Using state-of-the-art techniques to develop water management scenarios in a lake catchment

Elias Dimitriou[1] and Ierotheos Zacharias[2]

[1]Hellenic Centre for Marine Research/Institute of Inland Waters, Mavro Lithari, Anavissos-Attiki, PO Box 712, 19013, Greece. E-mail: *elias@ath.hcmr.gr*

[2]Department of Environmental and Natural Resources Management, University of Ioannina, 30100 Agrinio, Greece

Received 9 January 2006; accepted in revised form 28 August 2006

Abstract Integrated Management of the Water Resources is nowadays a prerequisite for environmental preservation and economic growth. The EU Water Framework Directive provides the guidelines to develop strategies and institutions to protect and restore the water resources in both qualitative and quantitative bases. However, the implementation of the proposed measures incorporates significant difficulties arising from the lack of necessary data, the fragmented approach often followed in water management and the incomprehension of the interactions between hydrologic systems and ecological components. In this particular study, a combination of remote sensing data, hydrologic models, ecological assessment techniques, GIS software and isotopic surveys have been adopted to extensively study the water resources of Trichonis Lake catchment, in Western Greece, in order to develop management alternatives aiming at protecting ecologically significant wetlands and meeting the local irrigation demands. The management alternatives have been developed with the contribution of local authorities by redistributing the monthly water outflows from the lake according to the ecological and anthropogenic demands and comprise five plans that attempt to minimize the environmental impacts from the regional water use while maintaining the economic activities unaffected.

Keywords Hydrologic modeling; lake catchment; water resources management; wetlands

Introduction

Integrated Water Resources Management (IWRM) is a multidimensional concept that includes various scientific, socioeconomic and environmental aspects. This has raised obstacles in assigning a consistent definition, acceptable by both the scientific community and local authorities, until recently. Nevertheless, a short but comprehensive definition has been finally accepted and states: "The integrated management of water resources concerns a procedure that promotes the coordinated development and use of water, ground and other relevant resources, so as to maximize the economic and social wealth, without limiting the viability of the ecosystems" (Ågarwal *et al.* 2000).

The need for integrated management of water resources has become imperative during the last decades because of the noticeable decrease of high quality freshwater reserves. This is mainly caused by the irrational use of freshwater storages and the alarmingly high pollution rates (Turner *et al.* 1993). Beyond that, there has been an increased water demand as a result of the rapid development of human activities in the primary and secondary sector.

The management practices on local and regional levels in most countries until the present are inadequate and focus mainly on direct economic benefits without considering the environmental cost and the potential long-term economic consequences. This is accredited by the newly introduced Water Framework Directive (2000/60/EC) that imposes to the

Nordic Hydrology Vol 38 No 1 pp 79–97 © IWA Publishing 2007

doi: 10.2166/nh.2007.026

member states the development and application of IWRM plans that will incorporate "the polluter pays" principle and the concept of aquatic protected areas (water bodies that provide domestic water or ecologically significant aquatic habitats/species). This Directive also enforces water quality monitoring on a continuous basis and restoration of the good water quality in all European aquatic bodies based on physicochemical and ecological quality indices. For these reasons, the fast and credible development, review and update of water resources management plans is necessary today while special attention should be given to secure the protection of the ecosystems without compromising sustainable growth.

In the second half of the previous century most European countries have applied resource management plans (Robins *et al.* 1999). Various scientific and socioeconomic approaches have been adopted on an international level in order for integrated water management practices to be applied. Such is the case with the approach of "safe yield", which is defined as the amount of water that can be abstracted from underground or surface water bodies without degrading their permanent storages (Sophocleous 2000).

In most Mediterranean countries such as Greece, relatively reduced rainfall rates and low water reserves are observed that present significant spatial and temporal fluctuations. Until recently, there has not been a regime of rational water resources management, thus resulting in the appearance of water shortage and desertification phenomena.

This particular study aims to combine state-of-the-art techniques such as remote sensing, isotopic hydrology, scientific models and GIS tools to develop integrated water management plans for Trichonis Lake catchment which can be easily implemented and updated by the relevant local authorities.

Description of the area

The study area is Trichonis Lake catchment, a semi-mountainous area (average and maximum elevation: +340 m and +1980 m, respectively), located in Western Greece, prefecture of Aitoloakarnania (Figure 1). Trichonis Lake has the largest water volume compared to all the natural water bodies in the country ($2.6 \times 10^9\,m^3$) and its maximum depth reaches 58 m. The geology of the catchment comprises highly fractured calcareous formations in the northeast part, flysch formations in the western and northern parts and quaternary and pleistocenic sediments around the lake (Figure 1). The population of the area is approximately 20,000 people and the main economic activities of the area are agriculture, tourism and manufacturing (small scale factories, mostly olive oil refineries). The area belongs to Natura 2000 European protection network due to the significant wetlands existing around the lake while the water management in the area is applied by 2 local authorities (local offices of the Ministry of Public Works and Ministry of Agriculture).

Methods

Remote sensing and GIS

In the primary stage of the study the topographic and geologic maps have been digitized and imported in ArcView (GIS software). A Landsat 5+ image has been used in the Image Analysis package to map the land use of the study catchment with the contribution of relevant existing information and orthophoto maps provided by local authorities. After the geometric correction of the image and its enhancement with the histogram equalization method a combination of supervised and unsupervised classification of the area's spectral signatures occurred with the ISODATA algorithm (Zacharias *et al.* 2004). The land categories predefined in the algorithm were agricultural fields, forests, urban and abandoned areas and open water surfaces. The map produced has been compared to existing maps and the above process has been repeated to improve accuracy. The land use map of the area has been used in combination with irrigation demand indices to estimate the water needs for the

