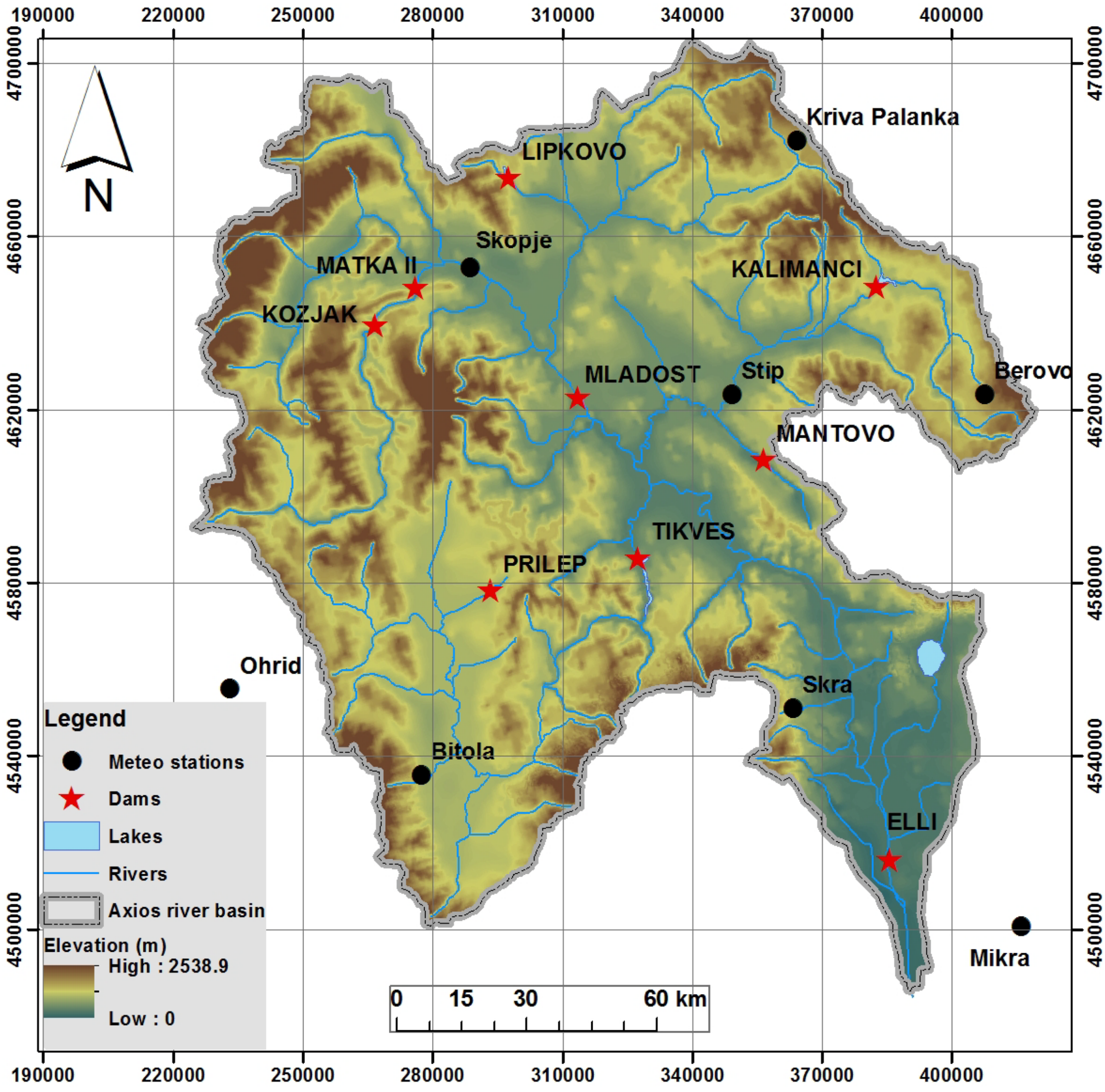

Fig. 3. Distribution of meteorological stations and the location of major dams in the Axios River basin

