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Remote Sensing and GIS Techniques for Selecting a Sustainable Scenario for Lake Koronia, Greece

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Abstract During recent decades, Lake Koronia has undergone severe degradation as a result of human activities around the lake and throughout the basin. Surface and groundwater abstraction and pollution from agricultural, industrial, and municipal sources are the major sources of degradation. Planning a restoration project was hampered by lack of sufficient data, with gaps evident in both spatial and temporal dimensions. This study emphasized various remote sensing and geographic information system techniques, such as digital image processing and geographic overlay, to fill gaps using satellite imagery and other spatial environmental, hydrological, and hydrogeological data in the process of planning the restoration of Lake Koronia, following Ramsar guidelines. Current and historical remote sensing data were used to assess the current status and level of degradation, set constraints and define the ideotype for the restoration, and, finally, define and select the best restoration scenario.

Keywords Wetland restoration · Remote sensing · GIS · Ramsar guidelines

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Introduction

Recent pressures from human development in the vicinity of Lake Koronia (prefecture of Thessaloniki, northern Greece) during recent decades have resulted in the rapid degradation of water quality and quantity in the lake. Contaminant concentrations have increased, and the water level has dropped by 80% since the 1980s. As a result, the ecosystem has suffered drastic changes that have also affected human communities.

The lake–wetland ecosystem is protected by a number of binding actions, including the Natura 2000 network, Ramsar Convention, and a Common Ministerial Decision that designates it as a national park. In addition, a resolution at the 8th meeting of the Contracting Parties to the Ramsar Convention on Wetlands (COP8) called for immediate restoration plans. Although restoration has been proposed at regional, national, and international levels, previous restoration plans did not conform to international guidelines (Water Framework Directive 2000/60/EC, Ramsar Bureau), were not self-sustainable, and promoted major public debate.

The Ramsar Convention Bureau, recognizing the importance of wetland restoration and its increased interest among Contracting Parties, urged its experts on the Scientific and Technical Review Panel to define principles for wetland restoration. Guidelines adopted by Resolution VIII.16 (2002) provided further guidance on tools and methods, including case studies, for wetland restoration (http://ramsar.org/strp_rest_index.htm). They provided a step-by-step process of identification, development, and implementation for a restoration project. A minimum set of data is required to implement a restoration plan, which is not always available. Crisman and others (2005) pointed out the importance of including both vertical and horizontal approaches in management schemes of shallow lakes and wetlands in addition to vertical management, which implies a need for spatial geographic information. These datasets, both geographic and nonspatial, require extensive time and resources for development and are frequently the most expensive part of any restoration project.

Ecological restoration requires a clear vision of the expected outcome of the process, an understanding of ecological processes needed to restore and maintain the ecosystem, and specific skills and techniques to accomplish the work (Zalidis and others 2002). Historical data for the structure and function of a wetland must be examined to develop a baseline condition for the ecosystem (Steedman and others 1996). Synthesis of this database for the wetland should delineate present ecological conditions, including relationships between the wetland ecosystem and its watershed, functional relationships within the system (foodwebs, productivity, etc.), as well as future development scenarios of the system. In addition, understanding the role of terrestrial–wetland and open water–wetland ecotones is key to the development of long-term management plans (Mitraki and others 2004).

As restoration projects tend to be very expensive in terms of both time and money, particularly if they are unsuccessful (Keddy 1999), new technologies are employed to reduce these costs. Recent advances in remote sensing technology have led to increased interest for environmental application. Remotely sensed data have a number of advantages relative to other data sources: They are a consistent method of data collection, broadly cover the entire study area, allow easy multitemporal comparison, are cost-effective in medium to large study areas, and offer a unique way to study inaccessible or highly protected areas. Subsequent analysis of remotely sensed data in a geographic information system (GIS) can provide useful environmental information. Remotely sensed data have been used for monitoring forest parameters, including mapping (Pax-Lenney and others 2001), biomass estimation (Israelsson and Askne 1995), and defoliation (Radeloff and others 1999). They have also been employed in aquatic ecosystems to estimate sea surface temperature (Marullo and others 1999), assess water quality (Allewijn and others 1995; Shafique and others 2001; Pal and Mohanty 2002), and characterize marine eutrophication (Nezlin and others 1999). Human environmental impacts have also been studied with remote sensing and GIS techniques, including point sources and nonpoint sources (El Raey and others 1998; Sifakis and others 1998) and detection of oil spills (Lu 2003). Al-Khudhairy and others (2000) employed SHYLOC (system for hydrology using land observation for model calibration) to estimate water levels in ditches and channels of a wetland being restored in central Greece using remotely sensed data and auxiliary hydrological modeling. Recently, the SPIN project (Spatial Indicators for Nature Conservation, 2000–2003; www.spin-project.org) examined the usefulness of a set of indicators derived using satellite images and GIS modeling for characterizing the status of protected environments, including a wetland in northern Greece.

The purpose of this study was to demonstrate the extent to which remote sensing and GIS techniques can contribute to the selection of a sustainable reference condition, as part of a restoration plan for Lake Koronia. To achieve this, several geographic information layers were created using remotely sensed data in a GIS environment. This information together with field data were used to assess the current status and level of degradation. The constraints of the restoration were set, and the ideotype was then defined. Finally, the restoration scenarios were developed, and the optimum was selected for restoration of Lake Koronia.