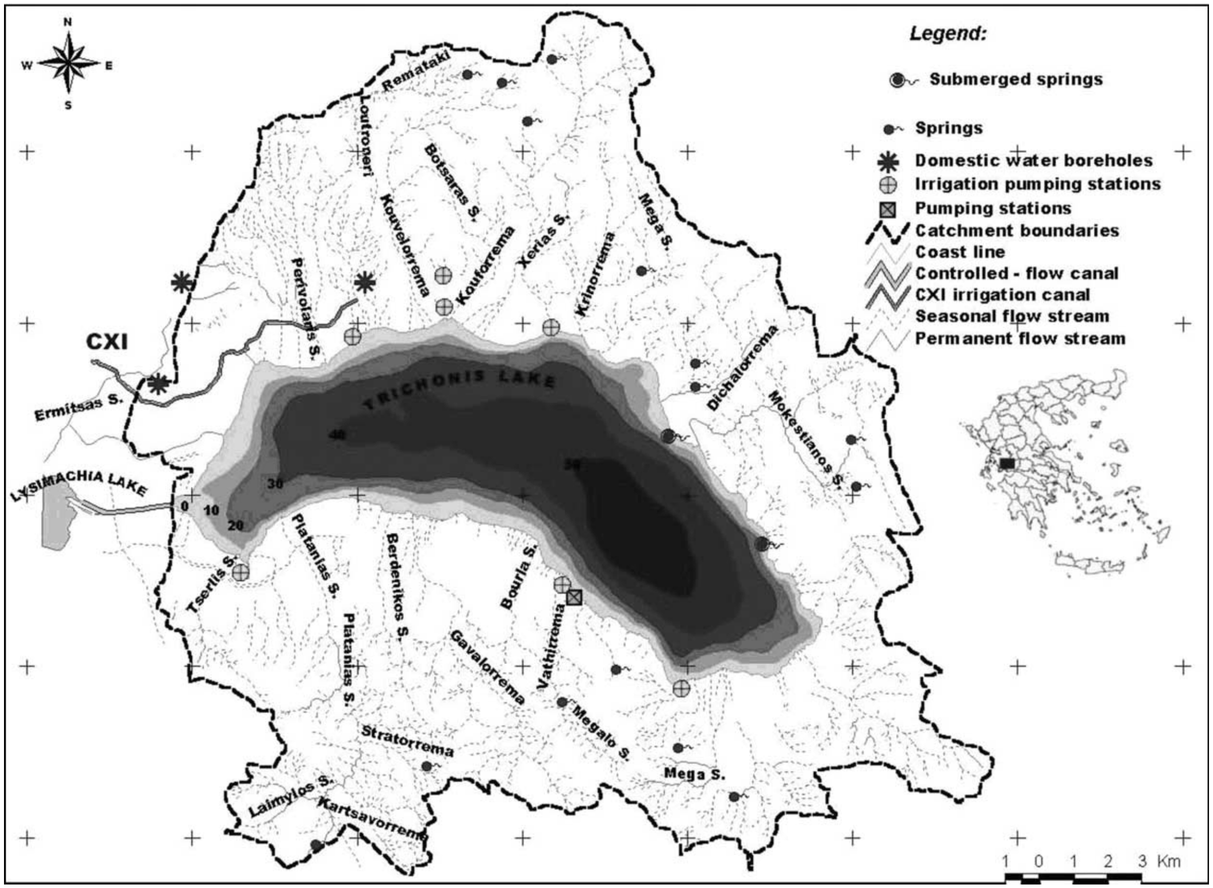

Figure 1 Trichonis Lake cathment and the main water management infrastructure in the area

study catchment's cropland. This result has contributed to the calculation of the area's water budget and to the development of water management alternatives.

Isotopic study

An isotopic study of the broader area followed to identify interactions between different water bodies existing inside and outside of the particular catchment. For this purpose tracing efforts by using the stable isotopes of oxygen in the water has been conducted, which is a widely applicable technique for studying the hydrogeologic conditions of karstic areas (Attendorn and Bowen 1997; Harris *et al.* 1998). Seasonal water sampling from 25 points (12 springs, 10 samples from river/streams and 3 samples from the lake) occurred in May, July, September, November and December 2003. The samples were analyzed regarding their $\delta^{18}O$ value in the NCSR Democritus Laboratory of isotopic hydrology and the results underwent a statistical elaboration to estimate the recharge altitudes of the sampling locations as well as to identify points that have similar temporal variations in their isotopic values which could indicate common recharge areas. For this purpose the diagram presenting the relationship between $\delta^{18}O$ values and recharge altitudes has been developed by using sampling locations of known, local recharge areas which is a common practice when no rainwater $\delta^{18}O$ measurements at different altitudes are available (Leontiadis *et al.* 1996; Leontiadis and Nikolaou 1999). Thus, springs located in very high altitudes and episodic streams with small catchment sizes have been used to quantify the relationship between $\delta^{18}O$ and recharge altitude and this relationship has then been applied to the rest of the sampling locations for estimating their altitude of recharge. Moreover, the aim of this process was not to calculate the exact recharge altitude for each studied location but to cluster the area's water bodies according to potential common recharge zones. For the results' interpretation all the available hydrogeologic and tectonic information have also been used to increase the reliability of the study's outcome. This approach has been implemented to increase the accuracy of the water budget estimations and therefore to ensure realistic water management alternatives development. Moreover, justifying the out-of-the-catchment groundwater recharge component through the isotopic study resulted in the optimization of the lake's water budget model conceptualization by incorporating the specific hydrologic component in the model and quantifying it.

Water balance estimation

The precise calculation of the monthly water balance components of Trichonis Lake occurred in the second stage of the study by using monthly data for the period 1987–1997, which have been tested for their homogeneity and reliability while the particular time period has been chosen because the necessary time series are complete and representative of the hydrometeorologic regime of the area as observed in the last 40 years.

The model used for the estimation of the monthly water budget of the lake has been extensively used in similar applications and represents a simplified form of the hydrologic cycle:

$$P + R + U_{\mathrm{input}} + V_{\mathrm{input}} - (E + U_{\mathrm{output}} + V_{\mathrm{output}}) = \Delta S \qquad (1)$$

where P: direct rainfall into the lake (m^3), R: surface runoff that discharges into the lake from its catchment (m^3), U_{input}: groundwater recharge in the lake (m^3), V_{input}: any additional water inflows (human induced) to Trichonis Lake (m^3), E: evaporation from the lake's surface (m^3), U_{output}: water that outflows from the lake (m^3) and V_{output}: any further water outflows (human induced) from the lake (m^3), ΔS: monthly changes in water storage (m^3).

The integration of the rainfall measurements recorded in a network of 5 gauging stations has been conducted by using the Kriging method and corrected with the semivariogram of the area's altitudes as produced by the DEM of the catchment and Surfer software. The actual evaporation from the lake has been estimated by the relevant Penman–Monteith equation for open water surfaces and the irrigation needs covered by the lake have been calculated from respective data provided by local authorities. The surface runoff towards the lake has been estimated on a monthly basis from relevant coefficients acquired from recent hydrologic investigations in the area (Lazarides *et al.* 1994) and the appropriate rainfall data. The groundwater recharge in the lake was indirectly estimated by the monthly water budget models since the potential contribution from water bodies existing outside the study catchment did not allow for alternative estimation techniques. Thus, the monthly changes in the lake's water volume have been accurately estimated by utilizing the Digital Bathymetric Model (DBM) of the lake, water level measurements and the relevant volumetric algorithm developed in 3D Analyst software that transformed the monthly water level fluctuations in water volume changes. Therefore, after the estimation of the aforementioned water budget components in Trichonis Lake the only unknown parameter of Equation (1) has been estimated which were the monthly groundwater inflows to the lake.

Water management scenarios

All the above findings of the hydrologic model have been input into a special spreadsheet program developed to contribute in designing and optimizing the water management scenarios. Special attention was paid to the conversion of water volume into water level elevation, so as to be able to estimate the fluctuation level for the various management plans. The main water management infrastructure of the area is the controlled flow canal, which connects Lysimachia and Trichonis Lakes and gives the opportunity to regulate the outflows of Trichonis catchment towards the downstream areas of Acheloos River.

