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An integrated approach to watershed management within the DPSIR framework: Axios River catchment and Thermaikos Gulf

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Abstract The coastal zone of the inner Thermaikos Gulf has been influenced by eutrophication during the past decades. The conditions of the catchment area-coastal zone continuum are assessed under the holistic Driver-Pressure-State-Impact-Response (DPSIR) framework. Major socioeconomic drivers, such as industrial and agricultural development as well as urbanization, exert substantial environmental pressures on the Axios River and the Thermaikos Gulf. The Thermaikos Gulf is a highly complex system, being affected by nutrient inputs from four rivers and the City of Thessaloniki. Moreover, the Axios River which is the most significant contributor of freshwater and nutrients to the gulf, is a transboundary river shared between Greece and the Former Yugoslav Republic of Macedonia (FYROM). The two countries have not yet established a mutual management plan to control freshwater and nutrient discharges. Long-term analysis has shown that presently, more than 11,800 t of nitrogen and 3,400 t of phosphorous are released annually into the marine system. In the Antropocene era, and particularly during the past 20 years, freshwater discharges have decreased and riverine nutrients have increased, whereas inputs from domestic and industrial effluents have a decreasing trend. However, nutrient over-enrichment impacts, i.e. eutrophication, harmful algal blooms and hypoxia still have to be addressed in order to identify whether the coastal system is recovering, or whether further actions should be undertaken to control nutrient inputs from the Axios River and/or other sources. Response actions, such as the improvement of Thessaloniki's wastewater treatment plant, have proved to play a positive role in the reduction of domestic wastewater input in the gulf, whereas similar facilities are completely lacking in FYROM. On the other hand, several parts of the Axios River delta are designated as protected areas, in an effort to protect environmentally rich habitats. These efforts are often disputed by local stakeholders, which have conflicting interests in the use of the hinterland and the coastal environment. The need of an integrated catchment-coastal zone management plan appears as a fundamental priority in order to protect, improve and maintain the environment, taking into account the need for economic development of the area. The DPSIR conceptual framework appears to be a valuable tool, as it enables parallel assessment of socioeconomic and environmental issues. In combination with the application of numerical models, the DPSIR analysis may provide suggestions for sustainable and environmentally-friendly measures to policy makers.

SI: Pirrone

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Introduction

Fundamental changes in the Earth's system have been observed since the invention of the steam engine (1784) and particularly after the 1950s, giving birth to the new term 'Anthropocene era' (Crutzen and Stoermer 2000;

Meybeck 2001a, 2001b). Human impacts on river basins during the Anthropocene have been documented on all continents, especially regarding the alteration of natural hydrological regimes and the general degradation of the water quality in continental (and coastal) aquatic systems (NRC 2000; Meybeck 2002).

The origins of 'catchment management' can be traced back to biblical times (Newson 1997), and remnants of ancient water management technology can be found today in many parts of the Mediterranean region. In recent years, public authorities have proactively exerted control over their watersheds in order to secure supplies and reclaim land for agricultural purposes. Therefore, Mediterranean catchments, especially their coastal zone, have been modified and degraded to a great extent. For example, the loss and/or degradation of coastal wetlands in the 20th century amounts to 73% of marshes in Greece, 86% of the most important wetlands in France, 60% of wetlands in Spain and 15% of lakes and marshes in Tunisia (MedWet 1996). The reasons for this have been the prevention of water-born diseases, the development of agricultural land and the expansion of cities. On the other hand, river dams are one of the major factors for coastal erosion and wetland loss (Poulos and Collins 2002).

Catchment management represents a complex problem and therefore requires fully integrated approaches. By 'integrated approaches', we refer here to a 'team based' learning process for experts, decision makers and stakeholders (Ledoux et al. 2002). The Driver-Pressure-Status-Impact-Response (DPSIR) sequence, is increasingly used to address integrated management issues in the marine environment (Turner et al. 1998; Elliott 2002).

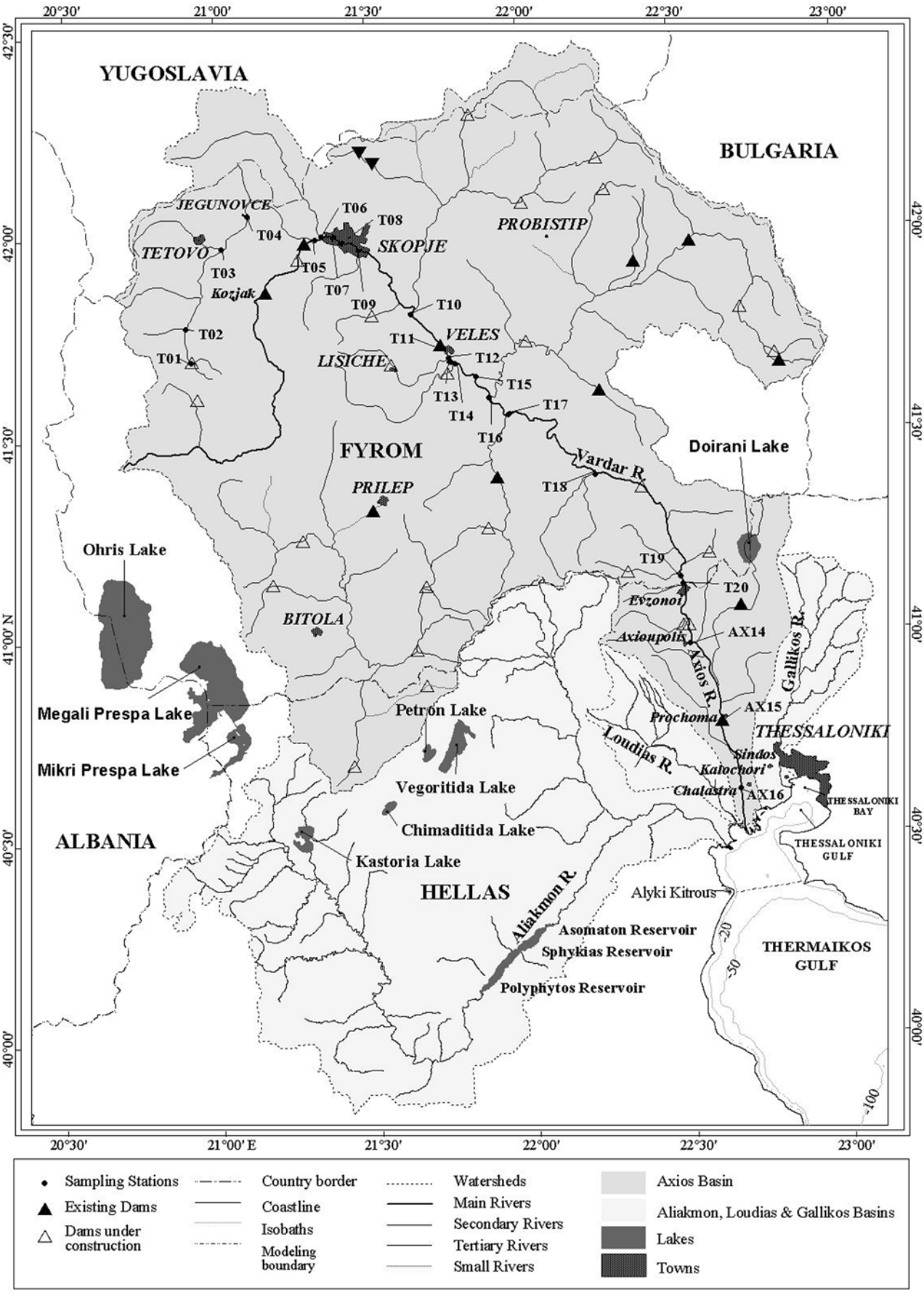
The DPSIR approach is currently applied, within the framework of the EUROCAT Project, in six European catchments, to address various stressors of the marine environment. In the case of the Thermaikos Gulf in the NW Aegean Sea (Fig. 1), eutrophication has been identified as a major problem that requires management action. The inner Thermaikos Gulf is a shallow (< 50 m) marine bay which receives freshwater from four rivers, namely the Axios, Aliakmon, Loudias, and Gallikos. However, in the past, the discharge of untreated urban and industrial sewage as well as agricultural-stock-breeding runoff increased the levels of nutrients in the rivers. Of all the rivers, the most important in terms of freshwater contribution is the Axios River. The Axios River, with 83% of its watershed area belonging to the Former Yugoslav Republic of Macedonia (FYROM), has been reported to be the second most polluted Greek river, in terms of nutrients, organic matter, oxygen concentration and selected heavy metals (Skoulikidis 1993). Even though the Axios River contributes only 10% to the major Greek river discharges (~78% of total Greek river runoff), it carries 1/3 of the total phosphate load of these rivers into the Mediterranean (Skoulikidis 2002). In addition, the Thermaikos Gulf receives domestic and industrial effluents from the second largest city of Greece, Thessaloniki, with a population of 1,200,000. Until recently, none or only a part of the sewage was treated. These elevated nutrient inputs in the sea have resulted in substantial levels of eutrophication (Gotsis-Skretas and Friligos 1990; Balopoulos and Friligos 1993) and the occurrence of algal blooms (Moncheva et al. 2001). Currently, the wastewater treatment facilities in Thessaloniki are being substantially upgraded.

This paper reviews the current state of our knowledge concerning the integrated assessment of nutrient inputs in the inner Thermaikos Gulf, where the Axios River catchment (hereafter AXCAT) represents: (1) the largest part of the watershed of the Thermaikos Gulf coastal system; and (2) the major contributor of freshwater and nutrient fluxes. In addition, the other rivers and the city of Thessaloniki are assessed as nutrient sources, in order to estimate the total diachronic input of nutrients into the gulf. The structure of the present work follows the DPSIR scheme, analyzing concurrently each one of its components. Therefore, socio-economic drivers, environmental pressures, the state of the watershed and the coastal environment are addressed, and the consequential impacts on human welfare are discussed, along with the policy response options. However, the main scope is limited to a number of issues referring mainly to the impacts of nutrient over-enrichment on the coastal zone. For example, the impacts of heavy metal pollution or elevated pesticide levels will not be addressed here. The importance of these issues is appreciated, but the concept would be too wide for an efficient analysis. The data used in this study were obtained from a wide variety of sources that differed in their scope, methodological approach and temporal coverage (including the census, specific studies and smaller quantitative and qualitative publications). This review is by no means exhaustive; it represents work in progress, focusing on the major analytical questions of a prospective analysis of AXCAT's main management issues and options. It combines descriptive, analytical and evaluative dimensions, and presents some interpretations of the available evidence, along with suggestions for further research and integrated coastal zone management.

Regional setting

The inner Thermaikos Gulf

The Gulf of Thermaikos is located in the northwestern part of the Aegean Sea; its northern part is named Thessaloniki Gulf after the city of Thessaloniki. The catchment area of the Thermaikos Gulf is ~40,000 km^2, and the main rivers are Axios, Aliakmon, Loudias and Gallikos (Fig. 1). The bottom relief is smooth, as a result of continuous sediment input from the rivers. Water depths in the gulf of Thessaloniki are less than 30 m (Karageorgis and Anagnostou 2001). The gulf of Ther-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AX14
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AX16
Vardar R.
Axios R.
Gallikos R.
Loudias R.
Aliakmon R.
Doirani Lake
Ohris Lake
Megali Prespa Lake
Mikri Prespa Lake
Petron Lake
Vegoritida Lake
Chimaditida Lake
Kastoria Lake
Evzonoi
Axioupolis
Prochoma
Sindos
Kalochori
Chalastra
THESSALONIKI
THESSALONIKI BAY
THESSALONIKI GULF
Alyki Kitrous
Asomaton Reservoir
Sphykias Reservoir
Polyphytos Reservoir
THERMAIKOS GULF
-20
-50
-100
Sampling Stations
Existing Dams
Dams under construction
Country border
Coastline
Isobaths
Modeling boundary
Watersheds
Main Rivers
Secondary Rivers
Tertiary Rivers
Small Rivers
Axios Basin
Aliakmon, Loudias & Gallikos Basins
Lakes
Towns

◀

Fig. 1 The catchment area of the Thermaikos Gulf

maikos forms a wide continental shelf. The area of interest within the EUROCAT project lies in the northern sector of the Thermaikos Gulf, where water depths are between 20 and 60 m. Water mass circulation is predominantly cyclonic (Robles et al. 1983; Balopoulos 1985; Sultan et al. 1987; Durrieu de Madron et al. 1992). Aegean water masses enter the gulf from deeper layers along the eastern coast and move counter clockwise toward the gulf of Thessaloniki. Riverine waters usually move to the south along the western coast; however, in some cases freshwater has been traced into the gulf of Thessaloniki under the forcing of westerly winds (Kontoyiannis et al. 2003). Water exchange with the Aegean Sea is stronger in the period of high river discharge. During summer and autumn, Black Sea waters are traced in the gulf of Thessaloniki (Hyder et al. 2002; Kontoyiannis et al. 2003). Water temperature varies between 10 °C and 28 °C, whereas salinity varies between 33 and 39 psu (Poulos et al. 2000). Elevated nutrient inputs from the rivers and urban as well as industrial runoff are the main causes of eutrophication, which has been reported as a major problem in the gulf of Thermaikos (Gotsis-Skretas and Friligos 1990; Balopoulos and Friligos 1993; Moncheva et al. 2001).