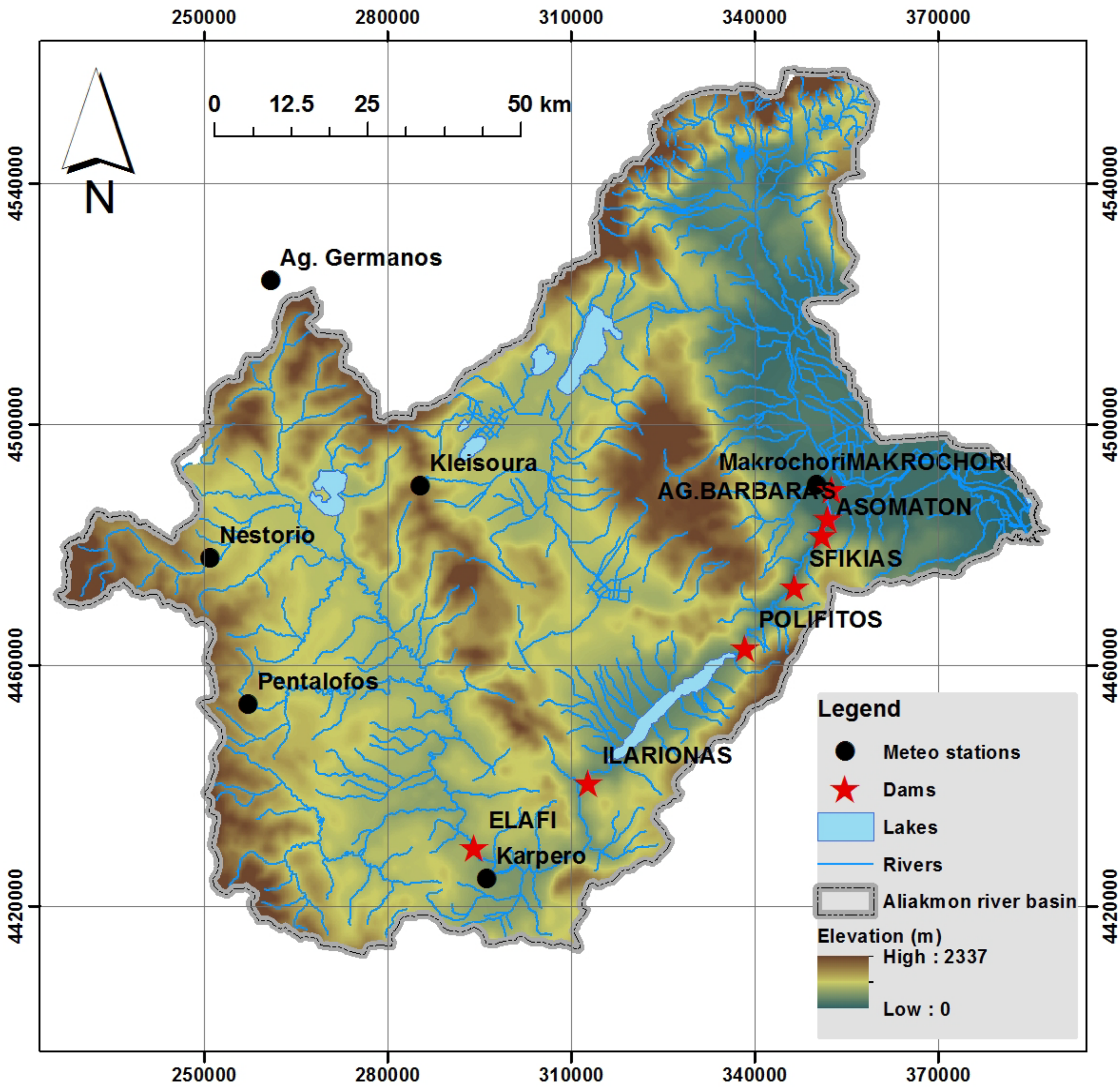

Fig. 4. Distribution of meteorological stations and the location of major dams in the Aliakmon River basin

There were not monthly or daily measurements of discharge available to calibrate the model in a detailed way but apart from the above mentioned calibration principles the available sporadic monthly and annual discharge figures from other relevant studies in the particular catchments have been taken into account for comparison and fine tuning of the model output. Thus, the calibration process incorporated data and information from three different independent sources with a strong physical background which was the best available option for these ungauged catchments. Winsemius et al. (2009) indicated the potential value of applying hydrological constraints based on ‘soft’ data and emergent properties (such as water balance levels), to reduce predictive uncertainty especially for predictions in data-scarce regions.

Hydrologic research on ungauged basins has progressed significantly during the last decades, making comparative hydrology an important tool for understanding the emergent processes regarding catchment response (Hrachowitz et al., 2013).

3.2. Water abstractions for human activities

The water needs for irrigation have been calculated using the exact extent of the irrigated land as provided by the CORINE Land Cover 2000 database (European Environment Agency, 2005) in combination with typical irrigation rates (6,500 m^3 ha^{-1} $year^{-1}$) provided by the Organization for Economic Cooperation and Development (OECD, 2000) for the broader region. The domestic and industrial water uses have been calculated taking into account the population of the study area and the respective OECD (2000) consumption rates (200 l per person per day). In addition, water losses through evaporation in the dams have been also estimated by using Hamon equation (1961). The irrigation rates per hectare, which have been used for the estimation of agricultural water abstractions, include the average demands of the dominant plants as well as some losses during the water transportation. The hydrodynamic model had the ability to simulate any amount of returning irrigation water to the river which in this case is very limited.

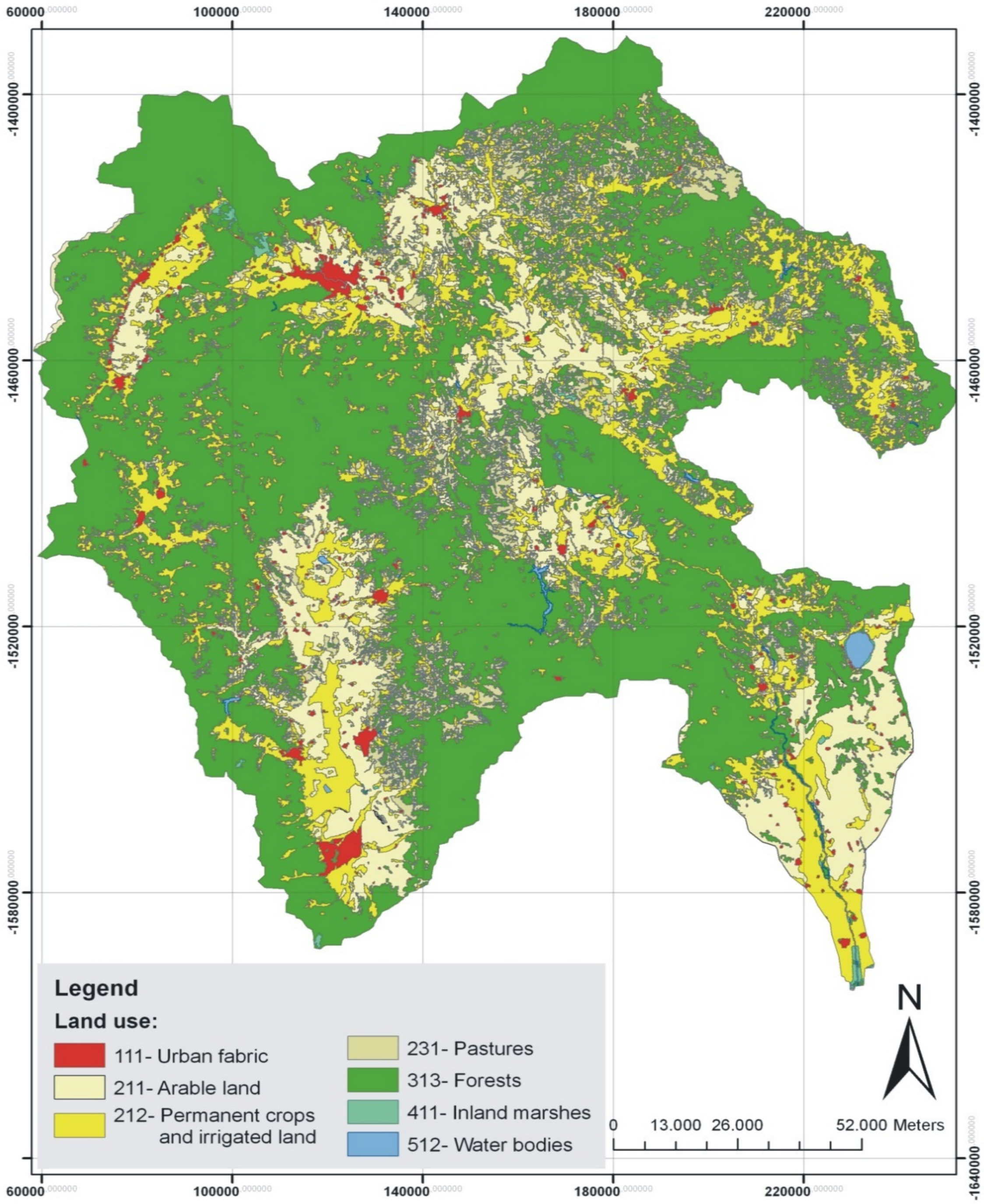

Fig. 5. Land uses in the Axios River catchment area

3.3. Riverine sediment discharges

Initially, the average annual gross erosion (in tones or m^3) in the study catchments was estimated using the RUSLE erosion model (Renard et al., 1997). This model is based on five major parameters (rainfall pattern, soil type, topography, cropping system, and management practices) with soil erosion described by the following equation (Renard et al., 1997):

$$A = R * K * LS * C * P \quad (2)$$

where: A (t ha^{-1} yr^{-1}) is the soil loss per unit area over a period (usually over a year) selected for R, R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the slope length and steepness factor, C is the cover and management factor, P is the conservation support-practices factor. The LS, C and P values are dimensionless. The soil loss model was set up in a grid-based GIS environment (ArcGIS 9.3 software), which was fed by the necessary geological, topographic, land use and soil data as well as by annual and monthly precipitation data (in raster formats) for the period 1981-2000, covering the minimum time period of 20 years recommended for the calculation of a long-term R-factor (Renard et al., 1997; Wischmeier and Smith, 1978). The land use map of the area was acquired from the CORINE 2000 database, the topography data came from the official map of the Geographical Military Service of Greece and the soil type was derived from the official soil type map of Greece from the Hellenic Ministry of Environment, Energy and Climate Change.