Another important element that is necessary for the creation of integrated water management plans is the exact evaluation of the present and future water demands. Therefore, the economic, population and development tendencies in the area of interest within the next 20 years have been taken into account in order to calculate the associated water demands. These tendencies have been estimated by relevant socioeconomic studies conducted in the area and by relevant statistical measurements provided by local authorities. Thus, the forthcoming demands were incorporated in the management plans in order to secure the coverage of future needs and eliminate the potential environmental impacts.

Moreover, the environmental needs of the area's ecosystems were quantified by conducting a bibliographic research to study the fauna and flora of the area, as well as the hydrologic conditions that favor their preservation. Recent studies of the land use and hydrologic changes in the area have indicated that the wetland zone has decreased by over 80% during the period 1937–2002, mainly due to high seasonal water level alterations (Zacharias *et al.* 2004). These annual water level fluctuations lead to the drought of a 100 m wide lacustrine zone in the southern part of the catchment during the summer period. Jia and Luo (2006) state that it is often very difficult to determine the optimal amount of water supply in a wetland area and therefore modeling approaches are used to provide qualitative understanding of the hydrologic alterations caused by human activities. Further, research conducted by Stutzman and Sullivan (1993) illustrated that additional water supply may be necessary to improve wildlife protection in semi-arid regions. In this way, given the existing boundary between cropland and the lacustrine zone as well as the geomorphology of the specific area, a preservation and restoration goal was set. This goal suggested reducing the extent of the lacustrine zone that becomes dry during the summer period by at least 50%.

The development stage of the management scenarios included a consultation process with the responsible local authorities and aimed at meeting all the anthropogenic and environmental water demands without altering the annual water budget of the lake. Furthermore, the water level fluctuations in monthly and annual bases attempted to decrease by homogenizing the monthly outflows of the lake through the controlled flow canal to establish favorable hydrologic conditions for the wetlands. The proposed changes in the water management scenarios were relatively mild so as to avoid important interference in the local hydrologic regime and consequently unforeseen environmental impacts.

Results

Remote sensing

The elaboration of the Landsat 5 + image provided the land use map of the study catchment which presented a high accuracy comparable to the relevant data from local authorities (Figure 2). In particular, the agricultural fields which cover the greatest extent of Trichonis catchment (35%, Table 1) have a slight difference in their coverage as estimated with the satellite image and the orthophoto map (6.3%, Table 1), while significant deviation is only observed in the urban and abandoned areas (64%) which, however, cover only 8% of the study area. This error has occurred because the ISODATA algorithm used for the image analysis cannot operate efficiently in bare rock areas and especially on mountain peaks and therefore a manual correction of the produced land cover map is essential which has been applied in this study. The forests comprise the second highest land category (34% of the total area) and the estimated differences between the satellite image and the orthophoto map is only 0.3% (Table 1). The coverage of agricultural fields is not expected to change significantly in the forthcoming decade since the area belongs to the Natura 2000 protection network and large scale alterations in the land use regime are not allowed, while at the same time the socioeconomic conditions of the country promote the reduction of agricultural activities and the increase of the secondary and tertiary economic sectors.

The results from the calculation of the land categories extent have been used for estimating the local agricultural water demands based on consumption rates per crop type and have also been incorporated in the design of water management alternatives.

Isotopic study

The measured values in the study catchment's springs credit the contribution of out-of-the-catchment water bodies in their recharge which is also supported by the existing hydrogeologic, topographic and tectonic conditions. In particular, the estimation of the springs' groundwater recharge altitudes indicated that there are 3 main recharge areas at altitudes of approximately 300 m, 480–580 m and 650–720 m (Table 2). Most of the sampling locations of the second group, that have a common recharge area, incorporate the main springs of Trichonis Lake catchment as well as sampling points of Fidakia stream which is located north of the study catchment, very close to the relevant hydrologic boundary and the dominant tectonic regime has obviously affected its flow direction (Figure 3, Table 2). Therefore, the hydraulic communication between this stream and Trichonis catchment springs is ascertained.

The general groundwater flow direction follows the dominant direction of the tectonic surfaces (NW–SE) and Panaitoliko Mountain provides a significant amount of water through Fidakia stream which recharges the karstic springs of the area (Figure 4). Trichonis Lake is also supplied by this system but there may be an additional contribution from Evinos River that cannot be validated with isotopic measurements. There is possibly a secondary groundwater flow constituent which is perpendicular to the main tectonic surface direction (E–W) and explains the significant yield of the submerged springs as well as the potential hydrogeologic communication between Evinos River and Trichonis Lake (Figure 4).

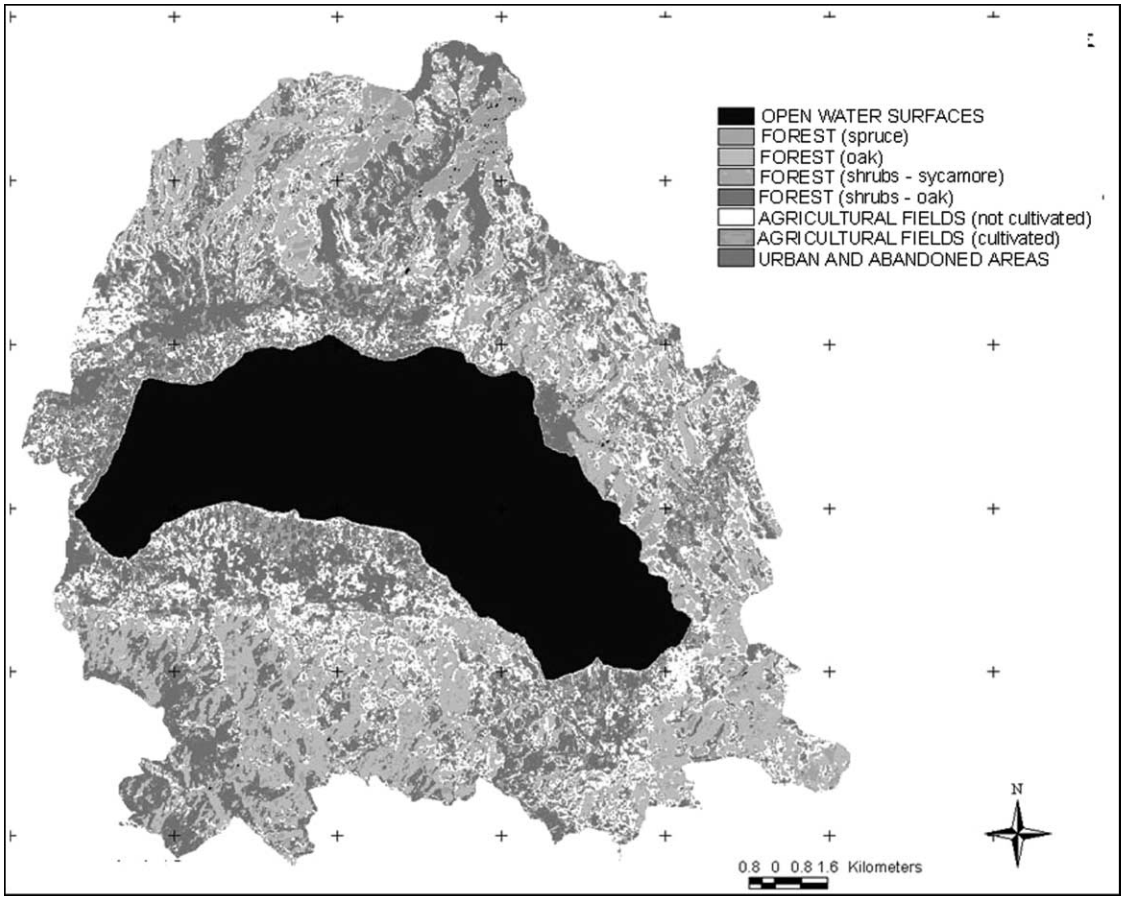

Figure 2 Land use map of Trichonis Lake catchment (developed by elaboration of a Landsat image)