The Axios River catchment

The Axios River basin is located in the central Balkan Peninsula (Fig. 1) and drains 80% of the Former Yugoslav Republic of Macedonia (FYROM), parts of Bulgaria, the Federal Republic of Yugoslavia and Greece (Hellas), the latter occupying the delta area. The catchment covers an area of approximately 25,000 km^2 and hosts a population of ~1,834,000, 1,600,000 of which reside in FYROM (the total population of FYROM is 1,800,000 according to a census in 1994) and 234,000 in Greece (census 2001). Average population density in FYROM is 81 inh/km^2, whilst sixty percent of the population live in urban areas. The average population density in the Greek part of the AXCAT is 60 inh/km^2. Furthermore, the population within the entire Thermaikos Gulf catchment, according to most recent census data, is estimated at 3,300,000 inhabitants.

The climate varies between continental in the northern part of the catchment and Mediterranean towards the coastal zone (Poulos et al. 2000). Mean annual air temperatures vary between 9°C and 17.5°C, while annual rainfall ranges from 400 mm to 1300 mm (Poulos et al. 2000). The western and north-western part of the catchment is mountainous, and the highest altitude is ~2,400 m, whereas at the eastern boundary altitudes reach 1,800 m. Altitudes in the river valley range between 250 and 750 m, and the delta area in the Greek side ranges from 0 to 250 m. Alluvial, lacustrine deposits and flysh-molasse cover the river valley and the delta. The mountainous areas are formed largely by metamorphic rocks, limestones, patches of granitoids, volcanic rocks, and ultrabasic formations (ophiolites, serpentinites and peridotites). The latter are important sources of Pb-Zn ores that are exploited in smelting factories located in Veles and Probistip.

Over the past decades, the river has suffered numerous human interventions. In the beginning of the 20th century the river mouth was located a few kilometers SW of Thessaloniki, threatening the access to the port, as a result of continuous siltation. The river course was altered artificially to the area where it discharges today; the construction commenced in 1930 and lasted four years (Evmorphopoulos 1961; Kotoulas 1984). Since then, the river propagated rapidly, building an extensive deltaic plain; however, recent observations have demonstrated that erosional processes have prevailed over the past thirty years (Poulos et al. 1994; Kapsimalis et al. 2002).

Materials and methods

Socio-economic analysis

Behavioral decision research and decision analysis give a basic structure for research into how prescriptive techniques can be used to improve the quality of group decision processes. Recent research (Kontogianni et al. 2001; O'Riordan 2001) indicates that stakeholder values are the key to a structured decision approach to public involvement.

Stakeholder values identify what matters to participants, and, in turn, highlight the consequences that require most careful attention, and the tradeoffs that matter most (Gregory 2000). According to Hammond et al. (1999), meaningful involvement in the decision making process requires not only an invitation to participate, but also a forum for careful deliberation, and a mechanism for incorporating the results of technical analysis. Focusing on stakeholder values early in the EUROCAT-Axios project, two major stakeholder groups were identified and selected: (a) community residents; and (b) state and local resource managers/technical experts. The focus group technique for eliciting preferences and trace conflicts between community residents was applied to three professional groups: farmers, fishermen/shellfish producers and industrial producers. To interpret the focus group results, the content analysis methodology was employed. The second stakeholder level (local and state resource managers) was approached in two different ways: (a) a pre-constructed questionnaire was dispatched to representatives of state agencies followed by a first round of discussions; and (b) the focus group technique was engaged for local resource managers. Useful input was received from all stakeholder groups approached for public involvement. The values elicited from stakeholders will be fed into multi-criteria analysis at a later stage. It is expected that

within next phase of research, stakeholders will be invited to enter the consultation process by interpreting factual scenarios. As Gregory (2000) states: '... disagreements in the expressed values of participants or differences in their interpretation of factual evidence are welcomed and examined in the context of what they can show decision makers about the links from stakeholders' support of, or opposition to, specific options to their underlying preferences'.

Nutrient inputs from the rivers

Long-term measurements (1981–2000), mainly obtained from the Hellenic Ministry of Agriculture (http://www.minagric.gr/), have been used for the assessment of nutrient trend analysis. This is the most comprehensive dataset available, based on monthly measurements, although very often many values were missing. To compensate for missing values, the algorithm of Skoulikidis (2003) was applied, wherever this was possible. Nutrient data for the FYROM part of the Axios River were three years (1996–1998) monthly averages (Levkov 2001), measured at 20 stations (Fig. 1). The water discharge is a key parameter required to calculate fluxes of nutrients; this was the most difficult parameter to acquire, as river monitoring is not conducted in Greece on a daily basis. However, all available data (monthly and daily measurements) for the Axios and the Aliakmon rivers were collected to estimate nutrient fluxes. Moreover, the Hydrometeorological Institute of FYROM has recently provided long-term mean daily discharge data, obtained from Gevgelija (1961–1996) and Demir Kapija (1996–2000) stations, situated near the Greek-FYROM border. Correlation of these data with the mean monthly discharge data obtained from the Greek stations (AX-14: Thessaloniki-Eidomeni Railway Bridge, AX-15: Prochoma, and AX-16: Chalastra, see Fig. 1 for location) was statistically significant; therefore, we have used this dataset to generate mean daily discharge values for the Greek stations. The latter data were integrated on a monthly basis to calculate the monthly water flux. The annual flux of nutrients was calculated as follows:

$$F_N = \Sigma\left((\Sigma Q_{ij}) * C_j\right)$$

where i = day of the month, j = month of the year, F_N = nutrient flux, Q_{ij} = daily water discharge during month j, and C_j = nutrient concentration measured during month j.

Nutrients, dissolved oxygen and chlorophyll *a* in the Thermaikos Gulf

The gulf of Thermaikos has been monitored regularly since the 1990s within the framework of national and EU projects, conducted by the HCMR. The data used in this paper are derived from a study performed over the continental shelf of Thermaikos Gulf, up to 50 m depth. The study included a full annual cycle of monthly observations of environmental parameters performed in the framework of the EU Metro-Med project (Pagou et al. 2000) and a national monitoring project funded by the 'Thessaloniki Water Supply and Sewerage Company S.A. - EYATH' (NCMR 2000). The sampling stations encompassed the inner area of Thermaikos Gulf, where a gradient of trophic conditions exists, from eutrophic in the shallow northern part, to meso-oligotrophic in the southern part. Integrated values were calculated by the trapezoid rule, from the surface to the bottom, and were divided by the depth of the integration, providing a weighted mean value.

Dissolved oxygen and nutrients: Samples for the determination of nutrients were collected in 100 mL polyethylene bottles from standard depths and kept continuously under deep freeze (−20°C) until analysis in the laboratory, by an ALPKEM Flow Solution III autoanalyser. Phosphates were measured on board by a Perkin Elmer Lambda 2S UV/VIS spectrometer. The methods described by Murphy and Riley (1962) for phosphates, and Strickland and Parsons (1968) for nitrates, were employed. For the dissolved oxygen determination, samples were analyzed immediately after collection with the Winkler method, as modified by Carpenter (1965a, 1965b).

Chlorophyll a: For chlorophyll *a* determination, 0.5–1 L of seawater was filtered through Millipore polycarbonate filters (diameter 47 mm, pore-size 0.2 μm) and stored immediately at −20°C. At the laboratory, the filters were ground in 10 mL 90% acetone solution, and measured on a TURNER 00-AU-10 fluorometer (Holm-Hansen et al. 1965)

Nutrient inputs from point sources

Two wastewater treatment plants (WWTP-1 of Sindos and WWTP-2 of Nea Michaniona) discharge processed domestic effluents directly into the sea, through underwater pipelines (Fig. 2). Treated industrial effluents from the WWTP-3 (Sindos) reach the Thermaikos Gulf, through a channel. Data concerning the nutrient concentrations of the effluents have been obtained from EYATH. The levels of nutrients in industrial wastewater have been estimated from data obtained by Tsagarlis (1998).

Other data

Statistical data on primary crops of FYROM (1992–2001) were obtained from FAO (2002), assuming that the entire country is drained by the Axios River. Similar data for the Greek part of the catchment were collected from the National Statistical Service of Greece (NSSG; http://www.statistics.gr/) at the municipality level, and afterwards the data were summed for the whole Greek part.

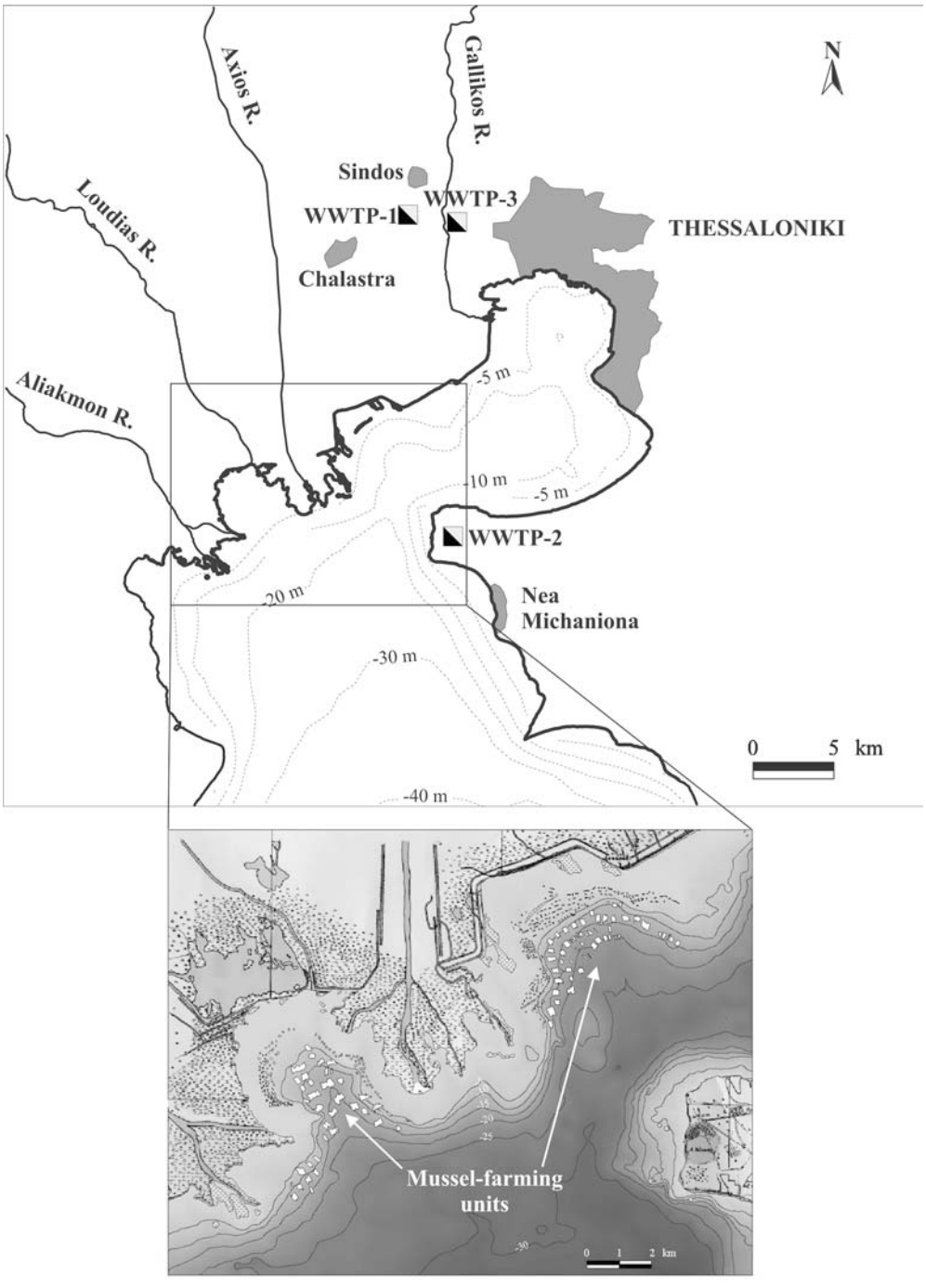

Fig. 2 Location and type of WWTPs. 1: municipal WWTP of Sindos; 2: municipal WWTP of Nea Michaniona; 3: industrial WWTP of Sindos. Inset map: location of mussel-farming units in the Thermaikos Gulf