Study Area

Lake Koronia (Prefecture of Thessaloniki, Greece) lies in a tectonic depression at N 40°41′, E 023°08′. Its watershed is approximately 780 km^2, and formerly it drained to Lake Volvi, then the sea. The two lakes and their wetlands have been listed as a Wetland of International Importance by the Ramsar Convention since 1975 (GR005: 16,388 ha), and have been proposed as a Site of Community Interest within the Natura 2000 network (GR1220001: 26,948 ha). In recognition of its ecological importance, it is protected by national and local legal frameworks.

The lake was approximately 4620 ha before 1980 with a maximum depth of 6 m. Since then, however, it has experienced a progressive decrease in area to 3600 ha in 1990 and 1700 ha in 2000, and it almost disappeared in 2002 when the maximum depth dropped to 0.8 m. During this period, water quality also declined as conductivity, nutrients, and chlorophyll increased (Mitraki and others 2004). The period of water quality decline coincided with the progressive reduction in lake level that was independent of regional rainfall trends (Mitraki and others 2004).

Numerous studies (Karavokyris and Partners and others 1998; Zalidis and others 2004b) have identified intensification of agricultural and industrial activities in the vicinity of the lake as the principal factors for these changes. Rapid development of industry in the 1980s and expansion of irrigation wells (HMEPPPW 1996) depleted water resources and discharged pollutants though streams and drainage canals.

Assessment of the availability of water resources in the basin started in 1973 to further development of irrigation and drinking water. The depletion problem was recognized after 1995, when studies from the Aristotle University of Thessaloniki and the Hellenic Ministry of Physical Planning and Public Works called for the development of management actions. The resulting restoration action, the Master Plan for the restoration of Lake Koronia (Karavokyris and Partners and others 1998), proposed pumping of deep groundwater, interbasin transfer of water, diversion of two streams currently discharging into Lake Volvi, installation of collective irrigation schemes, and treatment of industrial and municipal effluents. Some of the environmental impact studies of the Master Plan were not approved, as they were not self-sustainable and had also raised public debate.

Methodological Framework

Functional analysis at the watershed level was used to develop a sustainable restoration plan for Lake Koronia. Wetland functions, as sets of physical, chemical, and biological processes, define an ecosystem from which wetland values for humans derive. The functional approach of restoration seeks to identify which processes are degraded and which functions should be restored (Zalidis and others 2004a). According to Ramsar guidelines, restoration must be designed around characteristics of the entire watershed, not just the degraded wetland. Activities throughout the watershed can adversely affect the aquatic resource being restored. A site-specific restoration project might not be able to change conditions in the whole watershed, but it can be designed to accommodate watershed effects within a realistic context (Zalidis and others 2002). The functional analysis for Lake Koronia followed principles and guidelines adapted in COP8 (Zalidis and others 2004a) and was based on methodology proposed by Zalidis and others (2002) for selecting appropriate reference goals for restoration.

The adopted methodology included the following steps:

1. Watershed assessment. It was essential to identify the causes of degradation in order to minimize ongoing stresses wherever possible. In identifying these, it was important to look at upstream and upslope activities, as well as direct impacts on the immediate project site. A watershed assessment for Koronia was used to identify the main driving forces of lake degradation throughout the watershed and their importance.
2. Restoration constraints. Identification of possible restoration constraints included availability of natural resources, legislation, and the environmental and socioeconomic status of the area. Wetland restoration plans must be developed within local and national regulatory frameworks.
3. Establishment of the lake restoration ideotype. Restoration goals were established after determining the lake ideotype that is the desirable critical structural and functional characteristics for the restored lake to promote sustainability. Such goals were defined to reestablish a new sustainable ecosystem able both to perform desirable functions and to serve nature and humanity without external assistance. This was an open process involving all local stakeholders and *in situ* socioeconomic surveys.
4. Development and selection of the most appropriate restoration scenario. Development of possible restoration scenarios was based on both restoration constraints and the established ideotype. Functional evaluation of each scenario utilized techniques proposed by Adamus and others (1987) and Marble (1992), as modified by Zalidis and others (2004a) for use in Mediterranean wetlands. The functional performance of each scenario was compared with the ideotype, and the most appropriate restoration solution was selected.

Remote sensing techniques were used throughout to reduce costs for data collection and minimize erroneous restoration predictions. They provided a means for testing and enhancing understanding of fundamental wetland hydrological and ecological processes. Also, they were used to evaluate different restoration schemes. Thus, their key role was to ensure correct hydrology and ecology.

Data Gap Filling and Information Extraction

A set of environmental, hydrological, and hydrogeological data was considered essential for planning the lake restoration. Due to restricted availability of some of these data, several techniques were adopted to extract data from remotely sensed imagery for use in

GIS to fill gaps in existing datasets. A number of geographic information layers were produced and used in the restoration plan, which are presented as vector and raster datasets of appropriate thematic maps in the GIS. The list of all input data and sources of information, their characteristics, and their main use in the study is displayed in Table 1.

Environmental Data

Size, composition, and spatial distribution of habitats are indicators of the health of natural ecosystems. Moreover, closeness and intensity of human activities are a way to assess the function of foodweb support. Natural vegetation, as primary production, defines habitats of secondary or tertiary consumers. If human pressure is kept at a minimum and natural resources are not degrading, then foodweb support can be sustainable.