Table 1 Land categories in Trichonis Lake catchment as estimated by Landsat image elaboration and by existing orthophoto map

Land categories	Satellite image (km^2)	Percentage in relation to the total (%)	Orthophoto map* (km^2)	Differences (%)
Forests	137	34	137	−0.3
Agricultural fields	141	35	151	−6.26
Open water surfaces	94	23	97	−2.98
Urban and abandoned areas	32	8	20	63.56

*Orthophoto map has been provided by local authorities

Hydrometeorological conditions

The monthly rainfall records for the period 1951–2002 have been statistically elaborated and a linear trendline has been applied to the data which indicated that rainfall follows a long-term decreasing trend during the above period (Figure 5). The average annual rainfall is 962 mm while the range of the annual values is 1734 mm. There are significant interannual fluctuations in the examined time series, as well as discrete seasonality cycles between wet and dry periods (Figure 5).

Analyzing further the average annual rainfall values for each decade of the period 1951–2002, a decreasing trend between the decades' values can be observed on average (−6.53%, Table 3) while in the decade 1991–2001 a considerable reuction of this decreasing trend has been recorded. These seasonality patterns will have to be taken into account by the local authorities in the updating process of the developed water management scenarios in order to avoid potential disturbances in the hydrologic regime of the area and achieve the management's long-term objectives.

Water uses

In Trichonis Lake catchment most of the water consumption is attributed to agriculture as in many other rural areas around the Meditteranean. In particular, 97 km^2 of cropland (tobacco, olive trees, corn and alfalfa) within Trichonis basin and additional 175 km^2 outside this particular catchment are irrigated directly from Trichonis Lake (Bertachas *et al.* 2000).

Table 2 Isotopic investigations results (SMOW standard) and estimated recharge altitude for each sampling location

Clusters	Sampling location	Z	$\delta^{18}O$ (‰) (05/2003)	Recharge altitude (m)	Water body
1st cluster	Valtsorema	360	−5.672	290	River/stream
	Mavroneri	200	−5.769	309	≫
2nd cluster	Agia Sofia	320	−7.055	557	Spring
	Lefko	480	−6.967	540	≫
	Neromana	390	−6.876	522	≫
	Evinos A	340	−6.82	512	River/stream
	Evinos B	280	−7.043	555	≫
	Fidakia D	360	−6.951	537	≫
	Fidakai E	300	−6.841	516	≫
	Evinos Dam	400	−6.651	479	River/stream
	Myrtia	170	−6.659	480	Spring
	Thermo	340	−6.687	486	≫
3rd cluster	Kalithea	670	−7.459	635	
	Fidakia B	600	−7.629	667	River/stream
	Fidakia A	770	−7.816	704	≫

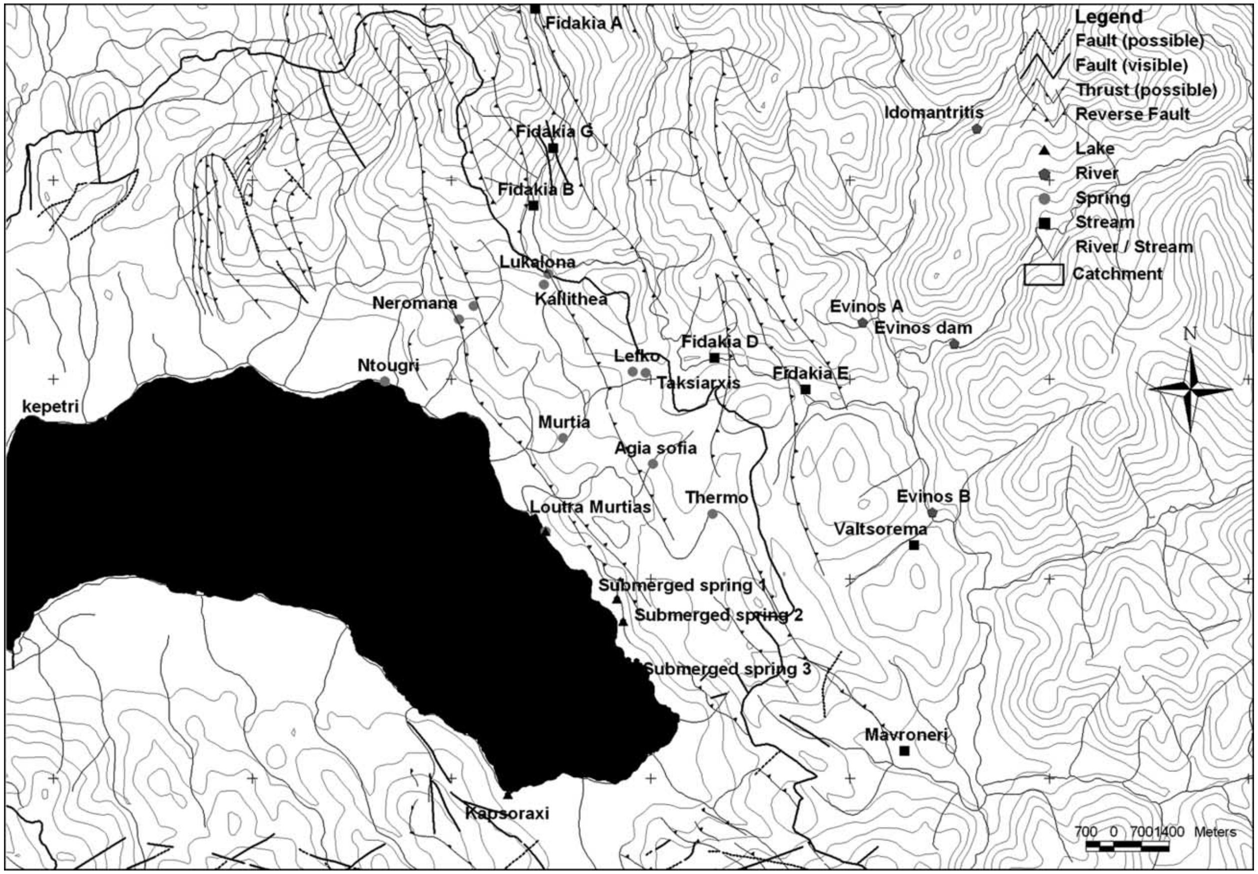

Figure 3 Isotopic study's sampling locations in the broader area of Trichonis Lake