After the calculation of the annual gross erosion in each of the study catchment, the subsequent sediment yields that reach the coastal area were estimated considering the sediment delivery ratios as evaluated for the Axios and Aliakmon catchment areas by the Public Power Corporation of Greece (0.20 and 0.43 of the gross annual sediment production of each catchment, respectively; Tzimopoulos, 2001). These estimates represent the potential annual sediment discharges of the rivers into the deltaic area of the Inner Thermaikos Gulf, in the absence of hydromorphological disturbances.

The sediment discharges in the particular coastal area after the human interventions in the area were lowered significantly due to the constructions of dams (18 hydropower dams exist in the study area) and due to the decrease of runoff as a result of the intensive water use mainly for agricultural and urban needs (Karageorgis and Anagnostou, 2001). Especially for the Axios River, it has been estimated that there is a negative temporal trend, concerning river discharge, of -41.9% (Ludwig et al., 2009), while according to Karageorgis et al. (2005), over the past 20 years, the freshwater supply has been reduced by 32% due to extensive withdrawal mainly for irrigation.

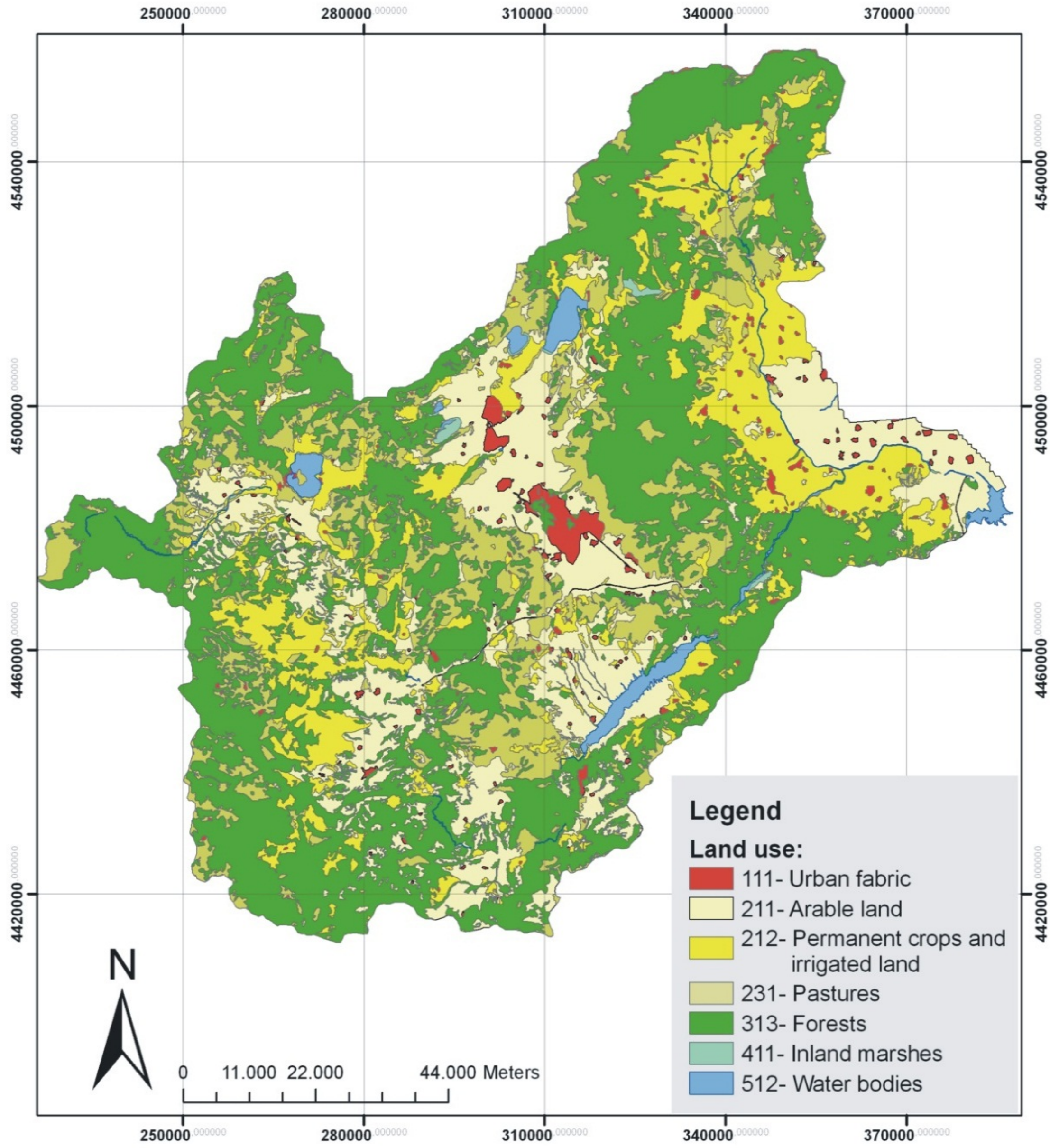

Fig. 6. Land uses in the Aliakmon River catchment area

In order to estimate the sediment retention capacity of the dams an empirical proportion of 50% of the sediment gross production in the dams' catchments was used (Vorosmarty et al., 2003). This sediment yield in the parts of the catchment that are not affected by dams (downstream of the dams) was calculated by using a power relationship between the suspended sediment discharge Q_s (Kg s^{-1}) and river flow rate Q_w (m^3 s^{-1}):

$$Q_s = a * Q_w^b \quad (3)$$

where a and b are coefficients that imply the degree of erodibility of drainage basin soils and the transport/erosion capacity of river flow (Morgan, 1985; Peters-Kummerly, 1973), respectively. For the rivers of northern Greece, a range of values between 2.3 and 3.4 may be assigned to the b coefficient (Mimikou, 1982; Panagoulia et al., 2006; Psilovikos et al., 1993) and the average value of this range has been used in this study.