The habitat map for the Koronia–Volvi wetland was completed in 2001 following the European habitat Directive 92/43/EEC. Despite detailed field sampling (which involved species identification and location using the Global Positioning System), existing base maps were outdated (1978), and the scale (1:50,000) was insufficient to describe spatial variability of the wetland. Instead, a photomap from 1996 at a scale of 1:5000 was used to define existing habitat boundaries correctly, supplemented by field sampling. Computer-assisted photo-interpretation was used for boundary correction rather than an automated procedure because of the very high scale and the black-and-white nature of the photomap. To increase the accuracy of the resulting map, more samples were taken either in ambiguous areas or when dramatic changes had occurred recently. The resulting map of habitat types was compared visually against the available ASTER/Terra satellite image to detect identification errors. Although this image was of lower scale (1:30,000) compared to the photomap (1:5000), its multispectral information was valuable. Certain habitat types (6420 - Mediterranean tall humid grasslands of the *Molinio-Holoschoenion*, 92D0 - Southern riparian galleries and thickets *Nerio-Tamaricetea* and *Securinegion tinctoriae*, and 72A0 - *Phragmites*) could only be differentiated using this multispectral information because their tone and texture appeared extremely similar in the black-and-white photomap.

The ASTER/Terra satellite image of 16 July 2003 was used. Its spatial resolution (ground sampling distance) was 15 m in the green, red, and near-infrared spectral wavelengths, and its geographic coverage was most of the Koronia–Volvi basin. Spectral classification was used to map land-cover types of the lake basin. A set of 20 samples was selected for each of the 9 land-

Table 1 Input data, sources of information, and their main use in the study

Dataset	Scale/resolution	Source (year)	Main use in the study
Photomap	1:5000/1 m	Ministry of Agriculture (1996)	Base map
Habitat polygons	1:50,000	Ministry of Environment (1978-2001)	Updated and scale-enhanced habitat polygons
Vegetation field samples	Selected locations	Ministry of Environment (1999-2001)	Updated and scale-enhanced habitat polygons
ASTER/Terra satellite image	1:30,000/15m	USGS (2003)	Updated land cover, habitat polygons
Location of pump wells	±5 m	Prefecture of Thessaloniki (2000)	Pressure from irrigated agriculture
Digital Elevation Model	40 m	Ministry of Agriculture (1996)	Source of hydrological data
Topographic maps	1:50,000	Hellenic Army Geographical Service (1980)	Reference for hydrological data and general information
Spatial interpolation of meteorological data	Available locations	Tzimopoulos (2004)	Lake's water balance
Historical extents of lake's shoreline	1:50,000–1:100,000	Pittas (2003)	Correction of bathymetry
Bathymetry	1:20,000	Dimanidis and Panagiotidis (1999)	Lake's water storage capacity and water loss
Geological maps	1:50,000	IGME (1978–1987)	Available groundwater
Depth of bedrock	Selected locations	BRGM (1972)	Available groundwater
Piezometric wells	Selected locations	IGME (2000)	Available groundwater

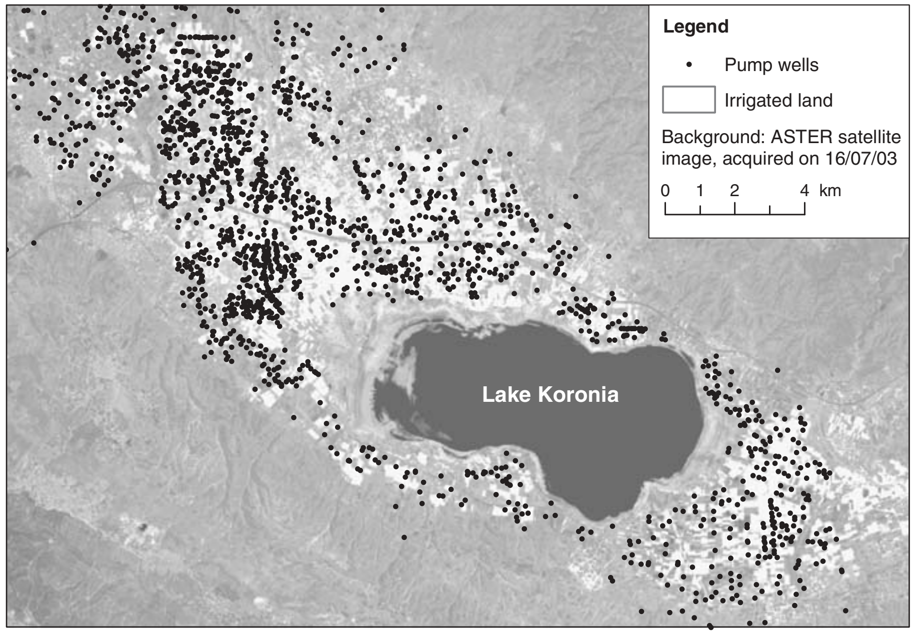

Fig. 1 Spatial distribution of irrigated fields and locations of pump wells

cover types from the satellite image using photo-interpretation of a standard false color composite visualization (R,G,B = Near-infrared, Red, Green). From these samples, statistics that describe the variability of reflectance for each land-cover type were calculated to form spectral signatures that were incorporated into the classification algorithm. Accuracy assessment was performed using 250 random samples, whose true land cover was identified similarly to other samples. The overall classification accuracy of the resulting land-cover map was 89% ($\hat{k}$ statistic = 0.81), which is acceptable considering the high spatial variability of the study area (Fig. 1). Settlements, irrigated land, and the transportation network were the land-cover types of highest interest because their proximity to the lake–wetland was a potential source of pollution.

