Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2012.748444

51 (2013) 2955–2976
March

Taylor & Francis
Taylor & Francis Group

A mathematical programming approach to restore the water balance of the hydrological basin of Lake Koronia

V. Manakou[a], P. Tsiakis[b,*], A. Kungolos[a]

[a]*Department of Planning and Regional Development, University of Thessaly, 38334 Volos, Greece*
[b]*Wipro Consulting Services, Wirpo Technologies, 3 Sheldon Square, London, W2 6PS, UK*
Tel. +44 7803 037395; email: panagiotis.tsiakis@wipro.com

Received 19 January 2012; Accepted 13 June 2012

ABSTRACT

Over the last four decades Lake Koronia, part of the Mygdonia Basin, operates under a negative water balance due to poor resource management and planning decisions. Lake Koronia is a Ramsar site in northern Greece that has experienced pronounced ecosystem degradation over the past 30 years associated with water level reduction and nutrient loading from agricultural and industrial activities. The objective of the present study is the optimal design of an environmental policy for theoretical and potentially in practice return to a sustainable state of the watershed of Lake Koronia and recommend a rational water resource management plan for the area to promote and support development. The use of mathematical modelling tools can assist in making the right decisions with respect to the water management. The increased complexity of simply managing ecosystems, due to many overlapping factors that affect the water balance, impedes the derivation of the optimal policy to address the problems. This paper presents an optimisation model that takes into account all potential investment options that will allow the restoration of the lake and surrounding area to a sustainable level, and determines the optimal operating policy to allow the ecosystem to recover while maintaining the financial stability of the area. Investment options include the transfer of water from larger water sources, creation of irrigation networks and canals, provision of subsidies to promote alternative land use for agriculture and others. The restoration of a sustainable positive water balance for the basin is possible even if future climatic conditions become more arid than the current. Critical aspects are crop manipulation, irrigation networks and a policy to manage water as a commodity rather than an unlimited resource.

Keywords: Hydrological modelling; Mathematical programming; Water management; Lake Koronia; Sustainable development

1. Introduction

Lake Koronia (Fig. 1) is located in northern Greece at latitude 40˚41´ and longitude 23˚09´ about 75 m above sea level (Fig. 1). It is located approximately 15 km north-east of Thessaloniki. Along the north-eastern shore of the lake is the town of Lagkadas, the major centre of urban development. There are about 20 small villages spread throughout the watershed.

*Corresponding author.

Third International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE 2011) & SECOTOX Conference, 19–24 June 2011, Skiathos Island, Greece

1944-3994/1944-3986 © 2013 Balaban Desalination Publications. All rights reserved.