Analysis of the Axios catchment - coastal area according to the DPSIR framework

Drivers

Socio-economic drivers, which are adopted here, remain on broad issues, i.e. the political situation in the Balkans, Greek development policy for the area, and the citizen's life-style, driven by major EU/national legislative frameworks. In other words, driving forces are translated here as the back up forces, which 'drive' the society to enforce or decrease the pressures to the environment. The major socio-economic drivers that affect the total Axios catchment area (FYROM and Greece) can then be summarized as follows: (1) the wider political and economic destabilization of the Balkans region leading to uncertainty, delay in the rate of growth and difficulty to tackle environmental degradation; (2) the new Greek Development Strategy for the role of Thessaloniki as the new Metropolitan center of the Balkans (Balkan and Black Sea area Cooperation Pole); and (3)

the European Union Policies, especially the Common Agricultural and Fisheries Policies, the Water Framework Directive, and the Habitat Directive.

Destabilization of the Balkans region-FYROM policy

The Former Yugoslav Republic of Macedonia is in a period of transition in moving towards a market-based economy. Within this framework, it is apparent that FYROM is seeking to make progress in the field of environmental protection, and very keen to comply with EU environmental requirements and standards (NEAP 1996). Nevertheless, the adoption of new environmental legislation and the creation of new institutional structures by FYROM need to be supported by investment, implementation and enforcement. Specific environmental management recommendations given by UNEP for the water sector in FYROM include the following: 'an integrated river basin management plan should be developed and implemented for the Vardar (Axios) River. The approach should be consistent with the EU Water Framework Directive and take full account of transboundary considerations'.

The Kosovo conflict placed an additional burden on the already over-stretched resources of FYROM, although the direct environmental impacts of the influx of 261,000 refugees were found to be minimal (UNEP 2000). With regard to UNEP's conclusion, two key areas of environmental improvement have been identified for the State of FYROM: (a) the implementation of environmentally acceptable industrial processes, including measures for adequately controlling the use of chemicals; and (b) adequate handling, storage, treatment and disposal of waste, whether solid or liquid, hazardous or non- hazardous, municipal or industrial. According to Krstic et al. (1999), the Axios River is heavily polluted, primarily due to lack of wastewater treatment facilities.

UNEP identifies a chronic lack of investment in environmental protection although the economic context of the last decade in FYROM has led to decreased industrial output and consequential reductions in pollution.

Greek policy

According to the new Regional Development Plan 2000–2006 of Greece, the general development goal for the region is the utilization of the new metropolitan role of Thessaloniki in the Balkans area, along with the reinforcement of intra-regional balance and sustainability. The main strategic objectives for achieving this goal are the following (Konsolas et al. 2002):

1. Development of Thessaloniki into a metropolitan center with international functions. Emphasis is given on the areas of transport- communication, culture, urban infrastructure, infrastructure and services for enterprises. Actions include the creation of an integrated trans-modal transport network with hubs in major centers of production activity, and their connection with trans-European and inter-regional transport networks.
2. Protection and utilization of the natural environment. Emphasis is placed on: (a) urban and industrial waste, adopting measures for combating inner water and coastal pollution, and completion of infrastructure for treatment of liquid and solid waste; and (b) management of the natural and anthropogenic environment with special actions for rational management of water resources and their protection from unsuitable cultivation practices, design and implementation of integrated protection programmes for biotopes and wetlands.
3. Reduction of intra-regional disparities and sustainable development. Emphasis is given on upgrading of health services, modernization of the railway network, improvements in infrastructure of regional sea ports, promotion of local production through agriculture and agro-industrial restructuring in the region's plains, modernization and development of fishery and stock raising, reinforced protection and preservation of agricultural land.
4. Decrease of unemployment and provision of equal opportunities in education and skills. Emphasis is given to integrated employment programmes for immigrants, repatriates and socially excluded groups to enter the labor market.
5. Within the third Community Support Framework 2000–2006, the Central Macedonia Funding Programme, which will finance the above-mentioned actions, has a total public expenditure of 1.2 billion €.

European Union Policies

On a European scale, the recent Water Framework Directive (WFD) stands prominently in offering tools in support of an integrated management of watersheds. In this line, adopting the 'wise use' imperative of the European Union is a prerequisite, as is also taking explicitly into account a number of factors considered to affect specifically the management of Mediterranean catchments, as: (a) developmental needs and economic inequality; (b) pressure from population growth, immigration and mass tourism; and (c) social and cultural conflicts.

Pressures

Pressures are identified for the Axios River catchment area, as well as the coastal zone of the Thermaikos Gulf. In this sector, all catchment pressures are mentioned, while the emphasis is given in describing those pressures which mostly influence the coastal zone.

Main pressures in FYROM

Pressures exerted in the catchment from FYROM are: environmentally unacceptable industrial processes and practices, waste (solid or liquid, hazardous or non hazardous, municipal or industrial), increased water demand for drinking water and irrigation.

Industry Industry is the dominant economic sector in FYROM, accounting for 35% of the gross national product (GNP) and 39.9% of employment in 1994 (NEAP 1996). UNEP (2000) identified environmental 'hot spot' conditions in five of the sites visited during its field mission in FYROM: the ferro-alloy plant in Jegunovce, the OHIS A.D. organic chemicals plant in Skopje, the lead smelter 'MHK Zletovo' in Veles, the lead and zinc 'Rudnici Zletovo' mine in Probistip, and the electrical power plant in Bitola. The overall risk assessment suggests that these sites require urgent attention in order to halt serious hazards to public health and the natural environment. Treatment of the industrial sewage takes place only in a few factories. For example, in 1993, a wide range of industries discharged 420 million m^3 of wastewater, of which only 6% was treated (NEAP 1996). However, these sites are more important as heavy-metal sources. For nutrients emissions, the most important point source is the fertilizer plant in the industrial zone of Veles. The plant produces yearly 60,000 t of fertilizers, using sulfuric acid from the neighboring smelter and imported phosphorites from Morocco. The plant's wastewater loadings of phosphorus and nitrogen are equivalent to those that would be generated by population centers of 4.6 million and 0.4 million people, respectively (UNEP 2000), which corresponds to 4,600 t for phosphorus and 1,600 t for nitrogen, annually.

Agriculture Agriculture is the second important economical sector in FYROM, accounting for 22% of the GNP. Nearly half of the total area of the country is used by agriculture, split equally between cultivated areas and pastures. Concerning intensive agriculture in FYROM, although the trends are decreasing, pollution is present. Fertilizer use has been declining over the last 10 years; there was a rapid decline in the 1990–1993 period because of the phasing out of input subsidies, import constraints and the financial difficulties faced by farmers. Over the period 1994–2000, the consumption of total (nitrogen and phosphate) fertilizers decreased from 47,000 t to 39,000 t (FAO 2002). Nevertheless, fertilizer use remains quite high. Pesticide consumption has declined dramatically over the past 10 years, i.e. from 2,706 t in 1983 to 659 t in 1993. Herbicide consumption has declined similarly. Analysis suggests that there are few problems in FYROM regarding retention of pesticide chemical residuals in vegetable products, partly because pesticide use is much lower than in Western Europe, and partly because standards are respected. Wheat, maize, rice, tobacco, and barley are the primary crops in FYROM (Figs. 3a-e). Their production during the last decade shows relatively small variations, and clear increasing or decreasing trends could not be identified.

Irrigation in FYROM is based on a system of seventeen dams, with a reservoir capacity of more than 500×10^6 m^3, which distributes water through pipes and canals to ~800 km^2 of land (Fig. 1). Continuously decreasing rainfalls during the 1990s have generated inefficiency in water supply, especially during the summer months. However, FYROM plans to irrigate 4000 km^2 by the year 2025, based on the construction of high-capacity dams (Lisiche and Kozjak dams are currently in a final stage of construction). As dams collect water during high flow periods and release it during the dry months, this policy finds the Greek side largely in agreement. However, possible environmental impacts of regulated-low flow during winter months have not been assessed at all.

Livestock Animal husbandry is intense in FYROM, with sheep, cattle, pigs, and hens (poultry) representing the most important livestock (Figs. 4a-d). Throughout the past decade, a slight decrease in livestock occurred, except for pigs, which exhibit a 16% increase (FAO 2002). Pastures cover about 6,340 km^2, corresponding to ~10% of the land. Animal feeding requires high water availability, posing additional pressure to water resources. Moreover, livestock manure is an important non-point source of nutrients, contributing to the enrichment of topsoils in nitrogen (N-surplus). Organic fertilizer production totals about 3 million tonnes, which satisfy about 30% of the country's total fertilizer demand (NEAP 1996).

Urban Urbanization has gradually developed in FYROM, and to date, ~60% of the people live in large cities, e.g. Skopje, the country's capital with some ~450,000 inhabitants. Wastewater treatment plants exist only for three cities, Ohrid, Prespa, and Doiran, but their sewage network is still incomplete. Municipal untreated wastewaters that are discharged into the Axios River were estimated at 4,700 t yr^{-1} for nitrogen, and at 857 t yr^{-1} for phosphorus (NEAP 1996). The immediate construction of WWTPs, at least for the major cities, is a target of ultimate importance for the quality of the country's freshwater resources.

Drinking water resources for the urban population are relatively satisfactory, although water shortages appear occasionally and trigger conflicts between the different user groups (NEAP 1996). Nevertheless, water demand for expanding urban centers is expected to grow, posing additional pressures to the availability of freshwater resources.

Stakeholder mapping in Greece

Stakeholder mapping in the Greek part of the Axios River catchment has allowed us to define in more detail

the groups involved. It is rather difficult to analyze completely the pressures and the corresponding stakeholder groups of the Axios catchment-coastal zone, as dynamics of the river flow affect the activities in the delta region. Many occasional human activities intensify or stop according to the river flow, such as sand extraction. Additionally, some stakeholders are multi-professional, e.g. many rice farmers (practicing intensive agriculture) are also engaged in aquaculture (shellfish farming). These two stakeholder groups are greatly interested in freshwater and their interests have been contradictory several times in the past.

Farmers Farmers constitute the principal interest group in the Greek part of the AXCAT. The primary crops that make up more than 85% of the total crops are wheat, maize, rice, tobacco, barley, and cotton (Figs. 3a-f). Fruits and vegetables are also cultivated. A particular characteristic is that in the Axios delta area almost solely rice is cultivated, and the output of this area amounts to ~60% of the entire Greece production. The farming community is the largest consumer of Axios water. There is no direct control by the Ministry of Agriculture or any other state agency referring to the maximum allowed quantity of fertilizers and pesticides that can be used in rice cultivation. However, in Greece as a total, fertilizers consumption decreased from 696,000 t in 1990, to 457,500 t in 2000 (FAO 2002).

Shellfish farmers The second important user group is shellfish (mussel) farmers, a group strongly dependent on the freshwater of the Axios River, and in fact, the particulate matter supplied by the river. It has been estimated that a single shellfish filters ~70 g yr^{-1} of particulate matter, and uses 50% of it for growth (Widdows et al. 1979). The shellfish farming activity in the delta is profitable, comprising 85% of the total Greek shellfish output. The abundance of freshwater and particles near the Axios River mouth suggests that shellfish grow faster, resulting in larger profits for the shellfish farmers. On the other hand, scarcity of freshwater (and particulates) or contamination severely affect shellfish farming, decreasing productivity.