The land-cover type ''irrigated area'' constituted a different thematic map because it was considered the source of highest environmental pressure on the lake. A further comparison of the area mapped with that of irrigated land reported by local authorities was not significantly different. A separate thematic map was created that displayed the spatial distribution of irrigated fields and the location of the 2500 pump wells. Figure 1 gives a qualitative assessment of both the pumping impact on the aquifer and the source of agricultural pollution.

Hydrological Data

The Digital Elevation Model (DEM) (40-m grid) of the Koronia basin was used for surface hydrology analysis. Information layers including surface water flow direction, flow accumulation, and natural drainage network were produced using standard surface hydrology tools of the GIS software. These permitted delineation of the boundaries of subcatchments of the Lake Koronia basin. The accuracy of this geographic information was checked visually against elevation contours and the hydrographic network of topographic maps. Small errors in almost flat terrain were corrected to account for the inability of the algorithm to perform in such conditions.

Surface hydrology geographic information, in combination with time series of meteorological data, provided the information required for the water balance of Lake Koronia. Rainfall and temperature historical data (1985–2002) were used in conjunction with programming tools to estimate the trend of water availability in the Koronia basin until 2011, as described in Tzimopoulos (2004). This methodology incorporated the modified Turc method for estimating evapotranspiration, kriging interpolation for point measurements of meteorological data, and existing studies (Iosifidis 2002) regarding groundwater abstraction and recharge and surface runoff. This information revealed that available water in the basin became significantly lower from 1985 to 2002.

Bathymetric data were used to characterize the lake bottom. Available data included depth measurement from 109 points and the resulting bathymetric contours (0.5-m elevation step) from a survey conducted in 1998 on behalf of the National School of Public Health, Sanitary Engineering Department (Dimanidis and Panagiotidis 1999). The method used for point measurements combined a kinematic procedure using the

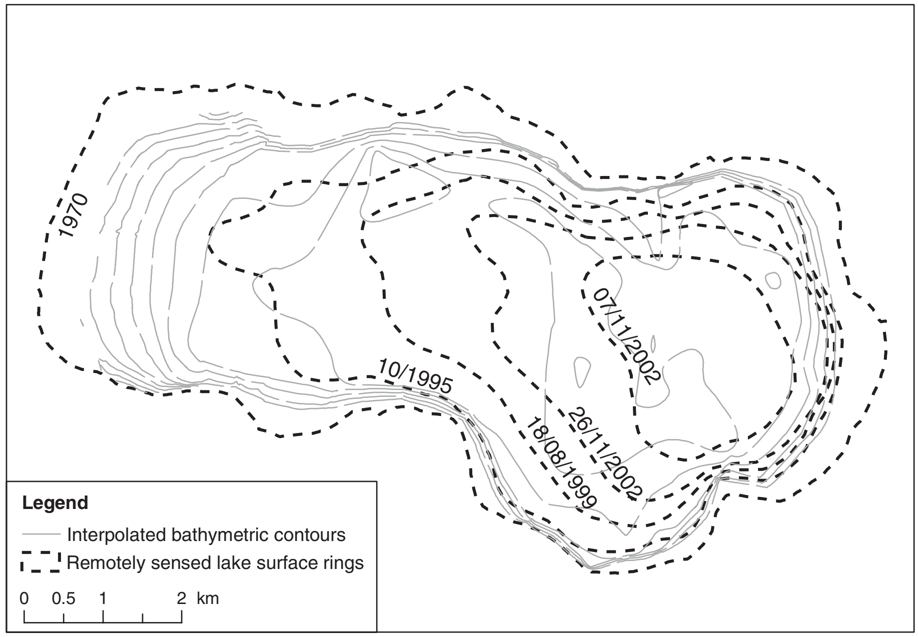

Fig. 2 Interpolated contours of Lake Koronia bathymetry versus shoreline ''rings'' derived from remote sensing (after Pittas 2003)

Global Positioning System for horizontal determination and classical geodetic methodology using a surveying rod for depth determination. Bathymetric contours were interpolated to a continuous surface using the ANUDEM algorithm (Hutchinson 1989). This interpolation process was selected because it performs well even with relatively small input datasets and uses a roughness penalty parameter that can be modified to allow the fitted surface to follow the smooth changes of the lake bottom. Visual examination of the original measured points with the bottom surface produced no discrepancies. Further comparison revealed a mean difference of 0.02 m (t = 2.268, df = 258, P = 0.024).

These data were considered current, as no drastic changes in the lake bottom were recorded, and this was verified by actual measurements taken at 20 locations. An additional check was performed using a time series of satellite images that covered the time when the water level dropped from 6 m to less than 1 m. Mapping of lake shoreline ''rings'' was used as a means of establishing bathymetric contours at certain depths. Remote sensing is an excellent means of mapping aquatic boundaries, with accuracy approaching 90% (White and others 1993). This work, as described in detail by Pittas (2003), employed an ISODATA classification algorithm to characterize the lake in a time series of archived Landsat MSS, TM, and ETM+ satellite images from 1995 to 2002, with spatial resolution ranging from 79 to 30 m. The ''rings'' of the shoreline where compared visually with the interpolated bathymetric contours (Fig. 2). A statistical comparison was also implemented to identify the similarity of the two datasets. Sampling was conducted at 1-km intervals along the shoreline ''rings.'' The elevation recorded on the shoreline ''rings'' was compared with the elevation of the interpolated lake bottom, revealing a mean difference of 0.11 m (t = 1.719, df = 57, P = 0.091). Differences were attributed to the alternate methodology and source of data: one being the result of satellite digital image processing and the other being interpolated surveyed data.