Therefore, by using the output of the RUSLE model for the period prior to human interventions with the flat sediment transfer rates, the amount of sediment reaching the coastal zone has been estimated (for the reference period). By using again the RUSLE output and the 50% sediment retention by the dams the amount of sediment trapped in the dams where estimated. For the area downstream of the dams, the remaining flow as estimated by the Water Balance study has been applied to Eq. (30), in order to identify the transfer of local sediments towards the sea. These last two estimations (sediment transfer upstream and downstream of the dams) were summed up in order to provide us with a figure showing the current sediment transport, which was compared then to the prior to human intervention sediment transport (impact from the operation of the dams).

4. Results

4.1. Alterations of river discharges

The annual averaged natural water discharge of the Axios River into the deltaic zone of the Inner Thermaikos Gulf was estimated at 159 m^3 s^{-1}, whilst that of the Aliakmon River at 48 m^3 s^{-1}. These values are in good agreement with Kontoyiannis et al. (2003) that indicate average annual values of 150 and 40 m^3 s^{-1} for the Axios and Aliakmon rivers, respectively. However, it should be emphasized that there are different estimations and measurements in various studies concerning the annual average discharges of the aforementioned rivers, which can be attributed to both different study periods and changes in the water abstraction schemes (e.g. construction of a dam, abandonment of irrigation networks etc.).

The results of the anthropogenic pressures scenario illustrated great water abstractions in both riverine systems throughout the hydrologic year. For the Axios River, the water losses with respect to the natural hydrologic regime reach 51% (77 m^3 s^{-1} from 159 m^3 s^{-1}) while the highest losses are observed during summer and autumn (Tables 1, 3 and 5, Fig. 7a). The contribution percentage of each human activity in the water losses indicates that 93% of the anthropogenic water consumption is spent mainly for agricultural needs, while the industrial and domestic demands cover only 5% of the total abstractions, and the losses from hydroelectric/irrigation reservoirs evaporation do not exceed 2% of the total losses. Hence, the annual remaining water amount in the hydrologic system of the Axios River after all the anthropogenic abstractions is approximately 2570x10^6 m^3 (77 m^3 s^{-1}).

Moreover, considering the water resources of the Aliakmon River basin, 39% reduction of the natural discharge is observed today (30 m^3 s^{-1} from 48 m^3 s^{-1}; Kontoyiannis et al., 2003), whilst greater water losses can be identified during winter and spring (Tables 2, 4 and 5, Fig. 7b). Approximately 75% of the annual water losses are consumed by agriculture, while 12% of the total water abstractions are used for industrial and domestic purposes and 13% of the water losses can be attributed to the evaporation from the hydroelectric/irrigation reservoirs (Table 5). Therefore, the annual remaining water amount in the hydrologic system of Aliakmon River after all the anthropogenic abstractions is approximately 938x10^6 m^3 (ecological flow, 30 m^3 s^{-1}). This estimate is analogous to relevant measurements of the river's discharge at its mouth in the hydrologic year 1997-1998 (34 m^3 s^{-1}, Karageorgis and Anagnostou, 2001).

Table 1. Average monthly and annual water budgets of the Axios River catchment, prior to human interventions (rainfall data: average of period 1981-2000)

	Oct	***Nov***	***Dec***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***July***	***Aug***	***Sep***	***Annual***
P (mm)	88	88	103	62	59	77	52	74	45	69	60	81	858
PET (mm)	60	40	28	28	35	42	66	104	129	154	133	97	916
P-PET (mm)	28	48	75	34	24	35	-14	-30	-84	-85	-73	-16	-58
ST (mm)	20	60	60	60	60	60	46	16	0	0	0	0	
AE (mm)	60	40	28	28	35	42	66	104	45	69	60	81	658
S (mm)	0	8	75	34	24	35	0	0	0	0	0	0	176
Corrected R (mm/yr)	**162**	**180**	**192**	**196**	219	250	**239**	**224**	**208**	**192**	**175**	**163**	200

P: precipitation, PET: potential evapo-transpiration, ST: soil moisture storage (max. of 60 mm), AE: actual evapo-transpiration, S: water surplus, R: run off

Table 2. Average monthly and annual water budgets of the Aliakmonas River catchment, prior to human interventions (rainfall data: average of period 1981-2000)

	Oct	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sep*	*Annual*
P (mm)	91	127	75	60	69	40	79	67	29	35	27	16	715
PET (mm)	130	75	40	22	14	26	59	93	149	190	224	207	1229
P-PET (mm)	-39	52	35	38	55	14	20	-26	-120	-155	-197	-191	-514
ST (mm)	0	52	80	80	80	80	80	54	0	0	0	0	
AE (mm)	91	75	40	22	14	26	59	93	83	35	27	16	581
S (mm)	0	0	7	38	55	14	20	0	0	0	0	0	134
Corrected R (mm/yr)	**70**	**76**	83	121	176	190	210	**185**	**159**	**134**	**110**	**92**	134

P: precipitation, PET: potential evapo-transpiration, ST: soil moisture storage (max. of 80 mm), AE: actual evapo-transpiration, S: water surplus, R: run off

Table 3. Average monthly and annual water budgets of the Axios River catchment, after human interventions (rainfall data: average of period 1981-2000)

	Oct	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sep*	*Annual*
P (mm)	88	88	103	62	59	77	52	74	45	69	60	81	858
PET (mm)	60	40	28	28	35	42	66	104	129	154	133	97	916
P-PET (mm)	28	48	75	34	24	35	-14	-30	-84	-85	-73	-16	-58
ST (mm)	20	60	60	60	60	60	46	16	0	0	0	0	
AE (mm)	60	40	28	28	35	42	66	104	45	69	60	81	658
S (mm)	0	8	75	34	24	35	0	0	0	0	0	0	176
cumS (mm)		8	83	117	141	176	176	176	176	176	176	176	
OUTFLOWS													
Irrigation (mm)	0.00	0.00	0.00	0.00	0.00	0.00	3.60	19.8	23.4	28.8	27.0	14.4	117.00
Households and	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.53	1.53	1.53	1.53	1.53	17.17
Dam reservoirs	0.32	0.19	0.09	0.05	0.04	0.06	0.14	0.23	0.36	0.47	0.56	0.51	3.02
R=S-outflows	-1.7	6.5	73.6	32.6	22.6	33.6	-5.1	-21.6	-25.3	-30.8	-29.1	-16.4	
Cum R (mm/yr)		4.8	78.4	111.0	133.6	167.2	162.1	140.5	115.2	84.4	55.3	38.9	
Corr. R (mm/yr)	**37.2**	42.0	**78.4**	**111.0**	**133.6**	**167.2**	**162.1**	**140.5**	**115.2**	**84.4**	**55.3**	**38.9**	97.2

P: precipitation, PET: potential evapo-transpiration, ST: soil moisture storage (max. of 60 mm), AE: actual evapo-transpiration, S: water surplus, R: run off