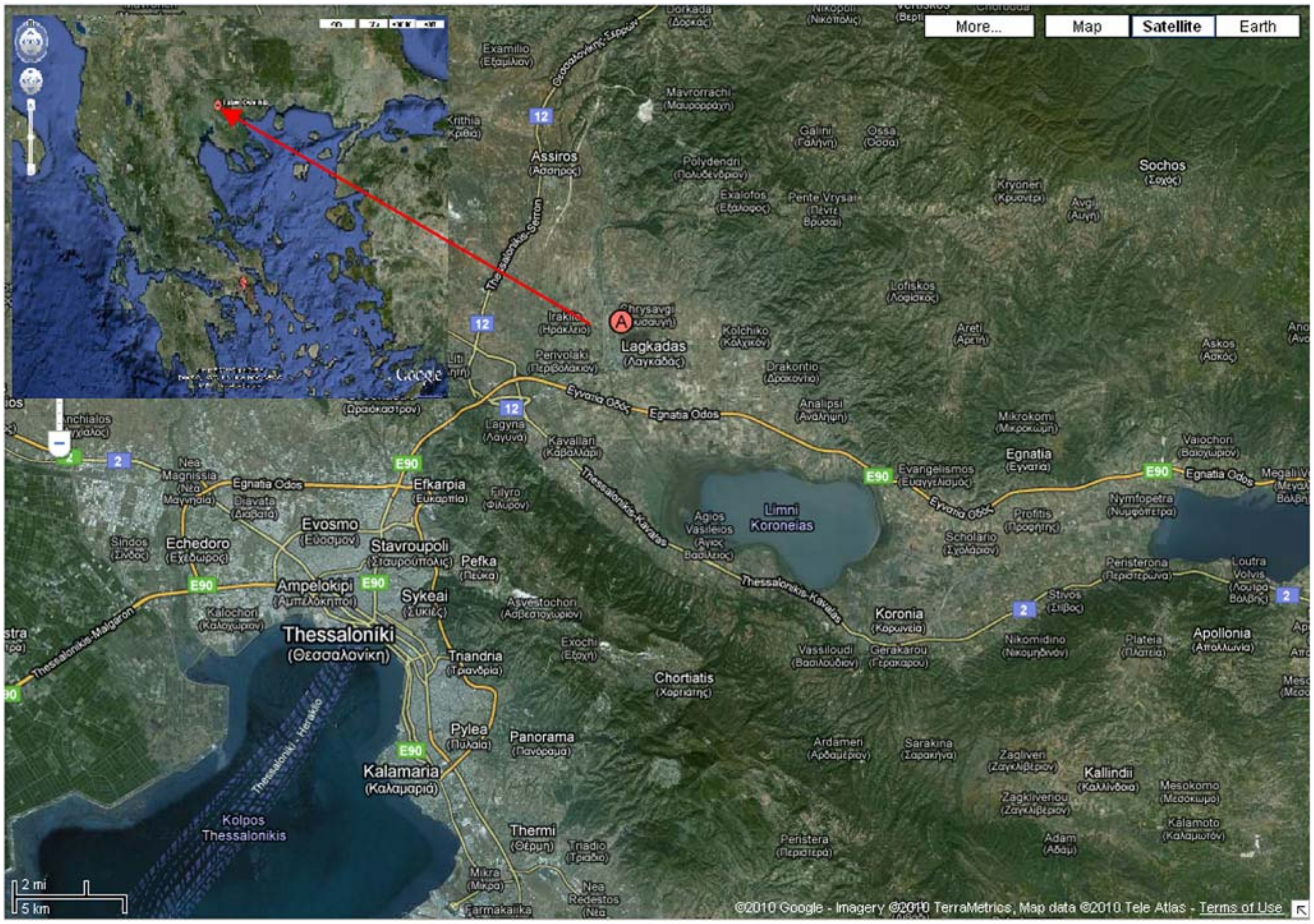

Fig. 1. Lake Koronia.

The watershed is about 350 km^2 and comprises the western part of the Mygdonia Basin, which has an east-west axis of 60 km. Mountains of 900–1,200 m elevation define its northern and southern boundaries and hills of 600 m elevation define its western boundary. The eastern part of the Mygdonia Basin constitutes the watershed of Lake Volvi, one of the largest lakes in Greece. Tectonic activities and major earthquakes created both the Mygdonia Basin and its lakes. Koronia is about 35 m higher than Volvi. Besides underground water discharge, Lake Koronia can potentially overflow to Lake Volvi through a canal. The Richios River is located in the eastern part of the Mygdonia Basin and connects Lake Volvi with the sea. Lake Koronia receives water from five creeks and a ditch initially constructed for flood protection. There is a shallow (0–50 m) and a deep aquifer (60–500 m). The whole area is protected by the Ramsar Convention, as a site of international importance for its value as wetland habitat.

The climate of the region is transitional between Mediterranean and temperate. It is characterised by a large annual temperature range (>20°C), a relatively even distribution of rainfall compared to the rest of Greece and a dry season lasting about two months. Annual precipitation during the last century ranged between 262 and 722 mm, while the mean annual value is 455.8 mm (Figs. 2 and 3). There are two precipitation peaks, first one in December and second one in June. Minimum monthly rainfall is during August. Temperature varies from 0 to 40°C, reaching the minimum in January and the maximum in July.

The current state of this lake is significantly altered from conditions at the beginning of the twentieth century. According to the first available data in 1977, Lake Koronia was eutrophic. Currently, it is hypereutrophic [1].