The detailed bathymetric representation of the lake bottom was used for calculating lake surface area (loss of water) and water volume (water storage) at any given level of water. Various hypothetical water levels (possible restoration scenarios) were compared against the digital bottom surface. From this three-dimensional comparison, a set of possible water surface extents was calculated to estimate water loss through lake surface evaporation. Finally, a set of possible water volumes was calculated to estimate water storage capacity of the restored lake.

Hydrogeological Data

The aquifer of the Koronia basin has both phreatic and pressurized subsystems that are separated by a clay pan (Mitsiou and Tsakoumis 2002). Based on data reported in the Master Plan for Lake Koronia restoration (Karavokyris and Partners and others 1998), the vertical extent of the phreatic aquifer ranges from 40 to 60 m and consists mainly of sand and gravel, with smaller clay layers. Its recharge is through both direct percolation of precipitation and leakage from streams and riverbeds, and a fraction of that is discharged to the lake. The vertical size of the deep pressurized aquifer is ~150 m, and recharge is through direct percolation and indirect side flow from the bedrock. Water from the aquifer system is mainly discharged through the 2500 pump wells surrounding the lake that are used mostly for irrigation and industrial practices. There is a negative water balance for the groundwater aquifer that directly influences the lake water level. The main reasons for this negative balance appear to be restricted recharge, increased water pumping, and depletion of agricultural water through evapotranspiration.

Additional mining of the geographic datasets supported this information. Geological maps of the basin, available at a scale of 1:50,000, were scanned and georeferenced in the common coordinate system. Other available data included the depth of the bedrock underlying the basin aquifer, in the form of contours, which resulted from soundings in the lake vicinity (BRGM 1972). Locations of 66 piezometric wells distributed around the lake were also obtained, along with water-level measurements in the high and low seasons of 1997 and 2000 (IGME 2000). These water levels were contoured by hand to define the continuous surface of the groundwater table. The kriging method of interpolation was also tested, but the results were not satisfactory for this dataset. Possible reasons for the poor performance could be either that the aquifer is confined or that extra collateral data were not available (De Kwaadsteniet 1990, Desbarats and others 2002). Next, three-dimensional GIS analysis was employed for information extraction, similar to the lake surface water. Volumes of available groundwater ($3150 \cdot 10^6$ m^3) and water deficit since 1982 ($257 \cdot 10^6$ m^3) were estimated. The latter was considerable for the lake basin and must be accounted for in the restoration process.

Determining a Sustainable Restoration Plan

Watershed Assessment

The first task in the lake restoration process was a watershed assessment to identify the main driving forces of the degradation, as well as their resulting pressures on the lake ecosystem. A functional assessment was adopted for this task, a state-of-the-art method for assessing the current status (Adamus and others 1987, Marble 1992). This was based on the hypothesis that ecosystem functions in the entire basin, rather than just the wetland–lake, are better indicators of environmental impact. In effect, basin functions reveal the environmental state and are of greater interest at local and regional levels.

The functional assessment was carried out within the framework of DPSIR (Driving Forces–Pressures–State–Impact–Responses) that allows analysis of interrelated factors that affect the environment and identification of appropriate measures (EEA 1998, 1999, 2001). In this case, a modified DPSIR model was used (Zalidis and others 2004c), where State and Impact are assessed in common through the functional approach. This common assessment was adopted because these levels are interrelated and a separate assessment would require an enormous amount of data, with a subsequent increase in cost and time. In addition, there was no reference for the State or the resilience of the environment on the Impact.

The functional assessment was facilitated by division of the watershed into Zones of Specific Functional Interest (ZSFI). In each zone, several functions are performed (e.g., groundwater recharge, foodweb support), but some are more important than others, depending on the ‘‘ecological’’ role of the zone in the watershed and the management priorities for the area (e.g., agricultural production or nature conservation). Also, different driving forces, which lead to pressures, are prominent in each zone (intensive agriculture, industrial activity, livestock). Topography also defines the selection of zones, as there are different functions of interest in the wetland than in the upper catchment. Protection zones that apply were considered as well because they pose a different level of restriction. Delineation of the ZSFI was therefore based on the spatial distribution of the following parameters: hydrology–geomorphology (which separates important functions and defines topography), land cover–land use (which separates driving forces that lead to pressures), and protection status. Using the appropriate geographic layers (large geomorphic units, DEM, land cover, and protection zones) in a GIS and performing overlay analysis with a set of criteria (relational and Boolean functions), polygons were derived that provided a synthesis of the above-mentioned parameters. Computer-assisted photo-interpretation of the satellite image was used both to correct errors due to misregistration of the geographic layers and to eliminate small polygons with no physical meaning. The resulting polygons, after being grouped according to similar characteristics, formed the ZSFI (Fig. 3). Four ZSFI zones were delineated: (A) upland, (B) lowland–high protection, (C) lowland–low protection, and (D) lake–wetland.