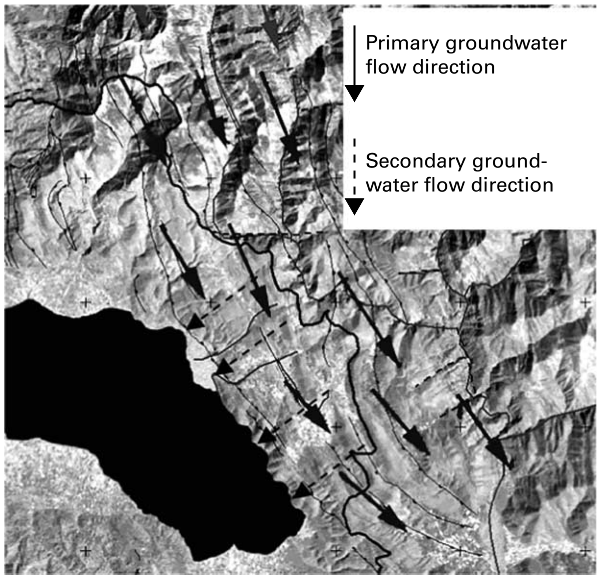

Figure 4 Primary and secondary groundwater flow direction in the broader area of Trichonis Lake

The water needed for irrigation of these areas is acquired by direct pumping from the lake and then is distributed through open canals towards the agricultural fields. The irrigation period has a 6-months' duration (April to September) and the water abstractions for this purpose reach $187 \times 10^6\ m^3$ annually. Most of this water volume (65%) is flowing outside Trichonis catchment through the controlled-flow canal that connects Trichonis Lake with the adjacent lake of Lysimachia. This canal also discharges water excess during the wet periods and therefore comprises an important managerial tool that can contribute in regulating the water transfer system in a sustainable and environmentally friendly way.

A significant proportion ($90.1 \times 10^6\ m^3$) of this irrigation water ($187 \times 10^6\ m^3$) is abstracted from the lake during July and August each year and during this period the water level presents its minimum values. Thus, these high peaks of abstractions should be eliminated by redistributing the water outflows during the summer months using the contribution of Lysimachia Lake as an natural reservoir.

The water consumption for domestic and industrial uses is not high in relation to agricultural water use. The area's population served by direct pumping from Trichonis Lake is approximately 20,000 people and, based on the average consumption rate for the specific

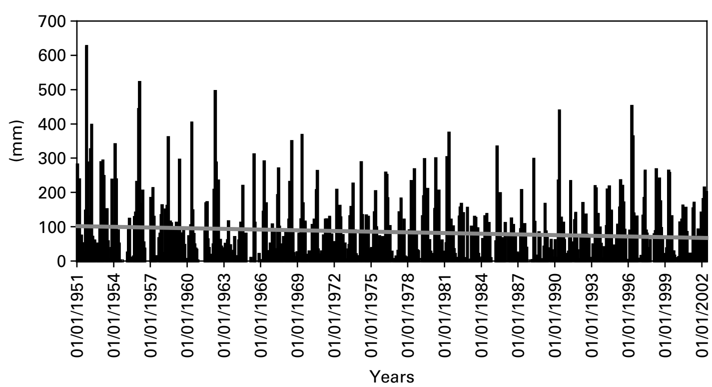

Figure 5 Monthly rainfall values and the average trend for the period 1951–2002

Table 3 Annual average rainfall for the past five decades in Trichonis Lake catchment

	1951–1961	1961–1971	1971–1981	1981–1991	1991–2001	Total change (%)
Average annual rainfall (mm)	1170	907	974	737	979	
Change rate (%)	–	−22.48	7.44	−24.35	32.86	−6.53

area which is 200 l/person/d, the annual water abstractions for domestic and industrial uses reach approximately $1.8 \times 10^6\,m^3$ (1% of the total water abstraction (Table 4)). This estimation is in accordance with the operational records of the respective pumping stations, provided by the public authorities.

Water balance components

The water budget of Trichonis Lake is slightly positive (Table 4) and this is mainly due to the significant external groundwater recharge originating from out of the study catchment mountainous areas, that compensates for the large water abstractions during the irrigation periods. Thus, approximately 36% of the annual water inflows to the lake come from groundwater recharge while 33% of the total inflows is supplied through the overland flow component. The most significant outflow from the lake is the discharge towards Lysimachia Lake through the controlled-flow canal (approximately 62% of the annual outflow) which is mostly used for irrigation purposes in remote areas, downstream of Acheloos River. Evaporation is also relatively increased from the open water surface of the lake (approx. 24% of the total outflows) since the local meteorological conditions (high solar radiation and relatively strong winds) facilitate this particular process (Table 4).

From a water management perspective, the external groundwater supply and the controlled outflow towards Lysimachia Lake are very important since they can be seriously affected by the various management activities and scenarios while they mostly determine the hydrologic regime of the area. In particular, potential future construction of water abstraction schemes outside the study catchment can impact the lake's water budget significantly (through the reduction of groundwater inflows) and the only regulatory infrastructure for applying water management in the area is the controlled-flow canal which is bound by its use for irrigation purposes.

Environmental and anthropogenic water demands

Environmental demands. The wider area of Trichonis Lake belongs to the European protection network of Natura 2000, mainly because of the extremely significant wetlands that developed around the lake and which are protected by the Ramsar Convention, too. These types of ecosystems are mainly threatened by artificial drainage efforts for agricultural use, destabilization of the natural hydrologic regime through construction and operation of water abstraction infrastructure and pollution, mainly by urban waste, agricultural fertilizers and pesticides (Mitsch and Gosselink 1993).

In the broader area of Trichonis Lake the priority habitat of calcareous fens (Habitat Directive 92/43/EC) exists and hosts many rare and endemic floristic species, while its geographic distribution is limited and it is considered an endangered habitat during the last decades (Georgiadis *et al.* 2001). Calcareous fens can be observed in semi-humid and humid climate, in various soil types (clayey, sandy, loamy, etc.) and they are sensitive to hydrologic alterations such as drought conditions during summer periods (Georgiadis *et al.* 2001). In the previous decades, calcareous fen habitats used to cover a significant part of the lakeshore zone

Table 4 Monthly and annual water budgets in Trichonis Lake (all values in $10^6 m^3$)