Management of the water resources of Mygdonia basin is a matter of research and strong interest by state and private organisations due to its importance for the economy of the area. Failure to provide a sustainable approach to manage the water resources of the Lakes and the surrounding environment will

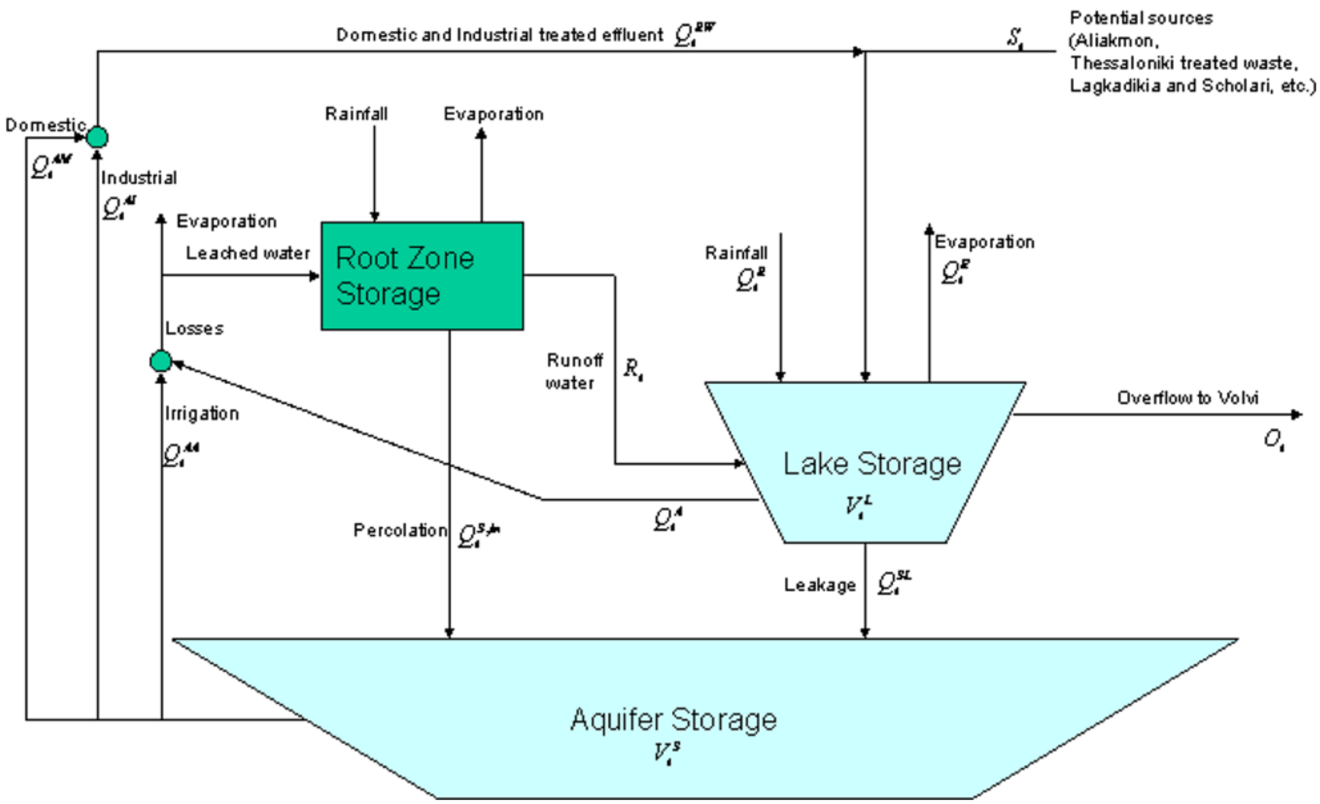

Fig. 2. Basin view with flows.

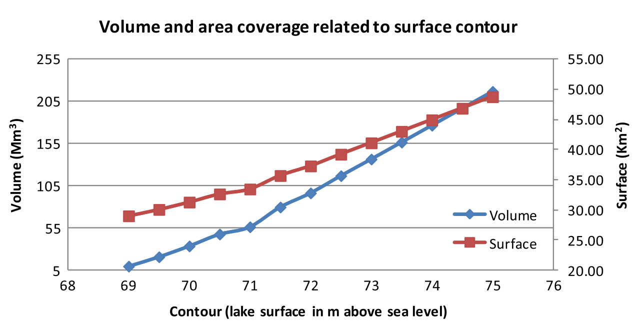

Fig. 3. Volume and coverage related to surface contour.

result in a downgrade of the quality of living standards and in economic downturn.

Knight Piesold Ltd. & Karavokyris and Partners [2] within the development of the MASTER PLAN for the restoration of Lake Koronia study the basin and propose a number of alternative solutions to reverse the trend. They also provide an in-depth analysis of the hydrological conditions that affect the water balance and basin. It is a work of high quality that includes a lot of data to be used as reference. This will be examined in detail within the literature review and throughout the work.