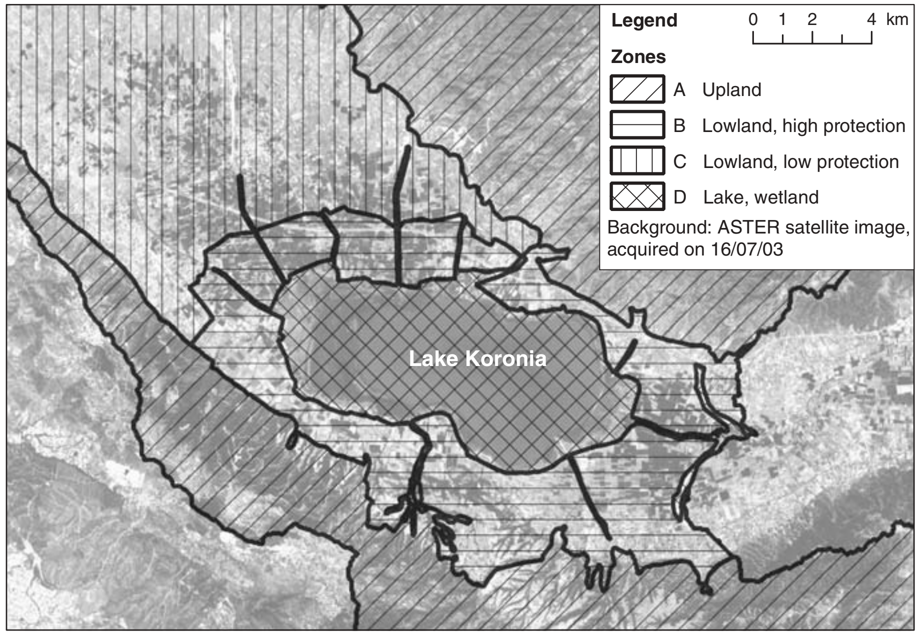

Fig. 3 ZSFI identified in the study area

Evaluation of basin functions of interest incorporated previously created geographic layers and additional information. Surface hydrology and recorded flow data of streams discharging to the lake were used to evaluate the function of lake water recharge and sediment transportation. Surface hydrology, in conjunction with hydrogeologic information, was used to assess water availability and groundwater recharge. Composition and distribution of natural and seminatural ecosystems, habitat types of Annex I of Directive 92/43/EEC, species populations of Annex II of Directive 92/43/EEC, and bird populations of Annex I of Directive 79/409/EEC were used to assess foodweb support. Nutrient removal and transformation and sediment and toxicant trapping were evaluated indirectly using available water-quality indicators of Directive 2000/60/EC. DEM and the lake bottom model were used to evaluate floodwater attenuation and water storage function. Finally, spatial distribution and density of pump wells and irrigated land were used to assess water resources depletion. Reported discharges of agrochemical, industrial and municipal effluents were used to assess water-quality degradation. Individual functional performance was marked in a qualitative scale, ranging from Low, Medium, High, to Very high. Functional evaluation was performed using hydrogeomorphic characteristics and elements of human intervention and activity. Marking was based on the proposed methodology by Adamus and others (1987) and Marble (1992) as modified by Zalidis and others (2004a). The function ‘‘support of wetland–lake functions’’ was difficult to mark in the same scale; therefore the scale Negative, Neutral, and Positive (Table 2) based on the effect of each ZSFI on the functioning of the lake wetland ecosystem was used, where neutral stands for noneffect.

Functional evaluation of the ZSFI revealed that natural processes in Zone A (upland) were responsible for large volumes of sediments entering the lake. The main transporters of these are streams with permanent and seasonal flow. As a result, water quality is degraded, and in the long term, water storage capacity of the lake is reduced. In Zone B and Zone C (lowland), agriculture was responsible for surface and groundwater pollution via agrochemicals (N, P, K), whereas industry and urban expansion were responsible for degradation of surface water quality due to discharge of large amounts of salts, nutrients, heavy metals, and toxic elements. Overexploitation of surface water and groundwater for industrial, municipal, and mainly agricultural use was responsible for modification of the water budget. The negative water budget of recent years (1982–2002) lowered the water table and increased the hydraulic slope from the streams to the water table. Eventually, groundwater discharge to the lake was minimized. In Zone D (lake–wetland), dense vegetation, mild slopes, and the location of the wetland on the west side had a positive contribution via interception of floodwater. Fish populations decreased in the 1980s and completely vanished in 1997. The conditions of habitat types in the lake–wetland are heavily or mildly degraded, and together with the high level of nuisance caused by human presence, birds and mammals populations have decreased. Overall, the

Table 2 Overview of the functional evaluation of the ZSFI

ZSFI	Functions of interest	Assessment of function
Upland (A)	Support of wetland–lake function	Neutral
	Foodweb support	Medium
Lowland–low protection (C)	Support of wetland–lake function	Negative
Lowland–high protection (B)	Support of wetland–lake function	Negative
Lake–wetland (D)	Water storage	High
	Floodwater attenuation	High
	Groundwater recharge	Low (degrading)
	Sediment and toxicant trapping	Low (degrading)
	Nutrient removal and transformation	Low (degrading)
	Foodweb support	Low (endangered)

Scale of assessment of function: Low, Medium, High, Very high

Scale of "support of wetland–lake function": Negative, Neutral, Positive

functional performance of the above-mentioned zones had and still has a negative effect on the structure and function of the lake.