Water volume ($\times 10^6$ m^3)	1	2	3	4	5	6	7	8	9	10	11	12	An.
Rainfall directly in the lake	8.2	8.7	7.8	8.2	5.4	1.4	1.6	2.5	3.2	6.9	19.4	17.8	91
Overland flow	18.9	21.2	20.2	16.3	8.8	1.3	0.4	0.2	0.5	5.4	24.2	33.4	151
Water inflow from CXI canal	–	–	–	3.4	7.5	9.2	11.5	11.5	4	–	–	–	47
External groundwater inflows	2.5	2	3.5	6.5	27	32,0	35.5	27	17	4	4	3	164
Total inflows	29.6	31.9	31.4	34.4	48.7	43.9	49,0	41.1	24.6	16.3	47.6	54.1	453
Evaporation from the lake	2.0	2.8	7.9	10.1	16.2	16.5	17,0	13.8	9.2	6.4	3.7	1.3	107
Domestic and industrial water	0.1	0.1	0.1	0.1	0.25	0.25	0.25	0.25	0.25	0.1	0.1	0.1	2
Irrigation within Trichonis basin	–	–	–	1.0	11.4	12.4	17.6	15.5	4.1	–	–	–	62
Outflow to Lysimachia Lake	22	20	16	15	20	24	30	30	18	18	33	35	281
Total outflows	24.1	22.9	24.0	26.2	47.9	53.2	64.8	59.5	31.6	24.5	36.8	36.4	452
Water excess/deficit in the lake	6	9	7	8	1	−9	−16	−18	−7	−8	11	18	

while nowadays its extent has been reduced to approximately 80% of the 1937 area which is mainly due to the lake's significant water level fluctuation throughout the year (Bertachas *et al.* 2000). In particular, the unsustainable management of the lake's water resources that incorporates significant water abstractions during the dry period of the year and abandonment of the water excess in the winter period causes great annual and seasonal water level fluctuations that rise up to 1 m and 0.5 m, respectively. This annual water level change (1 m) corresponds approximately to a horizontal distance of 100 m in the southern part of the lakeshore where the ecologically significant habitats are encountered. Thus, a sustainable water management plan to eliminate the water level extremes and provide gradual and slow water level fluctuations will minimize the human induced stresses to the local environment and assist in the sustainable development of the study area. Thus, with minor alterations on the regional hydrologic regime, a more than 50% reduction on today's increased water level fluctuation values will be attempted, as stated in the methodology, through the proposed management scenarios, establishing therefore improved environmental conditions.

The water storages in the area are of high quality since recent studies (Table 5, Bertachas *et al.* 2000) indicated that all the physicochemical parameters, measured seasonally in the lake, are well below the relevant EU limits (98/83/EC Directive). This is because even though the lake's water volume is considerable ($2.6 \times 10^9\,m^3$) the annual water inflows and outflows are significantly high (approx. 18% of its total volume) and therefore the water renewal time is relatively low (6 yr). Thus, the incoming pollutants (mainly nutrients from fertilizers) are flushed out of the system quite fast which obstructs the appearance of increasing concentrations in the lake's water. The proposed management alternatives will not affect the pollution levels in the area since the water budget modifications will be minor (only smoothing of the monthly outflows) and the annual hydrologic regime will remain approximately in the present status.

Future anthropogenic water demands. The future domestic water demand has been calculated by using the regional annual growth rate for the human population (1.5%) which provided a 20-year projection that suggests a population of approximately 40,000 people in the year 2011 (last population survey: 1991). Therefore, the future water demand for domestic uses will slightly fluctuate around $3 \times 10^6\,m^3$, which comprise a 67% increase in relation to the present values.

The industrial uses of water in Trichonis basin can still be considered insignificant since industry is a developing economic field in this area and the respective water needs are covered today from the domestic supply network. Thus the aforementioned calculations incorporate industrial water uses which constitute a relatively low proportion of domestic water consumption (~11%). However, the socioeconomic trends indicate that there will be a slight future development in the field of small scale industries and mainly in agricultural products manufacturing. Therefore, the water abstractions for this type of activity will double in relation to today's values but still the industrial consumption will not exceed 0.4% of the total water abstractions.

Table 5 Water quality measurements in Trichonis Lake and respective EC limits

Sampling dates	SO_4 (mg/l)	Cl (mg/l)	Na (mg/l)	NO_2 (mg/l)	NO_3 (mg/l)	NH_4 (mg/l)
April 2001	18.61	13.97	12.19	0.01	0.99	0.01
September 2001	0.4	0.44	13.3	0.03	0.9	0.25
March 2002	17.21	16.61	14.46	0.01	0.37	0.02
EC limits	250	250	200	0,5	50	0.5

The future water demands for irrigation have been calculated by using respective agricultural development indices produced by statistical data illustrating the relevant socioeconomic trends of the last decades. This process indicated that the agricultural land will not increase in this area in forthcoming years since there is a tendency for farmers to abandon farming in favor of other economic activities such as the services sector and industry. Moreover, the geomorphology of the area and the present land uses do not allow additional agricultural development to occur. Thus, future water demand for irrigation is expected to remain at present levels, and may even become lower due to the planned improvements in the relevant infrastructure, which will provide the opportunity for a more rational exploitation of the water resources.

Water management alternatives

In this particular study, a series of different parameters have been considered before the development of management scenarios. The lake's water budget has been accurately quantified, the existing and future anthropogenic water demands have been also estimated while the environmental water needs have been expressed as water level fluctuations in the lake. Specific criteria based on the above calculations have been set such as the maintenance of current hydrologic regime as far as the annual water budget is concerned, the coverage of at least 80% of the total irrigation demands and the reduction of annual and monthly water level variations by 50% in relation to today's values.

All the alternatives have been assessed for their feasibility as well as for their environmental impacts and finally the best available option has been chosen in collaboration with the responsible local authorities. A decision support software tool has been produced and offered to the water management authorities that allows updating of the water budget as well as testing of different management alternatives by quantifying the available water storages and the respective alterations in the water level (Figure 6). Moreover, the resulting management alternatives are briefly described as follows:

- The first scenario maintains the present water abstractions from the lake and their temporal distribution which covers all the human water needs but incorporates a high annual water level fluctuation (approx. 0.65 m annually and a maximum monthly fluctuation of 21 cm (Table 6, Figure 7)). This scenario does not fulfil the criteria of environmental preservation since it causes significant hydrologic disturbances to the existing wetlands as stated above.

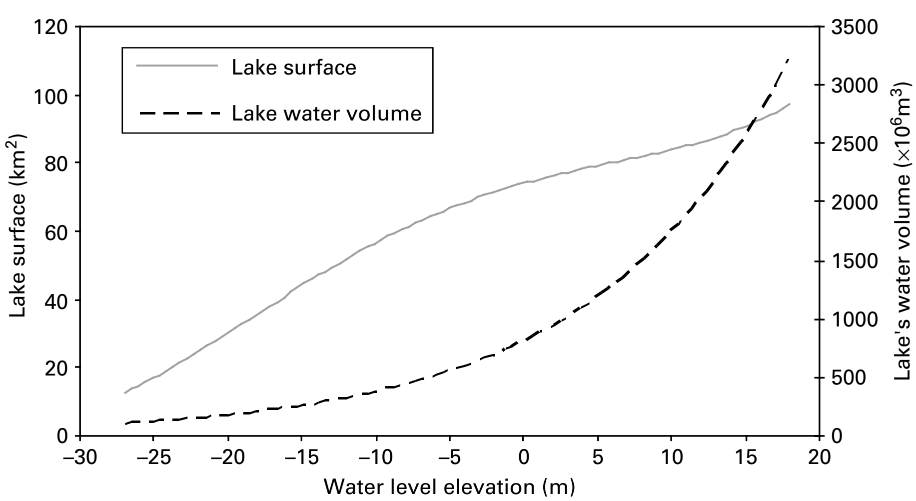

Figure 6 Relationship between Trichonis Lake's surface – water level and volume

Table 6 Management alternatives and expected impacts on the water level fluctuations and on the irrigation demands