Table 4. Average monthly and annual water budgets of the Aliakmonas River catchment, after human interventions (rainfall data: average of period 1981-2000)

	Oct	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sep*	*Annual*
P (mm)	91	127	75	60	69	40	79	67	29	35	27	16	715
PET (mm)	130	75	40	22	14	26	59	93	149	190	224	207	1229
P-PET (mm)	-39	52	35	38	55	14	20	-26	-120	-155	-197	-	-514
ST (mm)	0	52	80	80	80	80	80	54	0	0	0	0	
AE (mm)	91	75	40	22	14	26	59	93	83	35	27	16	581
S (mm)	0	0	7	38	55	14	20	0	0	0	0	0	134
cumS (mm)			22	60	115	129	149	149	149	149	149	149	
OUTFLOWS													
Irrigation (mm)	0.00	0.00	0.00	0.00	0.00	0.00	2.00	11.00	13.00	16.00	15.00	8.00	65.00
Households	0.38	0.38	0.34	0.38	0.38	0.38	0.38	0.43	0.43	0.43	0.43	0.43	4.77
Industry (mm)	0.55	0.55	0.50	0.55	0.55	0.55	0.55	0.63	0.63	0.63	0.63	0.63	6.95
Dam reservoirs	1.17	0.68	0.36	0.20	0.13	0.23	0.53	0.84	1.34	1.71	2.02	1.86	11.07
R=S-outflows	-2.1	-1.6	5.8	36.9	53.9	12.8	16.5	-12.9	-15.4	-18.8	-18.1	-	
Cum R		-1.6	4.2	41.1	95.0	107.8	124.3	111.4	96.0	77.2	59.1	48.2	
Corr. R	**48.3**	46.7	50.9	92.0	**95.0**	**107.8**	**125.4**	**114.5**	**101.1**	**83.3**	**66.2**	**56.3**	82.3

P: precipitation, PET: potential evapo-transpiration, ST: soil moisture storage (max. of 80 mm), AE: actual evapo-transpiration, S: water surplus, R: run off

Table 5. Anthropogenic impacts on the average annual freshwater discharges into the Thermaikos Gulf for the period 1981-2000

Natural water discharge $m^3\ yr^{-1}$	*Human-impacted discharge* $m^3\ yr^{-1}$	*Water losses %*	*Agricultural consumption %*	*Domestic and industrial use %*	*Evaporation in reservoirs %*
AXIOS RIVER					
5,000,000,000	2,430,000,000	51	93	5	2
ALIAKMON RIVER					
1,527,600,000	938,220,000	39	75	12	13

Table 6. Average annual gross erosion and sediment yield in the Axios River basin

Soil erosion classes $t\ ha^{-1}\ yr^{-1}$	*Classes*	*Area* km^2	*Area %*	*Gross erosion*	*Sediment yield*
0-2	Very low	19,502	80.0	8,862,000 t yr^{-1} or 6,817,000 $m^3\ yr^{-1}$ or 3.64 t $ha^{-1}\ yr^{-1}$	1,772,000 t yr^{-1} or 1,363,000 $m^3\ yr^{-1}$ or 0.73 t $ha^{-1}\ yr^{-1}$
2-5	Low	1534	6.3		
5-10	Moderate	1116	4.6		
10-20	High	927	3.8		
>20	Very high	1293	5.3		
Total		**24,372**	**100**		

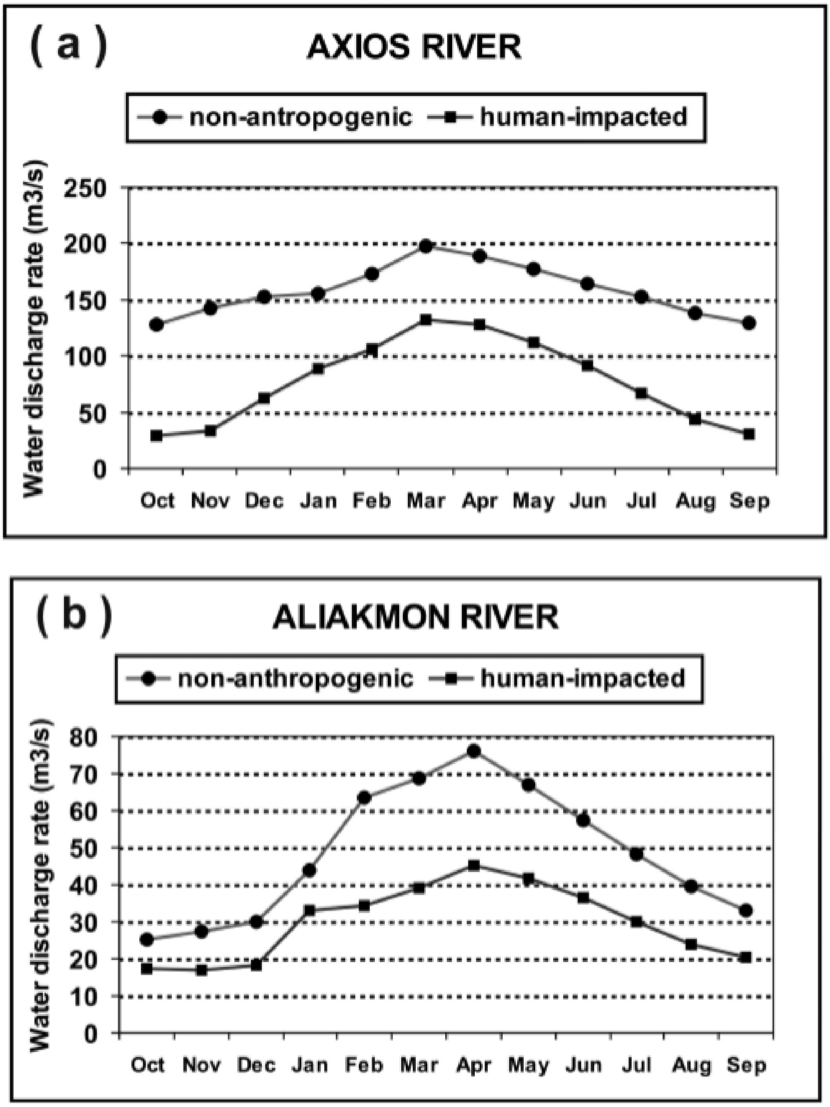

Fig. 7. Potential average monthly fluctuations of natural and human-impacted water discharges into the Thermaikos Gulf deltaic area for the time period 1981-2000