Establishing a Lake Restoration Ideotype

Certain restrictions and constraints were considered during the process of defining the restoration ideotype of Lake Koronia. These included: legislation restrictions (international and national), conservation of existing habitat types and species of the 92/43/EEC Directive, availability of natural resources, and the administrative, environmental, and socioeconomic status of the area.

This task of the restoration process utilized mainly archives and available studies on the current status of Lake Koronia, the problems that have emerged, and their causes. Historical geographic data regarding ecosystem state (e.g., habitats extent and location), derived from analysis of archived Landsat MSS, TM, and ETM+ satellite images (Pittas 2003) were implemented in a GIS in order to examine the process of degradation. The information layers created earlier with remote sensing and GIS techniques were also used to reform the list of constraints, using overlay functions, and expert opinion. In this task, environmental information layers were used to assess constraints posed by the numerous degraded functions of Lake Koronia that needed to be restored. Another sector where these information layers were used, together with hydrological and hydrogeological information, was the investigation of constraints posed by the restricted availability of natural resources. In summary, remote sensing and GIS information were used where geographic data were needed to benchmark the current situation so that the restoration process would avoid further degradation.

Following identification of restoration restrictions, restoration goals were established by determining the structural and functional characteristics that the lake should have after restoration. These form the lake ideotype, which is the ideal functional state that the lake should be under present conditions (Zalidis and others 1998; Zalidis and others 2004a). Based on the restrictions and watershed assessment (legal priorities/obligations, natural resources availability, and functional degradation), lake functions that should be remedied were, in order of importance, as follows: (1) support of biodiversity and habitats (foodweb support), (2) improvement of water quality (nutrient removal and transformation, sediment and toxicant trapping), and (3) improvement of the water budget (water storage, groundwater recharge, floodwater attenuation).

Having formed the ideotype and the most urgent goals of lake restoration, specific functions were examined individually. According to Zalidis and others (2004a), the functional analysis of the degraded wetland might be an effective tool in revealing past errors in the management of water and soil resources and designing wetland restoration schemes. Thus, in order to maximize societal and ecological benefits of the restoration project according to Ramsar guidelines, it was essential both to identify what functions must be present and to make reestablishment of missing or impaired functions a restoration priority. The Ramsar Bureau identifies that restoration of wetlands as parts of the river ecosystem—especially if approaches or strategies cover entire catchment areas—is a vital and necessary tool to restore lost functions and benefits, reduce the risks of downstream flooding, improve water quality, and reestablish plant communities and stocks of fish and other wildlife. In addition, the Ramsar Bureau urges Contracting Parties to produce

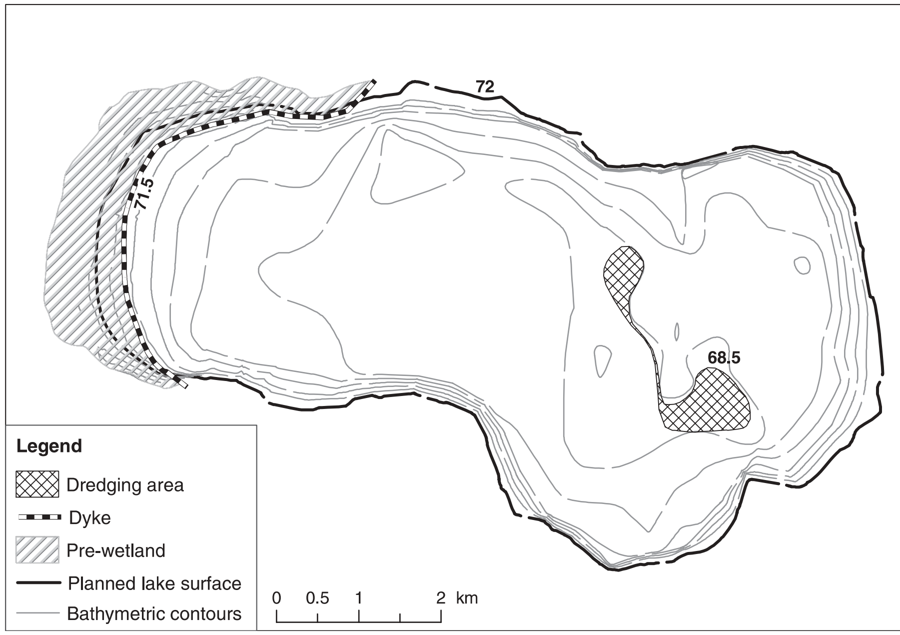

Fig. 4 Best scenario for restoration of Lake Koronia. Elevations are meters above mean sea level

information about wetland losses, including an assessment of the lost processes, functions, composition, and values of wetland areas. This information should include data about the restoration potential of these sites and the full benefits of restoration, including identification, at all appropriate levels (Ramsar 1999). Through this perspective, restoration interventions at wetland, watershed, or water management district scales had to be determined based on sustainability of natural functions (Zalidis and Gerakis 1999). In COP8, the Ramsar Contracting Parties called to identify the spatial need for restoration of wetland functions and to set environmental constraints for restoration in each case. The former approach was based on two assumptions: (1) spatial analysis of catchments should help both to identify areas where there is a need for restoration of wetland functions and to rank the relative need for restoration and (2) spatial analysis of catchments requires assessment of wetland functions at the catchment level (Ramsar 2002). In the last decades, several techniques of functional evaluation and assessment have been developed (Adamus and others 1987; Brinson 1985; Hruby 1999; Marble 1992), and the Scientific and Technical Review Panel (STRP) of the Ramsar Convention developed general guidelines for rapid assessment and monitoring of wetland biodiversity and functions as requested by the Ramsar Convention's Strategic Plan 2003–2008 (Ramsar 2005a, 2005b).