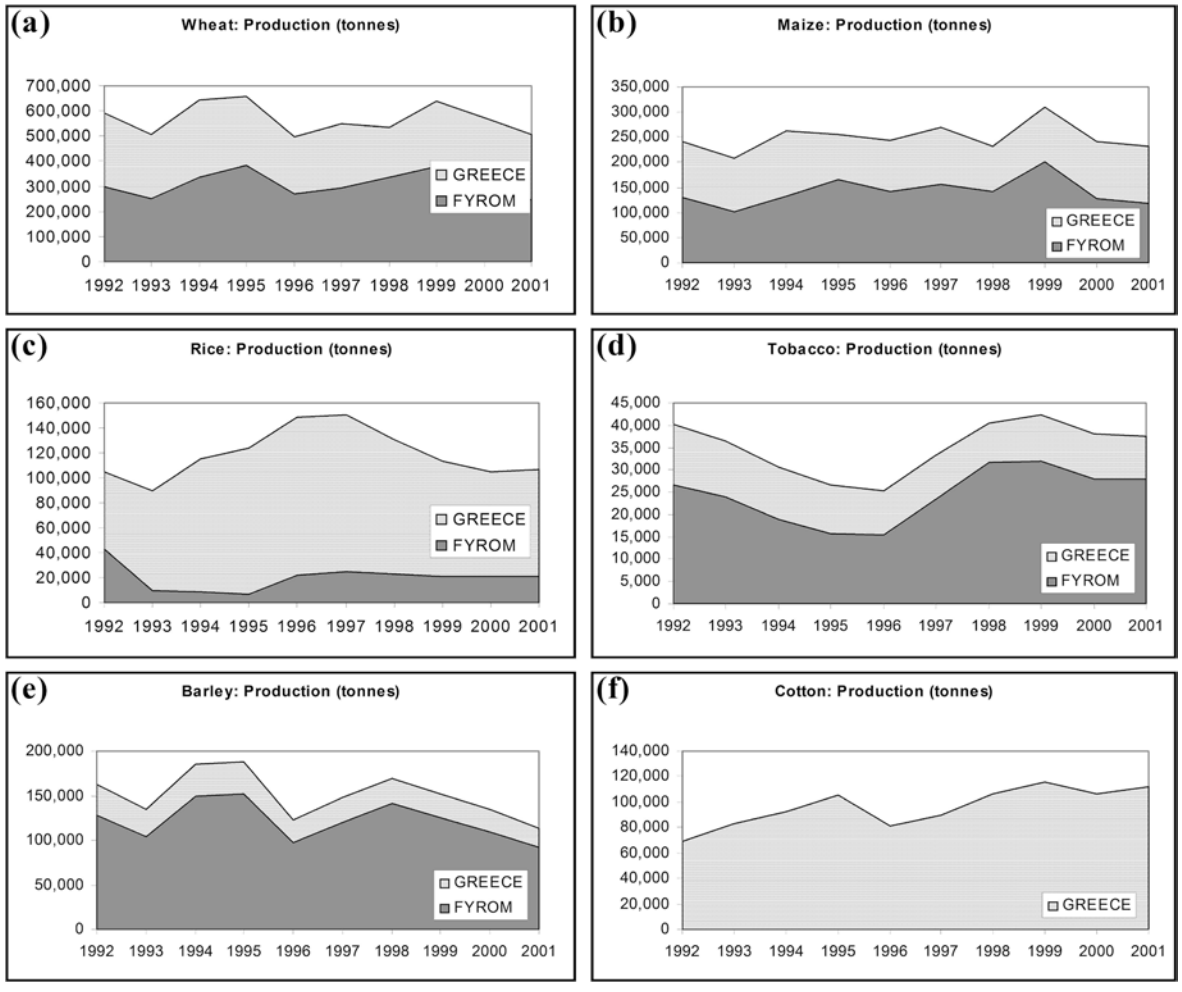

Fig. 3 Primary crops in the Greek part of the Axios RIVER catchment (source: National Statistical Service of Greece) and FYROM (source: FAO 2002)

Industrial sector Industry plays an important role in the economy of the area. Enterprises situated within the watershed total 3,735, which are mostly very small units. 182 are classified as small units (personnel 10–49), with a turnover of 300 million €, whilst medium and large units do not exist. These enterprises deal with textiles and apparel production, food and beverages, and there are a few metal and chemical factories.

At this point, it should be considered that the degree of industrialization of the catchment is relatively low compared to the delta plain (Thessaloniki County) that includes 57,260 very small enterprises, 1,696 small enterprises, and 229 medium/large enterprises. Of these, approximately 1,300 units require wastewater treatment (Tsagarlis 1998). The major industrial sector of the County is located in the western part of Thessaloniki, in the so-called 'National Industrial Site of Thessaloniki Prefecture', which includes more than 100 small-medium-large industrial units. Inside the site, wastewater treatment facilities have been provided since in 1978 a WWTP was constructed. The industrial sewage is processed and discharged in a channel. It has been estimated that large food industries, located within the Industrial Site of Thessaloniki, can fully treat their wastewater before discharging them into the river. However, many small and/or medium size enterprises situated in Thessaloniki and other counties draining into the inner Thermaikos Gulf have no wastewater treatment facilities, and their sewage is directly released into rivers.

Pressures in the Greek part of the Axios River catchment

Agriculture Water demand for irrigation constitutes the most important pressure factor within the Greek part of the catchment. A key component is the irrigation dam, located in Prochoma and named "Elesoussa" or "Elli's" dam (Fig. 1), some 28 km from the river mouth. The dam was constructed in the 1950s and irrigates about 300 km^2 through a system of channels, 200 km^2 of which are rice and maize fields. The irrigated area expands downstream of the dam up to the river mouth. Upstream of the dam, water is pumped from the river to irrigate other types of crops. Wheat is the most common (1,000 km^2), followed by cotton (320 km^2), barley (120 km^2), alfalfa (80 km^2), and tobacco (32 km^2). The dam is partially open during the winter/spring months and regulates the water flow, to retain water for the dry summer period (Konstantinidis 1989). Throughout the area, water is pumped from several registered and non-registered (illegal) drill holes, which affect the level of the groundwater table considerably.

Industry Industrial plants within the Axios River catchment comprise a cheese factory, three dye-houses, a slaughterhouse, a dairy factory and a canning plant (Table 1). Their relatively limited number and capacity indicate that industrial water use is not an important pressure factor. Likewise, nutrient emissions are low, as the industries effluents are processed (except for the Axioupolis dye-house and slaughter-house). The total annual input of nitrogen and phosphorus load originating from industrial sources situated within the AXCAT was estimated at 15 t and 12 t, respectively.

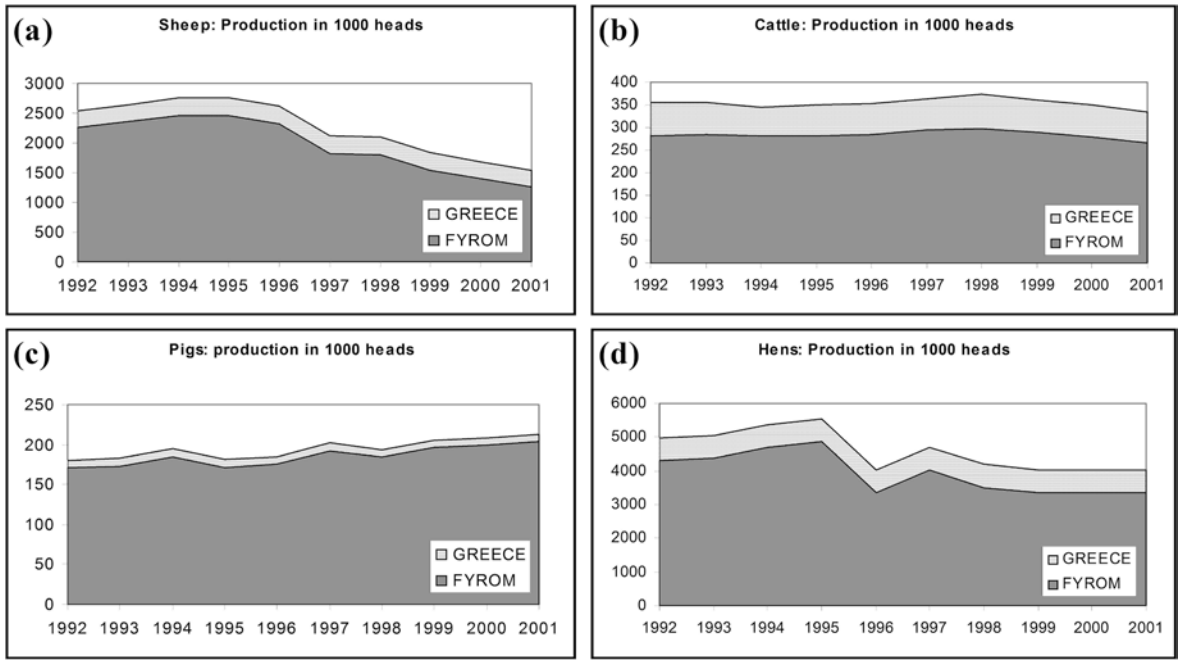

Fig. 4 Primary animal breeding in the Greek part of the Axios RIVER catchment (source: National Statistical Service of Greece) and FYROM (source: FAO 2002)

Table 1 Annual average input of nutrients in the Greek part of the Axios River from point sources (modified from Lazaridou-Dimitriadou 1998)

Nutrient sources	Wastes (m^3/d)	N-NO_3 (t yr^{-1})	N-NO_2 (t yr^{-1})	N-NH_3 (t yr^{-1})	P-PO_4 (t yr^{-1})
Cheese factory (KOLIOS)	140	0.358	0.008	1.533	6.132
Dye-house of Axioupolis	180	0.591	0.013	0.361	0.131
Ioannidis' Dye-house	320	0.117	0.014	0.467	0.280
Gouletias' Dye-house	700	0.767	0.031	0.664	0.562
Municipal slaughter-house of Axioupolis	120	1.095	0.011	0.438	0.372
MEVGAL-Dairy factory	600	1.752	0.088	2.365	3.395
BIOTOM-canning industry	1,380	0.252	0.050	0.453	0.453
Sewage of Axioupolis	27	0.345	0.002	0.493	0.246
Sewage of Polykastro	49	0.537	0.004	0.894	0.393
Sewage of Koufalia	20	0.292	<0.001	0.584	0.183
Sewage of Kyminon	-	<0.001	<0.001	<0.001	<0.001
Arjan-Agiak-Amatovo Channel	0.23	<0.001	<0.001	<0.001	<0.001
Anthophyto irrigation/draining channel	0.05	<0.001	<0.001	<0.001	<0.001
Industry total	3,440	4.931	0.214	6.282	11.326
Urban total	96	1.173	0.006	1.971	0.822
Agriculture total	0.28	<0.001	<0.001	<0.001	<0.001
SUM	3,536	6.10	0.22	8.25	12.15

Urban Nowadays, all communities and municipalities in the Axios catchment (population ~233,500; census 2001) satisfy their drinking water needs directly from the river or from groundwater. Census data show that the population of the area is growing slightly. During the decade 1981–1991, population growth was ~4%, whereas during 1991–2001, the population increase was more than 20%. These figures suggest that water demand for urban use will increase in the next years.

Pressures in the coastal zone

The main environmental pressures, which affected negatively the delta's area ecological character, leading to the destruction of 70% of the original wetlands during the 20th century, are numerous: water discharge decrease, drainage works, urbanization, and pollution. Moreover, the general decrease in rainfall, combined with over-use of water for irrigation, has resulted in severe salinization of the delta area, with a direct impact on the flora and fauna of the wetlands (Zalidis 1998). Nowadays, some of these activities have been stopped and their impacts have already been mitigated. The main pressures identified in the coastal zone, within the DPSIR framework, will be listed hereafter.

Agriculture Agricultural activity in the Axios delta area is intensive. Rice production in the area amounts to ~60% of the total Greek production (Fig. 3c), and takes place mainly in the delta area. The farming community is the largest consumer of Axios River water. Over the last decade, many farmers have switched to rice instead of cotton or vegetables, because rice is very tolerant to weather conditions, rice seeds are relatively cheap, and harvest is much easier. However, it demands vast amounts of freshwater (three to four times the water needed for other irrigated crops), thus, rice farmers have great interests to preserve the Axios River water resources. There is no direct control by any state agency for the maximum allowed quantity of fertilizers, pesticides, and herbicides used in rice cultivation. Usage of toxic pesticides, like the addition of parathion in water, can have direct impact in the local wild flora and fauna especially in the rice fields, which are a usual habitat for wildfowl.