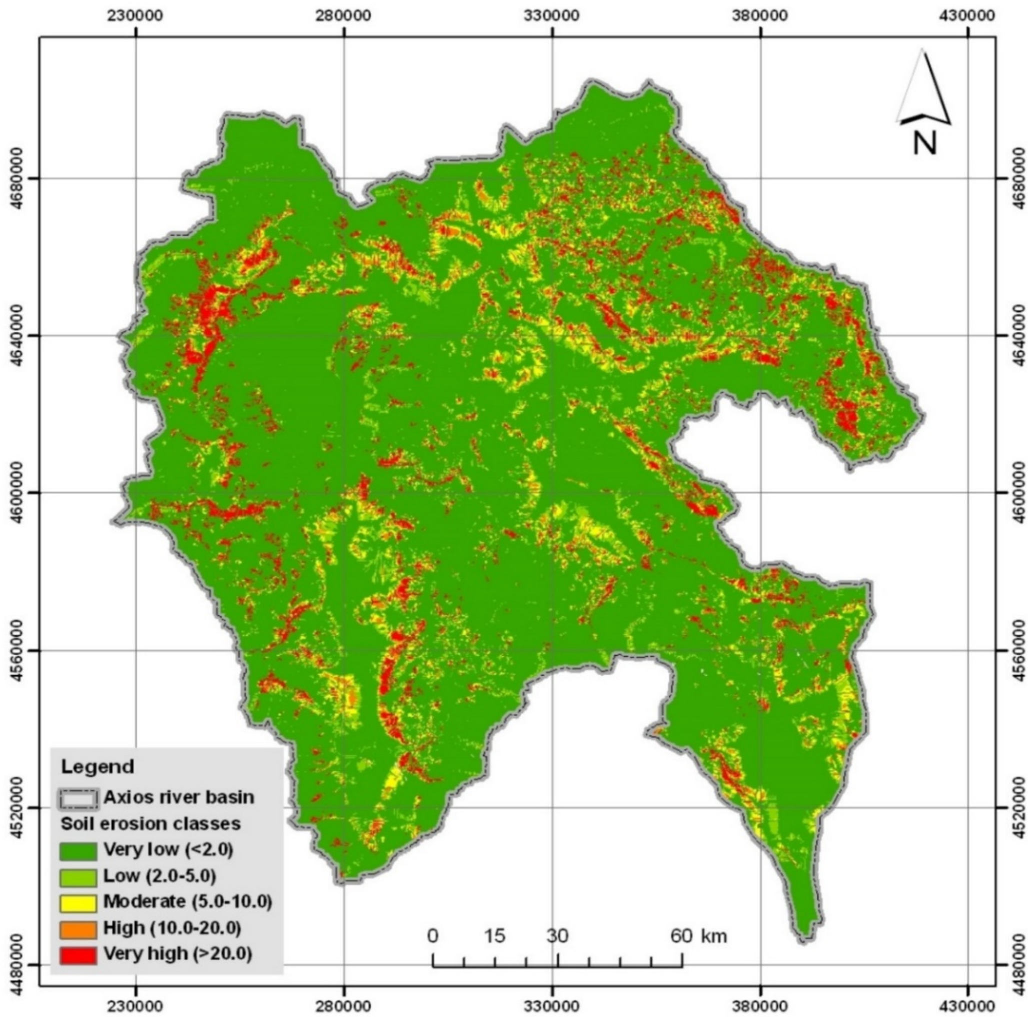

Fig. 8. Spatial distribution of soil erosion classes (t ha^{-1} yr^{-1}) according to the RUSLE model, in the Axios River basin

4.2. Alterations of the sediment yield

The gross sediment erosion in the Axios catchment reaches 8.86 10^6 t yr^{-1} (3.64 t ha^{-1} yr^{-1}), of which 1.77 10^6 t (0.73 t ha^{-1} yr^{-1}) were discharged into Thermaikos Gulf prior to the hydromorphologic alterations in the particular catchment (Table 6, Fig. 8). These results are very similar to those derived from previous relevant studies in the same basin, which have proposed a gross erosion rate of about 8.3 106 t yr-1 (Jovanovic and Vuckevic, 1957; Walling and Webb, 1987). Comparing the sediment discharges of the 'natural' scenario with those of the human interventions scenario (Table 8), a severe deviation from the natural condition is revealed. The sediment loss for the Axios River is estimated at about 90%, since 0.876 10^6 t yr^{-1} are retained by the dams and only 0.169 10^6 t yr^{-1} end up in the coastal area.

In the Aliakmon catchment the gross sediment erosion reaches 3 10^6 t yr^{-1} (2.68 t ha^{-1} yr^{-1}), of which 1.3 10^6 t yr^{-1} (1.15 t ha^{-1} yr^{-1}) were supplying the coastal area prior to human interventions (Table 7, Fig. 9). In the today's scenario only 24% of the natural sediment yield reaches Thermaikos Gulf since 0.38 10^6 t yr^{-1} remain inside dams and only 0.3 10^6 t yr^{-1} enter the coastal zone (Table 8). These results are similar to past relevant studies in the particular area that have estimated for Axios catchment an annual gross erosion of about 8.3 10^6 t yr^{-1} (5% difference with the particular study's result, Jovanovic and Vuckevic, 1957; Walling and Webb, 1987).

For comparison, Kapsimalis et al. (2005) have concluded that without any human intervention in the hydrographic network a sediment volume of approximately 2.2 10^6 m^3 per year could reach the deltaic zone of the Inner Thermaikos Gulf, which is lower than the one calculated by the present study (i.e., 3.7x10^6 t yr^{-1}). However, regarding the variable accuracy of the methods used for this kind of estimations, the observed deviation in the above estimated values is quite rational.

4.3. System response

Thermaikos Gulf coastal zone

During the period 1952-2000 many dams for irrigation purposes and hydroelectric power production were constructed (Kapsimalis et al., 2005).