In the case of Lake Koronia, the level at which these functions should perform was defined based on the watershed assessment and restrictions already identified. A qualitative scale was used, ranging from poor to very good (poor, moderate, good, very good). The desired level of performance for each function is listed in Table 3.

Remote sensing imagery and hydrological data (bathymetric contours) were used as source data to identify the location, shape, and size of the ideotype characteristics, which were then used to develop restoration scenarios. Despite the important functional role that the horizontal extent of vegetated areas has, the desired width and plant density of this zone is still under investigation. Crisman and others (2005) noted that the horizontal aspect of a management plan is of equal importance to the vertical in shallow lakes and wetlands. Therefore, a geographic visualization was essential to obtain a horizontal aspect of the lake–wetland ideotype and to design certain elements of the wetland restoration.

Restoration Scenario

Four restoration scenarios were examined reflecting different approaches to restoration. These were formulated considering restoration goals and the desired level of performance of the functions listed in the previous sections. The desired conditions of the new lake–wetland were the following: creation of deep habitats (lake depth of 4 m), replenishment of lake water (nonterminal lake), and maintenance lake size at present conditions (at least 3400 ha). These were implemented in the following scenarios: Scenario 1, no intervention in lake and wetland; Scenario 2, lake

Table 3 Current situation for functions, ideotype and functional evaluation of the best restoration scenario

Functions	Current situation	Ideotype	Restoration scenario
Groundwater recharge	-	o	o
Floodwater attenuation	+	+	+
Water storage	+	++	+
Sediment and toxicant trapping	-	++	++
Nutrient removal and transformation	-	++	++
Foodweb support	-	++	++

Scale of evaluation: –: low; o: medium; +: high; ++: very high

dredging; Scenario 3, wetland creation; Scenario 4, lake dredging and wetland creation. GIS was used to simulate and visualize the characteristics and geography of these potential restoration scenarios to facilitate their assessment.

Functional evaluation of the four restoration scenarios was based on the approach of Adamus and others (1987) and Marble (1992), as modified by Zalidis and others (2004a). During evaluation of the restoration scenarios, three-dimensional GIS analysis was used to simulate the lakebed and wetland shape. The area and volume that these features would occupy in the four scenarios were estimated with this technique, allowing for assessment of necessary water volumes and water evaporation from the water surface.

Following Ramsar guidelines and the functional evaluation described, the most appropriate solution for restoring Lake Koronia was selected, which includes lake dredging, water-level enhancement, and wetland creation (Fig. 4). The water level of the lake would be raised by 0.5 m and a wetland would be created at the western end of the lake at contour 71.5 m, defined by a dike. In addition, 117 ha of the lake bottom would be dredged by 0.5 m to increase lake depth and create deep-water habitat. Dredged material would be used to create the dike using the Confined Disposal technique (USACE 1987). The lake would cover 3500 ha, with a maximum water volume of $83.8 \cdot 10^6$ m^3. The maximum water depth of the lake would be 4 m. Control of water level and recycling of water would be achieved through hydraulic modification of the ditch connecting lakes Koronia and Volvi.

This scenario maximizes both vertical and horizontal aspects of lake management. The constructed dike will manage water levels in a wetland to the west, with open-water areas embedded within a highly vegetated marsh. It will also increase the depth of the lake selectively to provide a refuge for fish during a drought. This scenario should be able to perform wetland functions at the highest degree compared to the ideotype (Table 3).

Conclusions

Wetlands are transient but dynamic ecosystems. A basic research question is the self-sustainable level that the degraded wetland of Lake Koronia should be restored in order to support the water cycle of the catchment, as well as to meet the conservation objectives in the context of the river basin approach. Ramsar guidelines for wetland restoration provide a very good step-by-step procedure to answer this question. This study demonstrated the extent to which this procedure could be supplemented by remote sensing and GIS techniques.

Remote sensing was used extensively as a source of data because of cost–benefit advantages. GIS techniques were used mainly to visualize, analyze, and combine data to retrieve information regarding the ecological status of the catchment, the availability of natural resources in the area, and the assessment of pressures and impacts of human activities on the lake. Use of spatial data in the lake GIS was necessary to obtain a horizontal aspect of the wetland–lake ideotype.

The qualitative procedures adopted for the individual restoration tasks were validated to a certain extent via high-resolution photomap and satellite images. Statistical comparison was used to assess the accuracy of the results of the remote sensing and GIS procedures. The accuracy of the information provided was proven acceptable for the geographical extent of the lake basin.

Although the described procedure is adequate for the selection of a self-sustainable reference level for the wetland–lake restoration, there are certain limitations. Some information cannot be obtained using remote sensing and GIS techniques, including pollutant concentration and properties of the water that define its quality. Finally, fieldwork cannot be completely bypassed, but kept to a minimum, which decreases the cost of the project.

Having defined a sustainable scenario for the functional and structural rehabilitation of the lake based on the availability of natural resources, the revised restoration plan addresses the identification of appropriate measures and actions, both at wetland and watershed scale, in order to restore the lake and alleviate the sources of degradation at the watershed level.

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