Management alternatives	Expected annual water level fluctuation (m)	Expected monthly water level fluctuation (m)	Irrigation needs covered by Trichonis Lake (%)	Additional water demanded by Acheloos River to cover the irrigation demands ($\times 10^6 m^3$)
1st alternative	0.65	0.21	100	–
2nd alternative	0.50	0.18	100	–
3rd alternative	0.33	0.10	83	20
4th alternative	0.25	0.8	79	20–25

- The second alternative is the slight smoothing of monthly outflows through the sluice gate canal in such a way as to achieve the complete coverage of irrigation needs by the lake. This plan reduces the annual water level fluctuation by 25% (approx. 50 cm) and the maximum monthly fluctuation reaches 24 cm (Table 6, Figure 7). These hydrologic conditions, however, cannot be considered favorable for the environmental needs of the area.
- The third management scenario proposes a 8% reduction of the water abstractions for irrigation during the summer period, smoothing of the monthly outflows and respective increase in the water excess outflows during the winter. The additional amount of water needed for irrigation (approx. $20 \times 10^6 m^3$) can be provided by an adjacent reservoir that is used for hydroelectric power generation, through the existing canal system. The amount of water proposed to be abstracted by the aforementioned reservoir ($20 \times 10^6 m^3$) cannot cause significant impacts either in the neighboring catchment or in the electricity production plant since the hydroelectric company already offers, on an annual basis, more than $600 \times 10^6 m^3$ of water for irrigation in the broader area from Acheloos River system (Dimitriou *et al.* 2001). Thus, the additional requested amount is less than 4% of the total water quantity provided by the hydroelectric company as compensation to the local community and the responsible department has already accepted to cooperate in this management alternative. The response of the lake from the implementation of this plan will be a reduction of the annual water level fluctuation to approximately 33 cm and a respective decrease of the maximum monthly fluctuation to 10 cm (Table 6, Figure 7). This plan comprises a rational management scheme that meets the large water demands of the local fiscal activities without compromising the area's environmental preservation.

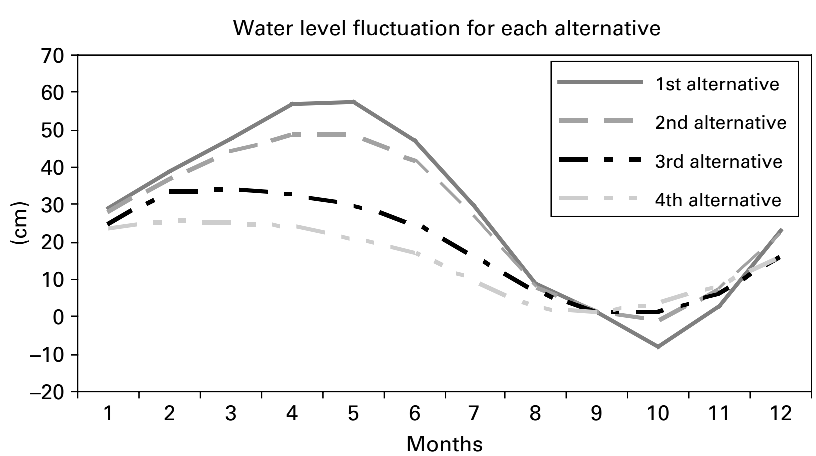

Figure 7 Water level fluctuations in Trichonis Lake according to various management scenarios

- The fourth alternative further reduces the water abstractions for irrigation by approximately 15% in relation to the present value, which leads to a significant minimization of the annual water level fluctuation (~25 cm annually, Table 6, Figure 7). The maximum monthly fluctuation is also considerably reduced (~8 cm) but these very stable water level conditions may incorporate unforeseen environmental impacts. Moreover, the increased outflows from Trichonis Lake towards the adjacent basin in the winter period raises the potential for flooding occurrence.

After extensive discussions with the local stakeholders, and particularly with the water management authorities, the third alternative was chosen for implementation since it satisfies the set criteria and does not restrict agricultural activities. Furthermore, if new irrigation techniques are adopted, such as dripping pipe systems, and watering based on soil moisture measurements or underground distribution networks are constructed, then there will no need for any additional water for irrigation as stated in the above scenario. The implementation of this plan will also reduce the irrigation excess water provided by the current management during the summer which is a critical period for the wetlands (Table 7, Figure 8). It was also agreed by all parties that, prior to the implementation of the third alternative, the second scenario should be applied for a year as a transitional stage in order to introduce the management changes progressively in the system and validate the calculations.

Discussion

One of the most common problems encountered during the development of water resources management schemes is the partial approach to the issue, which is mostly affected by the subjective priorities of decision-makers (Larsen and Gujer 1997). Today, most practicing engineers in water management tend to apply methods that address only sub-parts of the problem while multi-criteria decision analysis that combines different scientific approaches in an integrated way is hardly applied. In this way, certain parts of water management are stressed, such as the coverage of human needs, whereas important issues, which mainly concern future water needs, as well as environmental demands, are omitted or undermined.

The approach that has prevailed in many Mediterranean countries until today on the issue of integrated water management – the increase of the available resources with large scale water collection systems – is now gradually substituted by the management of demand aiming to decrease overconsumption. Thus, nowadays there are cost pricing methods, which take into consideration a significant number of variables, such as the full cost of water use (construction, operation and maintenance costs), incidental cost (profit from alternative water use), cost of social goals achievement and environmental cost (Ågarwal *et al.* 2000).

Another fact that restricts the development and application of water management plans is the difficulty in comprehending the natural systems, as well as the quantification of their processes. In particular, quantifying water requirements for various ecosystem types is nowadays under a scientific challenge but no concise relationships between hydrologic conditions and aquatic habitats have been inferred yet (Jia and Luo 2006). Many scientists used soil moisture models (Poiani and Johnson 1993), simple monthly water balance equations (Dunn and Roach 2001) and various mass balance or empirical models (Cui and Yang 2003) to estimate water requirements in wetland areas.