Zalidis et al. [3] re-visited the Master Plan and suggested a number of actions to partially restore Lake Koronia to a state that can support the local communities and wildlife. These actions are a subset of the Master Plan and more focused on point solutions that need to be applied to restore the lake in a sustainable manner.

In their work, Tzimopoulos et al. [4] presented the results of their study to estimate the water balance of Lake Volvi as part of the entire hydrologic Mygdonia basin. Turc's method was employed to calculate the water reserves and suggested measures to restore water resources. In another work, Tzimopoulos and Pliatsika [5] study Lake Koronia and the management of water resources providing an analysis of the water balance and its impact on the area suggesting methods to reverse the situation.

Gantidis et al. [6] present a work where quality parameters were determined in the water of Volvi and Koronia Lake during sampling period of one year. Physicochemical parameters (pH, conductivity and DO) did not show remarkable differences neither between sampling sites nor between sampling periods. Nutrient concentrations (nitrogen and phosphorus compounds) were higher in Koronia Lake than in

Volvi showing relatively small temporal and spatial variations that were attributed to agricultural and municipal activities.

WWF [7] reports that Lake Koronia is considered biologically dead. There are no fish since 2004, while thousands of birds recorded dead in three major incidents (1995, 2004 and 2007). Some minor restoration projects have started but scientists do not expect a complete restoration till 2017 the earliest.

The research and approaches suggested by the community are focusing on point solutions to restore Lake Koronia and the surrounding environment and they fail to include or integrate all decisions under a single model that will allow quantification of the impact and interactions amongst multiple stakeholders. In addition, due to high investment required to develop the solutions and the high uncertainty of the decisions it is imperative to understand the interaction of more than one measure that may be taken in parallel. The mathematical programming model suggested in this work considers:

- time periods,
- hydrological basin and the lake as part of it,
- investment strategies and
- scenario analysis.

The mathematical programming model suggested in this work considers a management model of deterministic nature to restore the water balance as a first step to a sustainable state for the Lake. It is a holistic model in the sense that covers the basin and not only the lake or aquifer. The model parameters are static in nature to allow a mixed integer linear model to be built. In addition, this work does not consider annualised flows, but follows a discrete time modelling approach that captures the weather aspects and their impact on the water balance of the basin. It also integrates the financial and sustainability aspects of the problem. Very quickly, it allows quantification of the impact of various decisions by changing certain parameters of the resulting optimisation problem.

Section 2 reviews the past efforts made in the area of lake restoration and available methods. Section 3 continues to present the problem statement and description, while Section 4 presents a mixed-integer linear programming (MILP) formulation of the problem for the optimal planning of water management and Section 5 examines potential restoration scenarios, while quantifying the impact of decisions. Section 6 concludes by summarising the results and highlights directions for further research.

2. Literature review

The wetland of Lake Koronia embraces a large number and important natural habitat types such as fresh water marsh, lacustrine and riverine forests, scrublands, as well as agricultural landscapes. The area provides an ideal habitat for a variety of flora and fauna species. It is a significant habitat of structural and species diversity (fishes, invertables, reptiles, birds and mammals) and also provides an important roosting and nesting site for many endangered bird species [6,8]. The whole area (Lakes Koronia and Volvi) is protected by the Ramsar Convention on Wetlands as a site of international importance for its value as wetland habitat since 1975, and has been proposed as a site of community interest within the Natura 2000 network. In recognition of its ecological importance, it is protected by a number of national and local legal frameworks.

In the 1970s, the lake was considered to be one of the most important and productive lakes in Greece, presenting an exceptionally ecological, social and economic interest. It occupied an area of approximately $46.8\,km^2$ with a maximum depth of 8.5 m [9]. Since then, it has suffered from a massive decrease in lake volume, with dramatic decrease in surface area and maximum depth. In the 1990s, the lake occupied an area of about $36\,km^2$ and in 2000 about $17\,km^2$ and it almost disappeared in 2002 when the maximum depth dropped to 0.8 m. The phenomenon was proved provisional, as the intense rainfalls during the winter months (beginning of 2003) had as a result the water accumulation again in the lake. Finally, to date, the maximum depth is >1 m. The main sources for these changes are intensification of agricultural and industrial activities. The challenges for survival that Lake Koronia is facing are not unique and many approaches can be adopted from the most reductionistic to the most holistic. The former type is based on analytic procedures, while the latter type is based on synthetic ones. Vollenweider [10] uses a matrix approach which combines in a realistic way reductionism and holism to exemplify the underlying ideas of analysis and synthesis in limnological research. Both types adopt specific steps, measures and planning efforts to overcome the problem of lake's degradation. Individualistic approaches follow the trajectory of a single "problem-solution" dipole, and can be successfully applied in one-issued cases. Such approaches have been applied on point-sources problems for the lakes Baikal—Russia [11], Toba—Indonesia [12] and Ohrid—Albania, FYROM [13]. However, the need for an integrated approach for the sustainable management of the aforementioned lakes was suggested.