Concerning the cost for irrigation, the pricing strategy of the local irrigation network (TOEV) does not reflect the full cost of the resource, but intends to cover only running expenses. The pricing policy is based on the average estimated price per hectare that each local irrigation network has set for irrigation.

Urban The total population for the five municipalities that administratively form the Axios delta area is ~48,000 inhabitants (census 2001) within 552 km^2. Local population density reaches 87 inh/km^2, slightly higher than the average of Greece (83 inh/km^2). During the decade 1981–1991, population increase was 10.5%, whereas during the next decade it was 5% (population density 75 inh/km^2 and 84 inh/km^2, respectively). The population trend in the delta area is continuously increasing due to the highly productive land, the multiplication of industrial units and the consequent labor demand. On this basis, urban development constitutes a substantial type of pressure in the Axios delta area.

In order to evaluate urban pressures in the coastal zone, the population within the municipalities bordering the coast has been considered. This estimate includes also the Thessaloniki metropolis (89% of the total county population). During 1981, the 'coastal' population was ~800,000, which increased to 860,000 in 1991

and to 940,000 in 2001. The overall increase in the period 1981–2001 was ~18%. Some of Thessaloniki's municipalities are heavily populated (population density > 20,000 inh/km^2), underscoring the role of the city as a major pressure area. In addition, recent plans of EYATH include the Axios and Aliakmon Rivers as potential suppliers of drinking water for the city of Thessaloniki.

Mussel farming During the last 20 years, a considerable growth in shellfish (mussel) production appeared in the Axios River coastal area. To date, more than 44 pole cultures and 229 long-line cultures occupy the marine area between the Axios River mouth to the NE (Chalastra area), whereas 37 pole and 120 pole cultures are situated to the SW of the Axios River mouth, covering a narrow zone of ~6 km (Fig. 2) (NCMR 2001). Shellfish production in the area reaches 85% of the total Greek production, and increased rapidly since the 1990s to more than 30,000 t per year (Fig. 5), whereas 70–80% of the product is exported to other countries. The value of the production amounts to more than 10 million € annually (Zanou and Anagnostou 2001), and about 1,000 people are employed in the units. Recently, the production has been considerably affected by the occurrence of harmful algae blooms (HABs), which sometimes result in the accumulation of toxins in shellfish, making it dangerous to consumers. It should be noted that toxins, although hazardous to humans, do not affect the mussel itself. As this problem is of paramount importance, it will be discussed in more detail in the 'Impact' section of the DPSIR analysis. Moreover, shellfish farming is accompanied by high amounts of solid waste (mainly shells), illegal construction of auxiliary premises, and occasionally severe hygienic problems.

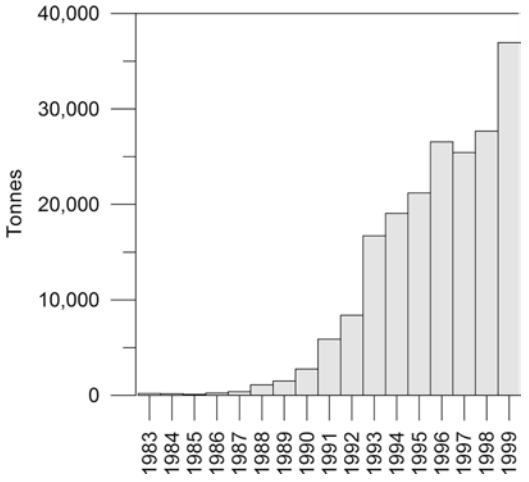

Fig. 5 Shellfish production in the Thermaikos Gulf (source: Ministry of Agriculture)

State

Water discharge

The annual flow regime of the Axios River was characterized by average flows during the 1970s (Karageorgis et al. 2003), a wet period during 1980–1985, a dry period during 1988–1994, and then a relatively wetter period during 1995–2000 (Fig. 6). The constantly decreasing trend in flow between 1980 and 1994 is proportional to respective rainfall variations. Similar to the other major Greek rivers (Skoulikidis, 1999), minimum runoff was observed during the period 1988–1994, when a dry wave affected Europe (e.g. Shuurmans 1990) and Greece (Lambrakis et al. 1997). The mean annual water discharge estimated from historical data is 5.0×10^9 m^3 yr^{-1}; however, recent (1995–2000) measurements revealed a considerable decrease in the order of 3.4×10^9 m^3 yr^{-1}. Similarly, mean annual solid discharges from historical data were estimated at $1–2\times10^6$ t yr^{-1}, whereas recent estimates were 10 to 20-fold lower (0.1×10^6 t yr^{-1}; Karageorgis and Anagnostou 2001). This significant reduction is related to the decrease of water discharge, as well as the construction of the Prochoma dam and several other reservoirs in FYROM.

Nutrients

Nutrients in the Axios River catchment The annual freshwater discharge variation of the Axios River is characterized by high values during spring (maximum in April) and a second peak during winter (maximum in

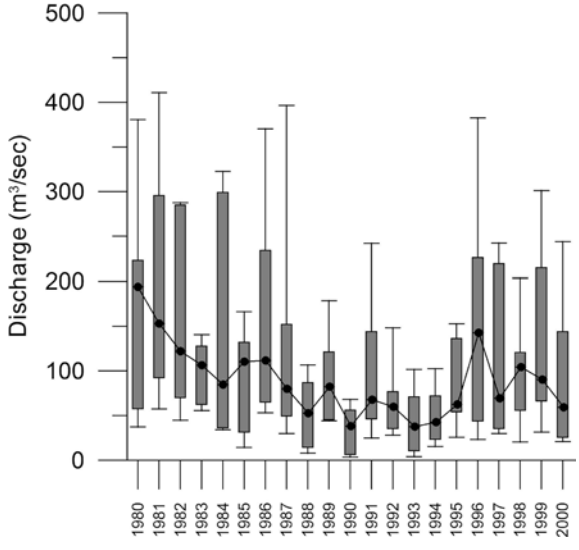

Fig. 6 Axios RIVER long-term (1980–2000) inter-annual variations of water discharge measured at the Thessaloniki-Eidomeni Railway Bridge station. A line is drawn between the median of each year. The bars represent the 25–75% quartiles and the upper and lower ticks represent the minimum and maximum values, respectively

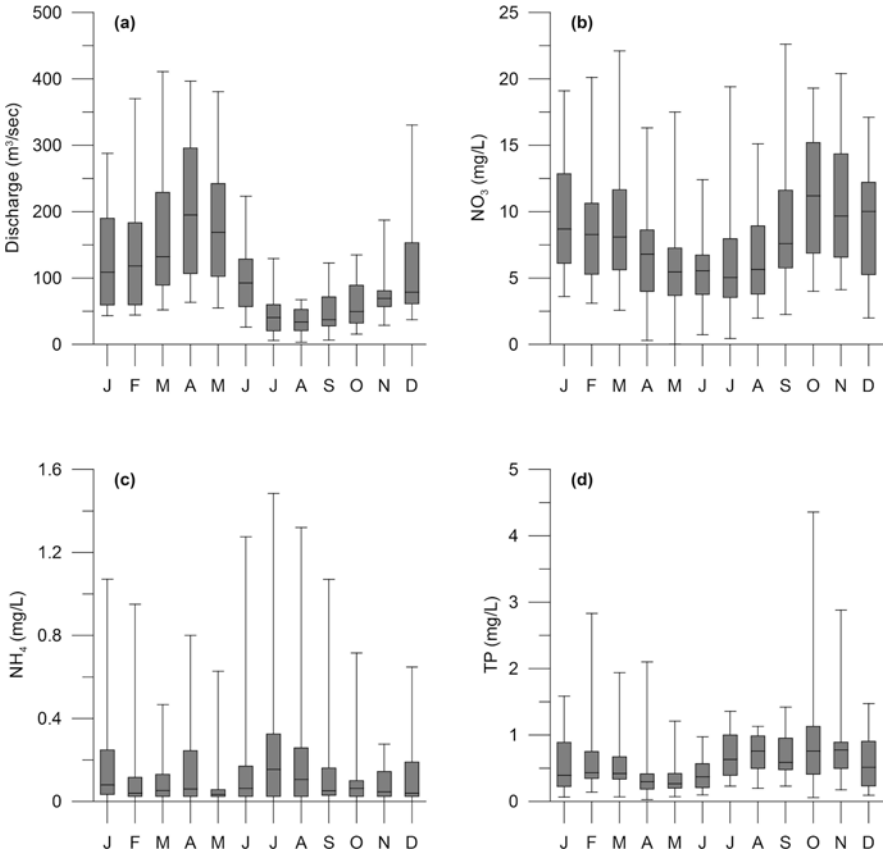

Fig. 7 Axios RIVER long-term (1980–2000) intra-annual variations of water discharge (a), nitrates (b), ammonium (c), and total phosphorous (d), measured at the Thessaloniki-Eidomeni Railway Bridge station. The bars represent the 25–75% quartiles and the upper and lower ticks represent the minimum and maximum values, respectively

February) (Fig. 7a). This pattern classifies the Axios as a snow-rain type-b river (Malikopoulos 1957).

When long-term surveys are available a 'chemical quality regime', may be defined on the basis of long-term monthly average concentrations (Meybeck 1996). Furthermore, the following interpretations rely on the assumption that single monthly measurements are representative for the entire month. The intra-annual variation of nitrates shows minima during the dry period (June to August; Fig. 7b). During the rise of the hydrograph (September to December), nitrate concentrations increase gradually, reaching the annual maximum in December. From January to May, nitrate concentrations decrease gradually. This type of intra-annual variation is attributed to arable land flushing during autumn and early winter and dilution during the springtime (Skoulikidis and Kondylakis 1997). Low concentrations during summer indicate that nitrate point sources are of minor importance. The variation of ammonium and total phosphorous shows maximum values during the dry period (July and August; Figs. 7c,d). This pattern, inverse to the variation of nitrates, is attributed to the combination of low flow and the contribution of point pollution sources (domestic wastewaters and seasonally operating industries). During high discharge, relatively low concentrations are observed; as in the case of nitrates, this is due to dilution. Ammonium also exhibits high fluctuations, especially during the dry period, probably due to episodic inputs. However, the long-term variation of the nitrate concentration, in general, reveals a gradual increase throughout the years (Fig. 8). For total phosphorus, the maximum median concentration is observed in October, because of flushing from agricultural land (Fig. 7d). On

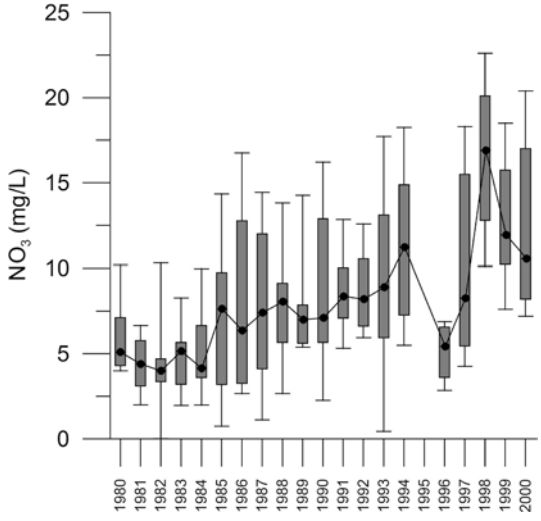

Fig. 8 Axios RIVER long-term (1980–2000) inter-annual variations of nitrates, measured at the Thessaloniki-Eidomeni Railway Bridge station. A line is drawn between the median of each year. The bars represent the 25–75% quartiles and the upper and lower ticks represent the minimum and maximum values, respectively

the other hand, total phosphorus fluctuations are relatively smaller, due to its lower mobilization, since it is readily absorbed on particulate matter (e.g. Lajtha and Schlessinger 1988).