In this particular study, a water balance model has been used in combination with state-of-the-art techniques to develop a water management plan that satisfies both anthropogenic and environmental demands. In particular, the most significant pressure on the lacustrine wetland habitat in Trichonis Lake catchment is the high water level fall during the summer period that dries up extensive wetland zones. Thus, based on the geomorphologic and land use conditions of the study area, a restoration goal of increasing the lacustrine wetted zone by approximately 50 m during the summer would achieve an important improvement in the

Table 7 Water outflows from the lake according to the present and selected management scenarios (irrigation excess/deficit is: outflow through canal - irrigation out of the study basin)

Water volume ($\times 10^6$ m^3)	1	2	3	4	5	6	7	8	9	10	11	12	Ann.
Irrigation out of the study basin				2.6	19.5	20.9	27.4	27.4	16.3				114
Outflow through canal (current)	22	20	16	15	20	24	30	30	18	18	33	35	281
Outflow through canal (3rd sc.)	20	21	23	24	24	19	22	20	16	10	38	44	281
Proposed changes in outflow	−2	1	7	9	4	−5	−8	−10	−2	−8	5	9	
Irrigation exc./ def. (current)				12.4	0.5	3.1	2.6	2.6	1.7				23
Irrigation exc./ def. (3rd sc.)				21.4	4.5	−1.9	−5.4	−7.4	−0.3				11

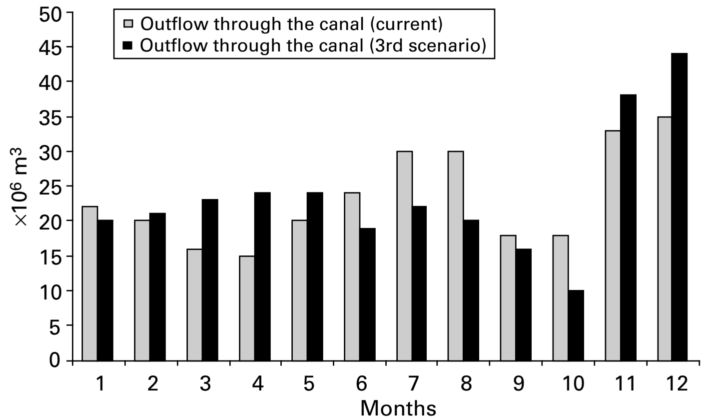

Figure 8 Monthly outflows from Trichonis Lake according to the present and the selected management scenarios

environmental regime of the area. For this purpose the developed water management plan should decrease the maximum annual water level fluctuation by 50% without compromising the agricultural production which is the main economic activity in the region.

The scientific innovation of this study originates from the combination of different novel approaches to develop a multi-objective water management scheme. Moreover, a Landsat image and remote sensing algorithms have been used to develop the updated land use map of the study catchment in order to estimate irrigation demands for the cropland. Further, the isotopic study of the broader area justified the existence of an external groundwater recharge component that supplies significant amounts of water in the geologically complex environment of Trichonis Lake catchment. This information improved the efficiency of the lake's water budget estimation since the groundwater recharge variable was not calculated based on local infiltration within the study catchment but as a function of the observed water level fluctuations caused by the differences between the water inflows and outflows in the lake.

The development of management alternatives and the evaluation criteria applied for the selection of the best applicable option has been realized in collaboration with the relevant local authorities. The transitional water management scenario has been successfully applied in the study catchment while the final management plan will be implemented shortly and it is expected to achieve the goals of environmental preservation and sustainable development of the area.

References

Ågarwal, A., Angeles, M.S.d., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., Villarreal, F.G., Jønch-Clausen, T., Kadi, M.A., Kindler, J., Rees, J., Roberts, P., Rogers, P., Solanes, M. and Wright, A. (2000). *Integrated Water Resources Management*, TAC Background Paper No. 4. Global Water Partnership-Technical Advisory Committee (TAC), Stockholm, Sweden.

Attendorn, H.-G. and Bowen, R.N.C. (1997). *Radioactive and Stable Isotope Geology*, Chapman & Hall, London.

Bertachas, I., Zacharias, I. and Koussouris, Th. (2000). *Evaluation of the Anthropogenic Impact on Trichonis Lake Catchment*. Final report, Life NAT '200099/GR/006499.

Cui, B.S. and Yang, Z.F. (2003). Classification of ecologic water requirements of wetlands. *Res. Sci.*, **25**(1).

Dimitriou, E., Zacharias, I. and Koussouris, Th. (2001). *Water Resources Management Plan for Trichonis Lake Catchment*. Life-Nature '99 project: 'Actions for the protection of calcareous bogs/fens in Trichonis Lake', Technical Report, NCMR/IIW.

Dunn, R. and Roach, G. (2001). Wetland restoration techniques in Indiana utilizing macrotopography measures. *ASAE Meeting*. Paper no. 01–2060. ASAE, St. Joseph, MI.

Georgiadis, Th., Dimitrelos, G., Theocharopoulos, M., Chochliouros, S., Verios, G., Lambada, S. and Ceramonte, M. (2001). *Study for the Calcareous Bogs/Fens Present State in Trichonis Lake*. Final report, Life NAT '99/GR/006499.

Harris, C., Oom, B. and Diamond, R. (1998). A preliminary investigation of the oxygen and hydrogen isotope hydrology of the greater Cape Town area and an assessment of the potential for using stable isotopes as tracers. *Water SA*, **25**(1), 15–24.

Jia, Z. and Luo, W. (2006). Modeling net water requirements for wetlands in semi-arid regions. *Agric. Wat. Mngmnt.*, **81**(3), 282–294.

Larsen, T.A. and Gujer, W. (1997). The concept of sustainable urban water management. *Wat. Sci. Technol.*, **35**, 3–10.

Lazarides, L., Macheras, G. and Notaras, G. (1994). *Water Supply to the City of Athens for Human Consumption from Trichonis Lake*, EYDAP, Athens.

Leontiadis, I.L. and Nikolaou, E. (1999). Environmental isotopes in determining groundwater flow systems, northern part of Epirus, Greece. *J. Hydrol.*, **7**, 219–226.

Leontiadis, I.L., Vergis, S. and Christodoulou, Th. (1996). Isotope hydrology study of areas in Eastern Macedonia and Thrace, Northern Greece. *J. Hydrol.*, **182**, 1–17.

Mitsch, W. and Gosselink, J. (1993). *Wetlands* (2nd edn), John Wiley & Sons, New York.

Poiani, K.A. and Johnson, W.C. (1993). Use of a simulation model in managing a semipermannet prairiewetland. In: *Wetland Symposium: Prairie Ecosystems:Wetland Ecology, Management and Restoration, Jamestown, ND, 9–13 August*.

Robins, N.S., Jones, H.K. and Ellis, J. (1999). An aquifer management case study – the chalk of the English South Downs. *Wat. Res. Mngmnt.*, **13**, 205–218.

Sophocleous, M. (2000). From safe yield to sustainable development of water resources – the Kansas experience. *J. Hydrol.*, **235**, 27–43.

Stutzman, J.W. and Sullivan, G.L. (1993). Restoring and creating artificial wetlands in Montana. In: *Wetland Symposium: Prairie Ecosystems:Wetland Ecology, Management and Restoration., Jamestown, ND, 9–13 August 1993*.

Turner, B.L., Moss, R.H. and Skole, I.L. (1993). *Relating Land Use and Global Land-cover Changes: A Proposal for an IGBP-HDP Core Project*, Global change report, IGBP report No. 24, HDP report No. 25. Stockholm, Sweden.

Zacharias, I., Dimitriou, E. and Koussouris, Th. (2004). Quantifying land-use alterations and associated hydrologic impacts at a wetland area by using remote sensing and modeling techniques. *Environ. Model. Assess.*, **9**, 23–32.