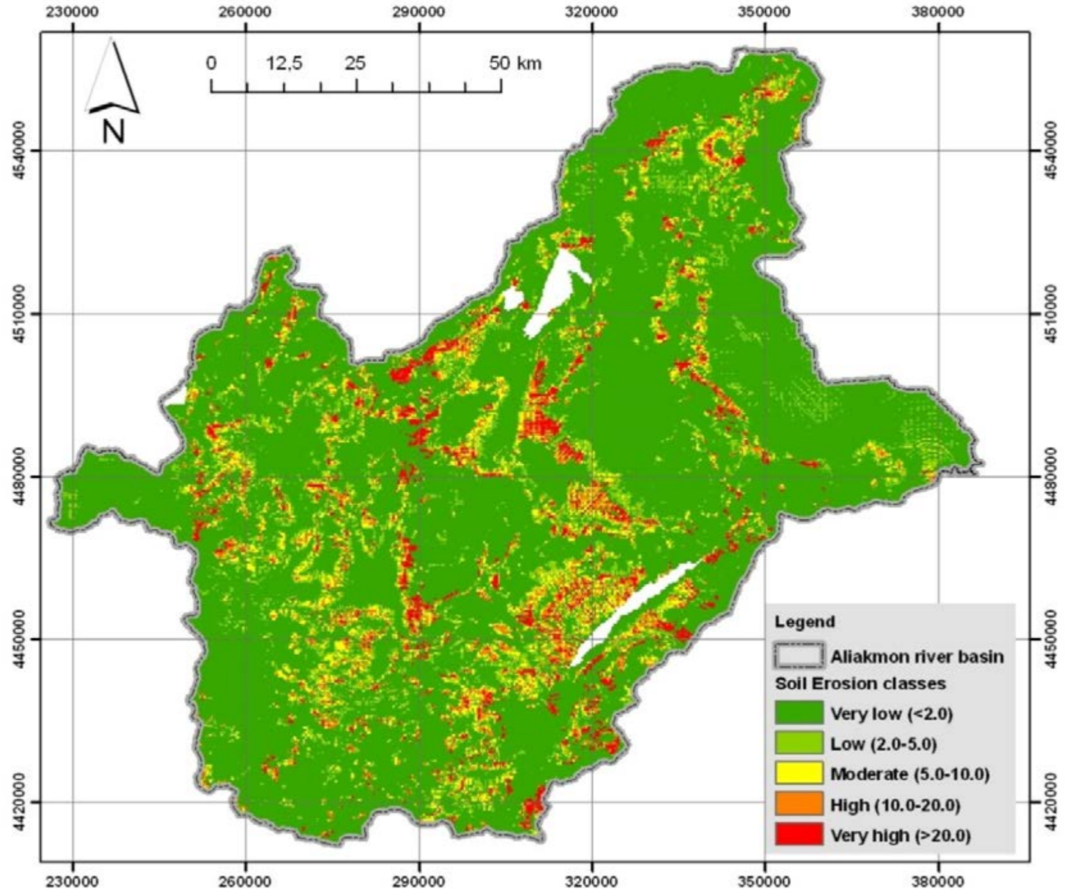

Fig. 9. Spatial distribution of soil erosion classes (t ha^{-1} yr^{-1}), according to RUSLE model, in the Aliakmon River basin

Table 7. Average annual gross erosion and sediment yield in the Aliakmon River basin

Soil erosion classes t ha^{-1} yr^{-1}	*Classes*	*Area km^2*	*Area %*	*Gross erosion*	*Sediment yield*
0-2	Very low	8,744	78.1	3,004,000 t yr^{-1} or 2,311,000 m^3 yr^{-1} or 2.68 t ha^{-1} yr^{-1}	1,292,000t yr^{-1} or 994,000 m^3 yr^{-1} or 1.15 t ha^{-1} yr^{-1}
2-5	Low	906	8.1		
5-10	Moderate	642	5.7		
10-20	High	499	4.5		
>20	Very high	411	3.7		
Total		**11,202**	**100**		

Table 8. Anthropogenic impacts on the average annual sediment discharges into the Thermaikos Gulf, for the period 1981-2000

Non-anthropogenic scenario t yr^{-1}	*Sediment losses due to*		*Human impact scenario t yr^{-1}*	*Total sediment loss %*
	Dams	*River flow reduction*		
AXIOS RIVER				
1,772,000	876,000	727,000	169,000	90
ALIAKMON RIVER				
1,292,000	382,000	601,000	309,000	76

The demand for irrigation water was substantially increased substantially, thus, freshwater was stored in reservoirs or pumped directly from the aquifers to support the cultivation of wheat, maize, rice, tobacco, and barley. Riverine water consumption still remains an increasing forcing since land reclamation projects have provided vast areas for agriculture. According to Karageorgis and Anagnostou (2001), Karageorgis et al. (2005) and Milovanovic (2007), the natural water discharges of the Axios River have lowered by 40-50% during the last 30 years, while its sediment discharges have suffered up to a 20-fold decrease. These significant reductions of freshwater and sediment influxes, identified also by the present study for the period 1981-2000, may have considerably contributed to a large-scale subsidence (maximum of 4 m) of particular coastal urban and industrial areas. Subsidence has started to occur since late 1960's in the entire Thessaloniki delta plain but it has been pronounced in the eastern part of the joint deltaic area of the Axios and Aliakmon rivers, in the Kalochori area (Fig. 2) near the city of Thessaloniki (Psimoulis et al., 2007; Stiros, 2001). This region (one of the major industrial zones in Greece) is mostly below sea level and under the threat of a permanent marine invasion. It has been occasionally covered by the sea with its major part remaining dry due to pumping operations and the occurrence of a number of coastal barriers, whilst some of its parts have been lost permanently under the sea water (Andronopoulos et al., 1991; Hadzinakos et al., 1990). This may well be due to the decreased fluvial sediment-laden inflows into the flood plain (Syvitski et al., 2009). Smaller-scale anthropogenic effects (e.g., drillings, loading of deltaic plain with heavy farm machinery) or natural processes such as oxidation of peat soils in the vadose zone and synsedimentary deformation may be superimposed.

On the other hand, the severe reduction of riverine sediment discharges has resulted in the deterioration of coastal deposits and the stimulation of rapid erosion processes (Kapsimalis et al., 2005), which have occurred for the first time in the history of the deltaic area. The deterioration of coastal deposits is manifested through an intense salinization of aquifers and soils in the joint deltaic area of the Axios and Aliakmon rivers, with an increasing trend from the north to the south (Poulos et al., 2002; Psimoulis et al., 2007; Stiros, 2001). Erosion has also affected the underwater topography and the Inner Thermaikos Gulf has entered an erosional 40-year period featuring overall sediment losses of at least 110,000,000 m^3 (Kapsimalis et al., 2005). Breakwaters and seawalls have been constructed in a length of about 22 km to protect the coast from erosion and these works are still in progress.

An indirect consequence related to the diminishing riverine freshwater supply to the Inner Thermaikos Gulf is that high discharges enhance (Karageorgis et al., 2006; Kontoyiannis et al., 2003; Poulos et al., 2002) the cyclonic circulation of the Thermaikos Gulf water masses contributing to the dilution/mixing of the Inner Thermaikos Gulf water volumes, which are enriched in various domestic, industrial and agricultural effluents (Kontoyiannis and Karamanos, 2000). This equilibrium is often disturbed during the summer months when low river water inflows reduce the dilution of nutrients (mainly phosphates) in the gulf's water masses, leading to stagnation in the Inner Thermaikos Gulf and decay of the existing algal blooms (Moncheva et al., 2001). It should be emphasized that although lower river discharges unload lower amounts of nutrients, the river plume is restricted within the Inner Thermaikos Gulf (in contrast with plumes of higher river discharges, which are directed into the outer Thermaikos Gulf; Karageorgis et al., 2000).