The spatial variation of nutrients is illustrated in a cross-section along the main river course (Fig. 9). The peak concentrations of total nitrogen and total phosphorus at station T8 (downstream of Skopje) and particularly at station T15 (downstream of Veles) indicate significant impact of wastewater discharges from the town of Skopje (waste water from the organic chemical plant and municipal sewage) and from the town and the fertilizer factory at Veles. In order to determine whether the water quality of the Axios River (concerning nutrients) is changing along the Greek stations, we have applied an ANOVA test for each variable (nitrate, nitrite ammonium and phosphorus) separately. The results indicate that we could not reject the null hypothesis ($\mu 1 = \mu 2 = \mu 3$) at the 5% significance level. Hence, the nutrients do not show different spatial tendencies.

Nutrient inputs from rivers and point sources to the Thermaikos Gulf It has been suggested that the four major rivers (Axios, Aliakmon, Loudias, and Gallikos) discharging into the inner Thermaikos Gulf influence significantly the trophic conditions of this coastal region by having a direct effect on primary production and the associated food web structure and functioning. In fact, these four rivers account for almost 40% of the freshwater inflow to the North Aegean Sea according to UNEP/MAP data. The elevated concentrations of nutrients in the river water of the inner Thermaikos Gulf are very likely due to the intensive agricultural, mining and smelting activities that take place in the river basin. The total annual flux of nitrogen and phosphorus was estimated at 9,700 t and 2,100 t, respectively for 1980–1985. Recently (1995–2000), these loads decreased to 9,200 t for nitrogen and increased to 2,400 t for phosphorus (Table 2). It is worth noting that during the drought period of 1990–1994, nutrient fluxes reached their minimum values.

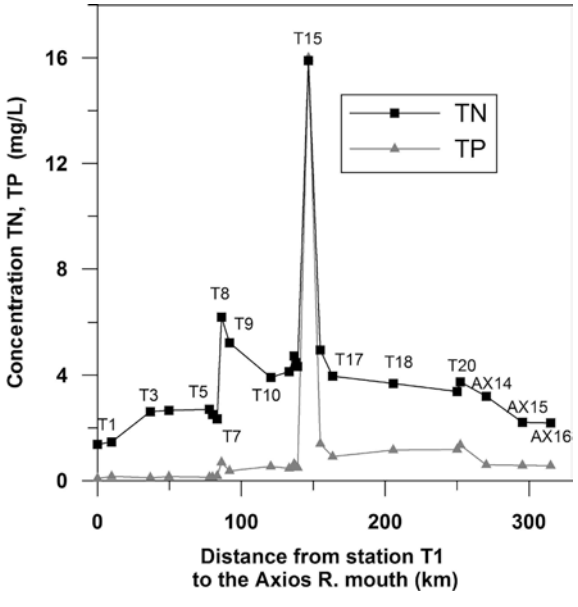

Fig. 9 Total nitrogen (TN) and total phosphorous (TP) variations along the Axios River course. Average concentrations of 1997–1998–1999

The urban effluents of Thessaloniki city (population 1,200,000) have been released untreated into the sea for several decades, as the sewage network was incomplete and wastewater treatment plants were nonexistent. During this period, more than 100,000 m^3 of effluents were discharged daily, resulting in a rapid deterioration of the Thermaikos Gulf's water quality and aesthetic degradation. The WWTP-1 of the city was built in the Sindos area (Fig. 2). The construction commenced in 1983 and finished in 2002. At this stage, the WWTP-1 operated as a tertiary system (according to EYATH, nitrogen removal is better than 80%), treating ~120,000 m^3 of sewage daily. In parallel, the WWTP-2 was constructed in the eastern (tourist) part of the city (Nea Michaniona), and started operation in 1997, with a capacity to treat daily ~25,000 m^3 of wastewater.

The industrial effluents of Thessaloniki were collected and transported at the WWTP-3 of Sindos, which was constructed in 1978 and upgraded in 1991. The facility treats 1,500–12,000 m^3 of sewage daily (average 7,500 m^3 d^{-1}) and releases 950 t of nitrogen and 243 t of phosphorus annually.

The diachronic variation of total nutrient inputs to the Thermaikos Gulf shows that, although the operation of the WWTPs has commenced recently, nutrient fluxes continue to increase; this may be explained by the increasing population and agricultural/industrial activities. However, some improvement should be expected in the short-term, as untreated domestic sewage has been constantly reduced since spring 2002.

Nutrient distribution in the Thermaikos Gulf The distribution of nutrients (mean integrated concentrations over depth) in the Bay and Gulf of Thessaloniki (Inner Thermaikos Gulf) during two contrasting periods (warm and cold) exhibits distinct patterns for both nitrates and phosphates (Fig. 10). Furthermore, the contribution of sewage to the total nutrient load is marked during both seasons and expressed by high nutrient concentrations in the northern part of the area. However, the significance of the riverine input is more pronounced along the western coast during the cold period (winter-spring) which represents high river discharge. In contrast, the warm period (summer-autumn), which corresponds to low river discharge, is characterized by low nutrient concentrations near the river mouths. It must be noticed also that along the western coast of the Inner Thermaikos Gulf extensive aquaculture activities exist (shellfish), which also contribute to the eutrophication of

Table 2 Nutrient inputs into the inner Thermaikos Gulf in 5-year time intervals

Nutrient point sources	TN (tonnes)				TP (tonnes)			
	1980–1984	1985–1989	1990–1994	1995–2000	1980–1984	1985–1989	1990–1994	1995–2000
Axios River	6,137	5,679	4,702	5,148	1,691	1,283	948	1,908
Aliakmon River	2,028	2,721	1,764	2,508	102	90	33	142
Loudias River	1,240	1,240	1,240	1,240	315	315	315	315
Gallikos River	340	340	340	340	29	29	29	29
River total	9,745	9,980	8,046	9,236	2,137	1,717	1,325	2,394
Pumping stations	1,524	1,524	1,524	1,524	161	161	161	161
Thessaloniki's untreated sewage	3,485	3,485	265	24	871	871	680	600
WWTP-Thessaloniki	-	-	672	950	-	-	153	243
WWTP-Michaniona	-	-	-	2	-	-	-	1
WWTP-Industrial zone	27	27	27	27	14	14	14	14
Total	14,781	15,016	10,534	11,763	3,183	2,763	2,333	3,413

this coastal area, since shellfish are highly efficient in the remineralization of nutrients.

High values of phosphate, nitrate and ammonium are recorded near the seabed in Thessaloniki Bay, especially during the warm period. Dissolved oxygen (values indicating hypoxia/anoxia) and nutrient data suggest that regeneration processes occurred in the near bottom layer of the shallower stations mainly under conditions of water column stability (Pagou et al. 2000). Furthermore, the N/P ratio exhibits much lower values than the theoretical Redfield ratio (Redfield et al. 1963), and the mean values ranged between 0.6 (spring) and 4.9 (winter). This indicates a strong relative nitrate deficit during all seasons which can be attributed not only to

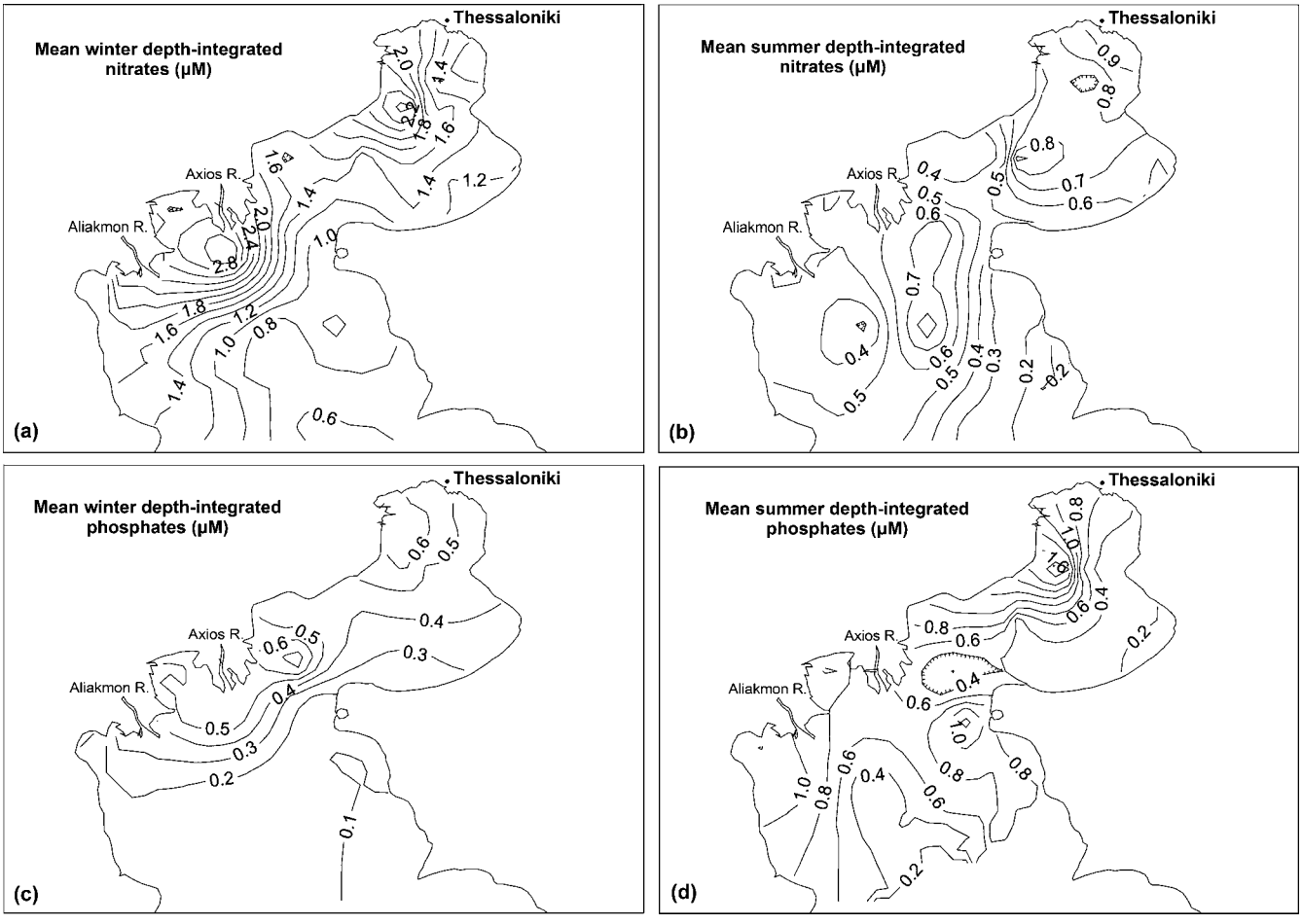

Fig. 10 Seasonal variation of depth integrated nutrients concentrations (μM) in the Thermaikos Gulf. (a) Winter nitrates, (b) summer nitrates, (c) winter phosphates, and (d) summer phosphates. Winter months: November to April, summer months: May to October

phosphate-rich sewage, but also to additional enrichment through the riverine inflow. Orthophosphate input in the Thermaikos Gulf from the rivers is in the same range or higher than that reported for the Rhône River, in the Gulf of Lions (EEA 1999).

Modeling of nutrients in the Axios River catchment The estimation of nutrient fluxes, the determination of spatial and temporal responses and the understanding of biogeochemical changes in the past, present and future in the Axios River catchment, and the eutrophication response in the coastal zone of Thermaikos Gulf, were accomplished by the use of harmonized models. The mathematical model MONERIS (Behrendt et al. 1999) is a watershed management model that models nutrient emissions in the Axios River. MONERIS was developed to estimate the nutrient inputs into river basins from point sources and various diffuse pathways. The model uses data of river flow, water quality, digital maps and extensive socio-economic and land use statistics. Meteorological, hydrologic and water quality data from point and non-point sources of pollution from FYROM and Greece were collected and used as input to MONERIS. The model was modified to better assess organic nitrogen emissions and nutrient retention in lakes in Mediterranean watersheds. MONERIS was integrated with the coastal zone model WASP 6.0 to assess the spatial and temporal response of the Axios catchment to nutrient loads and to evaluate the impacts to the coastal zone.

Modeling of nutrients in the Thermaikos Gulf The mathematical model WASP 6.0 (Wool et al. 2001) was used to simulate the hydrodynamics, nutrient dynamics and phytoplankton evolution in the Thermaikos Gulf. The model is a physical-based model that compartmentalizes the water body into high dispersivity, uniform concentration compartments. It then performs mass balances on water quantity and quality. In addition to the hydrodynamics, the model can simulate the carbon, oxygen, nitrogen, phosphorus and plankton concentrations in the water body. Monthly hydrologic and water quality fluxes from 1997–98 into the Gulf were collected and used to calibrate nutrient dynamics. The Gulf was compartmentalized into 12 compartments, six horizontal and two vertical. Salinity data were used to calibrate the hydrodynamic variables of the model. Monthly nutrient surveys were used to calibrate the concentrations of nitrogen and phosphorus in the Gulf. Model calibration was conducted by minimizing the root mean square error between field observations and model simulation. The model was able to capture the variation of salinity and nutrient concentrations very well (Nikolaidis et al. 2004). The model was used in combination with the watershed model to assess management scenarios to improve the water quality of the Gulf. Several scenarios were simulated to illustrate the significance of various landuse practices to the eutrophication of the Gulf.

Impacts

Impacts on functions of the ecosystem –ecological approach

Eutrophication-chlorophyll a and dissolved oxygen in the coastal zone Eutrophication, the manifestation of nutrient-enhanced primary productivity, often indicated by the presence, not only of high chlorophyll concentrations, but also by the presence of noxious phytoplankton blooms and bottom water hypoxia/anoxia, has been reported from a variety of marine environments (Rosenberg 1985; Anderson and Rydberg 1988; Justic et al. 1995). The frequency of eutrophic events has increased in many coastal areas, especially those affected by riverine inflows.

The fresh water entering the Inner Thermaikos Gulf at the surface layer is characterized by high values of dissolved oxygen, whereas the seawater influenced by sewage is characterized by low values. However, during summer, the most critical period for the occurrence of hypoxia in the Thermaikos Gulf, the measurements showed that dissolved oxygen varies from 2.6 mL/L to 7.6 mL/L. Lower values were recorded near the bottom of the northern part of Thessaloniki Bay, which is most strongly influenced by sewage outflows (Figs. 11a,b).

The seasonal horizontal distribution of chlorophyll *a* mean integrated concentration in the Inner Thermaikos Gulf (Figs. 11c,d), shows the significant contribution of sewage discharged at the northern Thessaloniki Bay to the eutrophication of the environment during the warmer period, whereas during winter the influence of the rivers can be equally important.

Harmful algal blooms (HABs) Changes in plankton community structure caused by nutrient over-enrichment often result in phenomena called red tides. They are characterized by the proliferation and occasional dominance of particular species of toxic or harmful algae (NRC 2000). For this reason, they are more correctly called Harmful Algal Blooms or simply HABs. One major category of HAB impact occurs when toxic phytoplankton is filtered from the water as food by shellfish, which then accumulate the algal toxins. Humans may suffer poisoning syndromes, which have been named paralytic, diarrheic, neurotoxic, and amnesic shellfish poisoning (PSP, DSP, NSP, and ASP) (NRC 2000). Other HAB impacts occur: (a) when marine fauna are killed by algal species that release toxins into the water; and (b) when blooms have sufficient density to cause anoxia, as large quantities of algal biomass sink to the bottom and decay, consuming oxygen.

In the case of the Thermaikos Gulf, data on phytoplankton responses to eutrophication from the 1980s to 1995 (Moncheva et al. 2001) demonstrated that frequent diatom blooms occurred during summer. The dominance of diatoms in the Thermaikos Gulf was

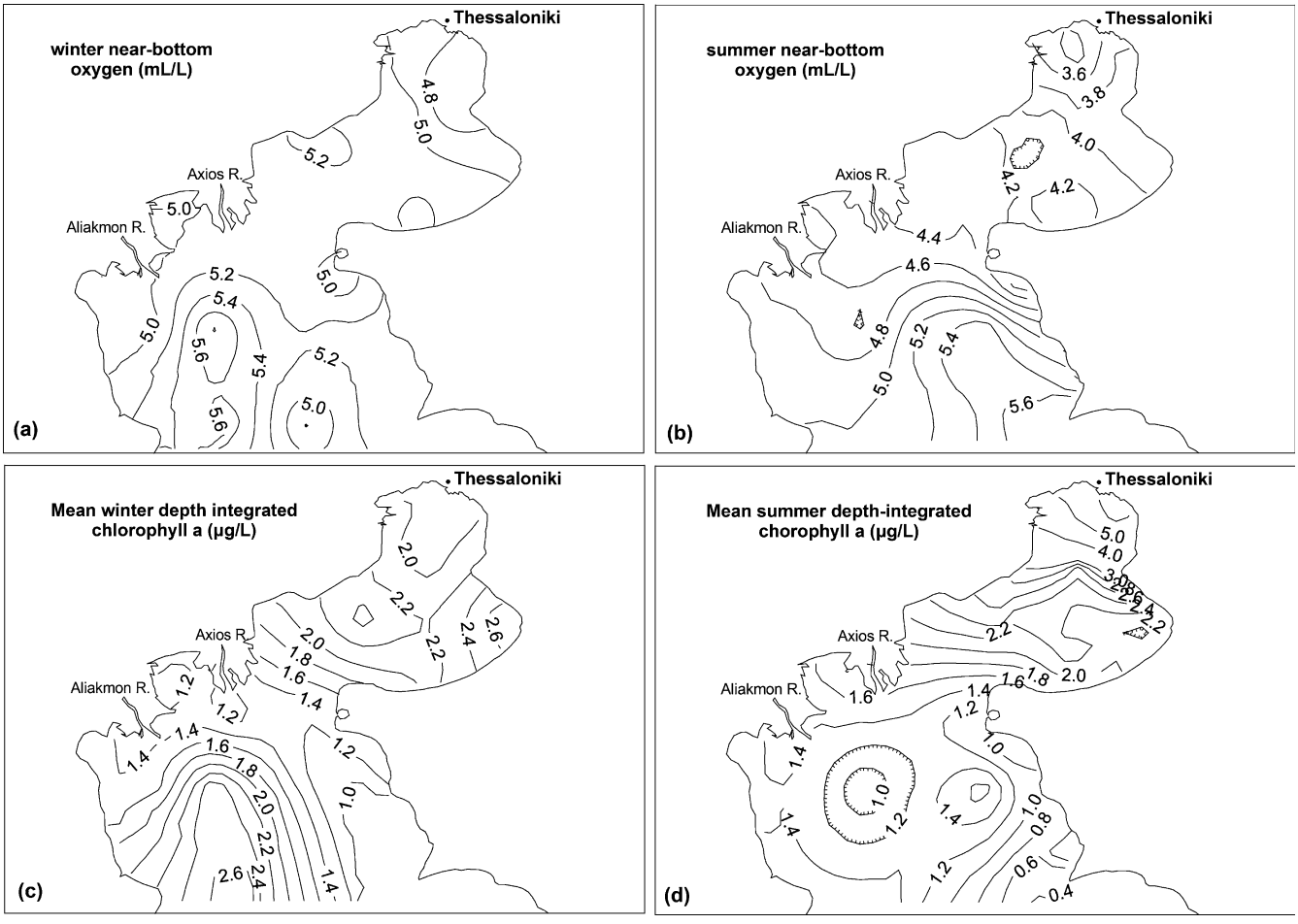

Fig. 11 Seasonal variation of near-bottom dissolved oxygen concentrations (mL/L) in the Thermaikos Gulf during (a) winter, and (b) summer. Seasonal variation of depth integrated chlorophyll-α concentrations (μg/L) during (c) winter, and (d) summer. Winter months: November to April, summer months: May to October

attributed to their higher efficiency in utilizing high nutrient levels (especially Si), mainly supplied by river run-off. However, after 1995, dramatic changes occurred. The diatom blooms changed to toxic dinoflagellate blooms that can be related to the low N/P ratios. Occurrence of HABs was related to the toxic dinoflagellate species *Dinophysis acuminata,* a DSP causative. The first confirmed bloom of *Dinophysis acuminata* was recorded from January to May 2000, with cell abundances $>5.0\times10^4$ cells/L and okadaic acid concentrations up to 1,600 ng/g of mussel tissue (8 times higher than permitted limits). The *Dinophysis acuminata* bloom was repeated in the two following years (January-April 2001, February-May 2002), with cell abundances not exceeding 1.5×10^4 cells/L.

Mussels affected by the DSP toxin were not released to the market at the times when blooms occurred. However, several months later, the mussels became non-toxic again, and finally the production was sold at lower prices. The economic losses due to the toxic blooms have been estimated at ~3 million € per year.

Local tourism The coastal area east and southeast of the city of Thessaloniki was a traditional tourist resort area for the local people during the 1950s and 1960s. The aesthetic degradation of the coast (e.g. increased water turbidity, production of noxious odors, pathogenic bacteria) inhibited swimming and recreation activities, moving the population further away to the neighboring Chalkidiki peninsula. It is difficult to assess the economic cost of this massive but gradual change. Apparently, certain properties have been substantially devaluated, while gasoline consumption (to reach clean coasts), traffic and automobile emissions increased. For example, Bockstael et al. (1989) applied a travel cost model to estimate the amount that individuals are willing to pay to travel farther or more often to sites with better water quality; applying this technique to the Chesapeake Bay, they found that on average a 20% reduction in nitrogen and phosphorus inputs would generate benefits of ~35 million $ (in 1984 dollars) from increased public beach use. Obviously, the same benefits could be obtained in the near future for the inner Thermaikos Gulf, if measures were undertaken and water quality was improved.

Impacts on functions of the ecosystem/human welfare approach

Analysis of focus groups The stakeholder analysis was designed for the identification of conflicting uses of environmental assets, the conceptualization of conflicts on the basis of property rights allocations among social groups, regions and nations, and the understanding of the institutional mechanisms by which costs and benefits are appropriated (Munasinghe 1992; Brouwer et al. 1999; Langford et al. 1999).

Three focus group interviews were undertaken in the summer of 2001, comprising representatives of local farmers, fishermen/shellfish producers, and industrialists in the Axios catchment area. A series of general questions relating to the catchment and its coastal zone was prepared for each group, and these formed the focus of the group discussion: degradation of water quantity and quality, the Axios delta values, state/stakeholders' relationship, economic activities and resulting conflicts and their attitudes towards the future of the area. The focus groups were organized in accordance with guidelines given by Morgan (1988), Morgan and Krueger (1993) and Stewart and Shamsardani (1990). Fishermen and shellfish producers were interviewed both in the same group discussion as they were identified as a cohesive set of individuals who rely on fishing as their main source of income, but also work in shellfish production.

Representatives of local farmers Farmers of the Axios catchment are organized in local and national cooperatives and unions, representing a very dynamic sector, not only for the region, but also for Greece as a country. They are considered as the main users of Axios water, either for irrigation purposes and/or for releasing agricultural runoffs into the river. Farmers are in the position to influence any future management scheme of the region through their strong lobbying position. In our research, this group comprised seven individuals who were between 40 and 50 years old. They were mostly concerned about water quantity and quality problems associated with the general development of the hinterland. In this respect, they recognize as main causes for the water quality degradation: (1) industrial waste dumping (especially in FYROM), (2) overuse of fertilizers and pesticides, and (3) lack of control measures both in FYROM and Greece. Concerning the water quantity, the same group has identified the following factors leading to changes in the state variables: (1) climate change, (2) increased irrigational needs due to intensive agriculture in the catchment area (Greece), which (according to them) leads to a non sustainable use of water by farmers, and (3) the unsuitability of the irrigation network. On the other hand, farmers stated that overuse of pesticides and fertilizers is not their fault, as they are acting under the scientific guidance of the state or private sector agriculturalists.

Unwise use of water by farmers is caused by their risk aversion behavior. They try to reduce the risk of irrigation water shortage in July and August by pumping up more water than needed earlier, in an attempt to make personal water savings. They are asking for a water management plan, which through sustainable use will ensure that irrigation water is available during the summer months. They were concerned that both agriculture and nature protection should be considered in future plans, and there were trade-offs to be made between the two.

The group commented on delta values focusing on wild fauna, which they think is positively linked to agricultural activities. They apparently were not conscious of the risks for the delta area. Farmers' representatives ask categorically for information on best agricultural practices, financing opportunities and the environmental state. Distrust of the administration was obvious throughout the discussion and expressed in many ways. Moreover, the group stated that they won't allow any management plan for the area to be designed without their participation. The worst conflict, revealed through this focus group, was with FYROM control measures for municipal and industrial wastewater dumping.