4.4. Ecosystem services

Impact on mussel-culture

Hundreds of mussel farms are located in the Thermaikos Gulf, covering an area of approximately 1.35 10^6 m^2, with water depths varying from 4 to 20 m. Mussel farmers constitute a group which is strongly dependent on the freshwater of Axios and Aliakmon rivers and, mainly, on the particulate silicate matter supplied by them. It has been estimated that a single shellfish filters approximately 70 g of suspended particulate matter per year and uses 50% of that matter for its growth (Widdows et al., 1979). The mussel farming activity in the deltaic area is profitable, comprising 50% of the total Greek shellfish production. The abundance of freshwater and suspended silicate particles near the river mouths contributes significantly to the faster growth of shellfish populations, resulting in higher profits for the mussel farmers (Skourtos et al., 2004)**.**

The value of the annual mussel production is estimated to be more than 10 million euros and a few thousand people are employed in the farming units (Zanou and Anagnostou, 2001). During the period 2000-2002, large quantities of mussels that affected by toxic algal blooms were not released to the market. The economic losses due to that event were estimated at about 3 million euros per year (Karageorgis et al., 2005). The development of toxic algal blooms (*dinoflagellate sp*.) from January to May (Karageorgis et al., 2005; Moncheva et al., 2001), due to the identified eutrophic state in the Thermaikos Gulf (Kontoyiannis and Karamanos, 2000; Nikolaidis et al., 2006), apart from increased nutrient inputs, may be attributed also to the deficit in riverine freshwater inflows (Giannakourou et al., 2005; Koukaras and Nikolaidis, 2004).

4.5. Impact on amenity, tourism and fishery

The coastal area east and southeast of the city of Thessaloniki had been a traditional tourist resort area during the 1950's and 1960's. However, the aesthetic degradation of the coastal waters (e.g., production of noxious odours, occurrence of pathogenic bacteria) due to the eutrophication has caused inhibition of swimming and other contact recreational activities. It is difficult to assess the cost of this massive (over the years) change in the touristic industry of the area but, according to Skourtos et al. (2004), the total annual economic benefit of restored, clean coastal waters of the Inner Thermaikos Gulf is estimated at 34.2 million euros.

Furthermore, the joint deltaic area of the Axios and Aliakmon rivers is one of the most important wetlands in Europe (Natura 2000, Ramsar site, and a National Park since 1998). Nevertheless, a large part (70%) of the original wetland area has been lost and the rest has been considerably salinized, with the flora and fauna biodiversity significantly declining (Albanis et al., 1996; Goutner et al., 2001; Zalidis, 1998).

However, the fact that the Axios and Aliakmon coastal wetlands are near the city of Thessaloniki, provides many ecotouristic opportunities, such as countryside walks, birdwatching, environmental education activities and agrotouristic activities (e.g. shellfish farming).

Moreover, the shallow waters in the deltaic coastal area provide shelter to the fry and, generally, serve as spawning places for the fish populations of the Thermaikos Gulf (Alexandridis et al, 2009). Therefore, the study area has a tremendous importance for maintaining the fishing grounds of the north Aegean Sea. For this reason, the degradation of the deltaic area in combination with the hostile fishing practices cause significant economic losses and have led to the depletion of fishing stock several times in the past (Kontogianni et al, 2005).

4.6. Policy

Although, state and public awareness rose after 1970 and generated plans and support for a more sustainable use of ecosystem's freshwater and sediment resources, the policy actions up to the start of the 21st century were not effective. This is apparent considering the severe anthropogenic impacts on the Inner Thermaikos Gulf as indicated also in the present study. Hence, if the existing policies and management practices remain the same in the future the identified impacts will be enhanced, with dramatic economic losses for aquaculture, tourism and fishery, as well as for the ecological status of the area.

Although the understanding of the functions and values of coastal ecosystems has been improved, the implementation of National, European and International laws for the accomplishment of sustainability requires concerted action and mutual cooperation between scientists and policy makers in order to be successful.

An integrated management plan for the study catchments should be developed and implemented based on scientific findings and being consistent with the various EU policies (EU Common Agricultural Policy, Water Framework and Habitat Directives) and International Agreements. On the regional scale, various actions could be incorporated into future policy measures including: (1) Gradual replacement of high water consumption crops (e.g., cotton, rice); (2) Change of the water pricing policy. The farmers should be charged with the real cost of the water volume consumed and not with a standard flat rate covering only basic running expenses of the irrigation networks; (3) Implementation of the 'minimum Ecological requirements flow' principle in the dams allowing higher water discharges, especially, during summer periods, to avoid stagnancy of the coastal waters and supply with more sediment the deltaic and coastal areas; (4) Partial removal of artificial levees in the canalised sections of Axios and Aliakmon rivers in order the deltaic plain to be fed again with freshwater and sediment; (5) Control of illegal water pumping in the deltaic plain; (6) Legislation imposing rules for the illegal sand extraction from river beds; (7) Upgrading of ecotourism and increasing public awareness for the protection of the area; (8) Further expansion of constructions protecting from erosion in the coastal zone under most threat.

5. Conclusions

An integrated assessment effort has been applied to evaluate the environmental, social and economic balance in the Thermaikos Gulf watershed with focus on the riverine freshwater and sediment resources. Agriculture, hydroelectric power generation, industry and urbanization, are the benchmark human activities that exert variable forcing on system's freshwater and sediment resources, altering the natural condition. Regarding the Axios River, during the last century, the freshwater discharge was reduced by about 51% with the sediment yield diminishing by about 90%, mainly due to construction of hydropower dams in the area. For the Aliakmon River, the relative reductions in freshwater and sediment discharges reached 39 and 76%, respectively. The extensive irrigation and hydropower production activities are the basic actors for this deviation from the natural condition.

The reduced freshwater and sediment influxes to the deltaic zone contribute to a negative ecological response and to economic, aesthetic and livelihood impacts. The ecological response comprises severe subsidence and erosion of coastal areas, great loss of significant wetlands, occurrence of phytoplankton blooms (occasionally of toxic species), and anoxic conditions in the sea water column. In addition, substantial reduction in the income of specific activities that depend on ecosystem services, like mussel farming, tourism and fishing has been recorded, while there has been significant aesthetic degradation of the marine environment during the study period.

Various actions have been proposed to tackle the identified problems, whilst long-term monitoring of the water and sediment fluxes from the Axios and Aliakmon River basins as well as of the coastal area should be conducted on a daily basis to evaluate the system's feedback under various policy actions.

Several environmental protection actions have been carried out in the coastal zone (e.g., extending the part of the deltaic area that is protected under the Ramsar Convention and Natura 2000 network), however, in order for these actions to be effective, they should also be applied beyond the boundaries of the coastal territory, focusing on the catchment scale. Moreover, major stakeholders, such as farmers and hydroelectric companies, should participate actively in the planned policy actions for improving the future use of the ecosystem services.

The SPICOSA project output reveals that science and policy integration for the management of the riverine water and sediment resources is required to address effectively the disorder among ecology, social and economic development. The implementation of such an approach to the Thermaikos Gulf coastal system will contribute to the consideration of all factors interacting in the watershed-coastal zone continuum, bridging at the same time socio-economics, natural sciences and policy actions.

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