Representatives of local fishermen/shellfish producers Although twelve representatives of local fishermen/shellfish producers were invited to the group discussion, only six attended. This is a rather weak group in terms of social and economic weight but an important one in terms of vulnerability. Fishermen and shellfish producers are also strongly dependent on future management plans since the location of their activity is in the proximity of delta areas considered to be of special ecological importance.

Discussion focused on the productive value of the Thermaikos Gulf and issues surrounding it, such as the development of aquaculture and the problem of pollution from agricultural (pesticides), industrial and municipal discharges. The representatives acknowledged that over-fishing had led to depletion of fishing stock in the past, and accepted that the state enforced laws to make fishing more sustainable. On the one hand, they felt the need to address the water quality issues, but on the other hand they feared that the designation of the delta area as a Ramsar site would be a potential threat to their economic activities and were ready to oppose it decisively.

Their perceptions of the impacts were framed in terms of the uncertainty in the markets for shellfish under the present conditions. The ensuing risks for the economic viability of shellfish production in the Gulf were perceived to be very high. The main reason for the expressed fear of loosing the market is negative advertisement. They do not believe that their production is threatened by quantitative and qualitative reduction due to eutrophication. They foresee large economic losses in the future; a fact that makes them reluctant to let their successors enter the sector. This pessimist attitude was

substantially supported by both the lack of definite scientific answers concerning water pollution and shellfish production, as well as the widespread belief that the state is unable to confront the problem.

Representatives of local industrialists The industrialists' focus group comprised seven people. This is the most powerful interest group in the watershed due to its financial status, institutional representation, and ability to lobby successfully for its interests. Its importance derives also from the fact that is the explicit target of criticism by other groups for the discharges into the Gulf. Although most of the industrial plants are located away from the Axios River, they are established within the wider catchment area, influencing the coastal zone.

This group provided the most vivid discussion, mostly about the potential for the development of industry and the problems of waste disposal regarding the coastal environment. Some of the group members pinpointed their own responsibility for water pollution, but did not acknowledge that the pollution problems of the gulf are severe. They linked existing problems to the use of agrochemicals and illegal dumping of municipal waste. Overall, the group perceived the problems of the Thermaikos Gulf area in terms of development potential, and in some respects considered the ongoing urbanization and intensive infrastructure building in the region as a national priority given Greece's arbitrator status in the Balkans.

At this point, we may refer to a study on the structure of social preferences for improving water quality in Thermaikos Gulf provided by Kontogianni et al. (2001) in order to complement the insights gained from the focus groups. In this study, a sample of 480 inhabitants of Thessaloniki was surveyed in order to analyze qualitatively the determinants of social preferences for a clean water environment in the inner Thermaikos Gulf and, at the same time, to quantify the willingness of respondents to pay in order to finance it. Among other things, the respondents emphasized the aesthetic deterioration of the Gulf as a main consequence of uncontrolled discharges. The motivations for accepting to participate in the cleaning-up scheme are complex and can be categorized as both 'consumer' and 'citizen' motivations (Sagoff 1988; Brouwer et al. 1999). Hence, the impacts on human welfare of a eutrophic and unpleasant Thermaikos Gulf, besides being linked to productivity losses, rest also on wider considerations referring to aesthetics and intergenerational justice.

Responses

Information to the stakeholders appears to be the main problem for the implementation of environmental regulations. The design of policies, as a societal response to the deterioration of the environment: (1) does not depict the stakeholders' opinion, reflecting only the facts and no values, and (2) is not accompanied by a proper downscaling of information, leaving a big gap of knowledge to the stakeholders.

All stakeholder groups declare that the enforcement of control measures by the state is minimal. Especially the group of industry representatives is unaware of the new environmental regulations and their impacts on industrial performance, expressing fears about sector viability in the case of a potential enforcement of regulations.

Catchment responses in FYROM

The terms, conditions and management of the water in FYROM are regulated by a law with the title *''Legislative for waters'' (Official Gazette of FYROM, no. 4/1998)*. The classification of water (mineral and thermal water are not included) is defined by the *''Decree for water classification''*, while waters from natural and artificial springs and lakes are divided into five classes according to the *''Decree for water categorization, lakes, accumulation and ground waters'' (Official Gazette of FYROM, no. 18/1999)*. The means for definition and preservation of the sources supplying the population with drinking water are determined by the *''Regulation for the means for determination and maintenance of the protective zones around the sources of drinking water'' (Official Gazette of Socialist Federal Republic of Yugoslavia, 17/1983*).

FYROM has identified the importance of the problems related to the quantity and quality of water resources early. Within the National Environmental Action Plan (NEAP 1996), several considerations focused on the improvement of the state of water resources. Some of the priorities/recommendations are: (1) to construct WTTPs for the major cities and improve the industrial units, (2) to manage water resources more effectively, constructing additional dams, (3) to develop a water resources plan using recently acquired data, (4) to introduce industry specific effluent standards, (5) to improve enforcement of existing regulations, and (6) to launch a permanent multi-parameter monitoring programme. Although it is clear that, in a political level, there is generally a good understanding of environmental issues, it remains to be seen whether the country will manage to allocate funding to materialize the some or all of the aforementioned plans.

Coastal zone responses

The ecological significance of Axios-Gallikos-Aliakmon-Loudias delta and their catchments explains why these regions have stimulated the interest of the Greek Ministry of Environment and Physical Planning (YPEXODE) and several national or international ecological groups. The first signs of environmental awareness have been shown through the establishment of the Information Centre by YPEXODE in Chalastra (Operational

Programme 'Environment', Sub-Project 3.2) in 1998. This was one of the main obligations since the delta area and a large part of the river were listed in the Ramsar Convention and the proposals for the Natura 2000 programme. The Information Centre is responsible for the scientific study of flora and fauna, preservation of the delta area, monitoring, and reports about the state and the threats inside the delta and its surroundings. YPEXODE was responsible for the financial and functional support of the Information Centre until recently, but there is now great uncertainty about its future.

The delta area is one of most important places for the migratory and endangered species of birds in Greece. That is one of the reasons why the Hellenic Ornithological Society (HOS) is quite active in this region. The objectives of the Hellenic Ornithological Society (one of the largest non-profit ecological organizations in Greece) are the study and protection of birds and their habitats, the promotion of these aims at the European level in cooperation with related European ornithological societies, and to inform and educate the public. It supports further the scientific and monitoring activities and publishes reports and statements about the natural conditions in the Axios River delta.

In addition, WWF Greece has expressed its interest in the area and has conducted a two-year project for the protection of the Pygmy Cormorant and the White-fronted Goose in the delta area in co-operation with the Hellenic Ornithological Society within the framework of the LIFE project. Furthermore, it supports financially the Information Centre and with the HOS is one of the supporters for a plan of establishing a Natural Park.

As the result of international and national efforts, the following legal framework of the Axios catchment and its delta is now in place:

Ramsar Site: The Axios delta and part of the river, up to 7 km upstream from the river mouth (67 km^2), are designated as a Ramsar site. The Ramsar convention is one of the most important conventions concerning the protection of the global avifauna. Greece has ratified the Ramsar Convention on 19/11/1974 and listed 12 wetlands including the Axios delta. Recent governmental actions aim at declaring also the Alyki Kitrous lagoon as a Ramsar site (Fig. 1).

Natura 2000: This is the official environmental programme of the European Union concerning the identification and protection of all environmentally rich habitats. In our catchment, the following areas are designed as *Natura 2000* sites: site GR1220002, Axios-Loudias-Aliakmon delta (112 km^2); site GR1220007, Axios River (77 km^2); site GR1250010, delta Axios-Loudias-Aliakmon-Alyki Kitrous (138 km^2).

Special Protected Areas (SPA): site GR1250010, delta Axios-Loudias-Aliakmon-Alyki Kitrous (138 km^2) has been designated as a Special Protected Area.

Joint Ministerial Decision: With the JMD 14874/3291 of 6/7/1998, the areas of Gallikos estuary, Kalochori lagoon, and Alyki Kitrous lagoon, were also designated as ecological important areas to be protected.

Game Reserve: Almost 30% of the area characterized as Ramsar site is also characterized as game reserve to be protected.

The improvement of the WWTPs and the sewage collection networks in the greater Thessaloniki are considered as response actions of paramount importance for the quality of the Thermaikos Gulf. The private (since 1998) EYATH company has invested so far more than 70,000,000 € (EC contribution 85%) to upgrade the city's sewage treatment infrastructure and for the period 2002–2006 has planned to invest more than 30,000,000 € for additional works. In addition, the company plans to use the pipeline network to support fiber-optics telecommunication services. Finally, EYATH has shown understanding, as far it concerns the role of the Axios River in the quality of the Thermaikos Gulf system, and plans to collaborate with FYROM to construct sewage networks and WWTPs in twelve cities. These actions would help towards the improvement of the overall quality of the Axios River.

Conclusions

The DPSIR conceptual framework was used to assess the environmental condition of the Axios River watershed and the Thermaikos Gulf, with particular focus on freshwater supply and nutrient emissions. Industry, agriculture, livestock breeding and urbanization, are the benchmark socioeconomic drivers that exert various pressures on the system, altering its natural conditions. Reduction in freshwater, and nutrient over-enrichment, are some of the most important types of pressures identified. Over the past 20 years, freshwater supply was reduced by ~32% due to extensive use of freshwater for irrigation. The release of untreated or partly treated domestic and industrial effluents, together with the extensive use of fertilizers in agriculture represents the most important contributors to nutrient loads. Presently, approximately 9,200 t of nitrogen and 2,400 t of phosphorus originate in the Axios, Aliakmon, Loudias and Gallikos Rivers, which discharge into the inner Thermaikos Gulf. An additional important source of nutrients is the City of Thessaloniki. Total annual

nutrient load, derived from all sources, has been estimated at 11,800 t of nitrogen and 3,400 t of phosphorus. The Axios River is the major contributor of nutrients, supplying about 44% of the total load for nitrogen and 55% of the total load for phosphorus.

Although difficult to quantify, the social and economic consequences of nutrient over-enrichment include ecological effects and economic, aesthetic, health and livelihood impacts (NRC 2000). The direct impacts have been the occurrence of phytoplankton blooms, occasionally of toxic species, anoxic conditions in the water column, and aesthetic degradation of the marine environment.

Several measures have been taken to tackle the problem. The establishment and continuous improvement of WWTPs in the wider Thessaloniki area are among the most important ones, whilst industrial and municipal point sources situated in FYROM continue to discharge untreated effluents in the river. The city of Skopje and the fertilizer plant in Veles are probably the main nutrient point sources identified. State response should focus upon this issue, together with a controlled use of fertilizers, in order to improve the current condition of the river. In any case, continuous monitoring of the Axios (and the other rivers) should be conducted routinely, accompanied by monitoring of the coastal area to assess the system's feedback in future managerial actions. Environmental protection actions have been undertaken in the coastal zone, designating parts of the river deltas as protected areas (Ramsar and Natura 2000 sites etc.). It should be noted, however, that local stakeholders (farmers, fishermen/shellfish producers, and industrialists) displayed contrasting opinions about the state of the environment and its potential future use, while expressing a general distrust of state decisions. On the other hand, all groups accepted that environmental protection is a major issue.

The DPSIR framework revealed that an integrated watershed-coastal zone management plan is needed to address effectively the problems of the Axios River-Thermaikos Gulf continuum. Moreover, bilateral agreements between Greece and FYROM should be established in order to control freshwater use and nutrient emissions in the Axios River.

The EUROCAT project aims to identify in more detail the parameters that will ensure beneficial responses of the system currently under pressure. The use of a loop of numerical models for the catchment (MONERIS) and the coastal zone (WASP) will enable the quantification of nutrient loads that should be achieved to reduce the impacts of eutrophication in the gulf. Moreover, specific management solutions (e.g. the construction of WWTPs in FYROM, fertilizer use reduction, erosion reduction, use of P-free detergents in FYROM etc.) will be assessed and their efficiency will be tested through the models. Finally, the applicability of the solutions will be tested by cost-benefit analysis and a number of hierarchically ordered policy options will be evaluated, until the completion of the project.

The application of the DPSIR framework analysis seems to provide a solid scientific tool useful for tackling environmental issues. It considers all factors interacting in the watershed-coastal zone continuum, while bridging socio-economics and natural sciences. The results of the DPSIR analysis will offer policy makers a list of applicable measures, with sound socio-economic and environmentally friendly background toward an integrated and sustainable watershed-coastal zone management.

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