Although these lakes have different characteristics from Lake Koronia is the approach followed that is relevant.

Integrated water resources management is considered to be the means by which the general concept of sustainable development becomes operational for the management of water recourses [14]. An integrated lake management approach must be based on the watershed approach as the health of a lake is integrally related to its watershed and to the extensive changes man has made to the lake as well as the surrounding ecosystem [15]. According to the US Environmental Protection Agency [16], the watershed approach is rather a framework for environmental management that activates public and private sector efforts to deal with highest priority problems within hydrologically defined areas, taking into consideration ground as well as surface water flow. Three key elements are suggested according to the watershed approach: (a) stakeholders should be involved throughout the process and shape key decisions, (b) the geographic focus of activities should be directed within the watershed and (c) sound management techniques should be based on science and data. The same approach is applied in EU countries as Water Framework Directive requires [17].

According to Jørgensen [18], the models are distinguished in various pairs of types depending on their characteristics and scope.

Haefner [19] distinguishes models according to their forms into:

- Conceptual or verbal (descriptions in a natural language),
- Diagrammatic (graphical representations of the objects and relations),
- Physical (representation of a real system) and
- Formal (mathematical).

The latter are further distinguished into process-oriented or mechanistic, descriptive or phenomenological, dynamic or static, continuous or discrete, spatially heterogeneous or homogenous and stochastic or deterministic.

In general, during recent decades, many different water models have been developed by researchers. Most of them address specific water quality problems. Such examples are those of Jorgensen 1995 [20] and Krivtsov et al. 2001 [21]. This work focuses on the quantitative problems rather than the qualitative problems of Lake Koronia as the writers believe that the peripheral measures will improve the water quality of the lake.

Changes in water quantity are very common in lakes. Thus, water balance is used for a large number of scientific purposes [22]. The water balance of a lake and its watershed can be determined by the changes in water level, where the link between level and outflow is stable. Therefore, the water balance can be reached by the calculation of each single element separately, or the watershed supply can be calculated through the study of the variations in level [23]. The water balance approach is originally developed to give a basic understanding of the physical water flow system. Thornthwaite was the first to introduce the term of water balance and it referred to the balance between the inputs of the water, expressed by precipitation and the outputs, expressed by evapotranspiration, stream flows and groundwater recharges [24,25]. Water balance is a valuable tool in the analysis of water problems in a regional scale.

The use of hydrological models on water balance is deemed necessary for lake's management purposes. Hydrological models are expressed either by partial differencial equations of mass and energy conservation or by empirical equations. The complicated nature of the hydrological modelling systems and the detailed data they need to run make their application limited in the study of watershed budget model. Instead of detailed hydrological model, the changes of water use are applied within this study on Lake Koronia.

Until today, there have been more than 20 studies concerning the hydrology, water quality and environmental restoration of Lake Koronia. The current review concentrates on the most important studies that are based on water budget models. These researches did not describe in detail the hydrology of the underground water resources.

In 1998, after cooperation between Greek and English private companies, the Master plan of Lake Koronia was created. Master plan is considered to be the most important work concerning the environmental restoration of the lake. It was the first attempt to improve both the quantitative and the qualitative characteristics of the lake and suggested various alternatives for achieving the objectives of the study. The main objectives of the Master Plan were to improve water quality of the lake, strengthen water capacity and propose measures to achieve environmental restoration of the whole area. It is regarded as a high-quality study, which presents an in-depth analysis of hydrological characteristics that affect the water balance of the basin. Concerning the water budget of Lake Koronia, Master Plan estimated a water shortage of 30 mm^3/y. It was believed that a water volume of

Table 1
Measures for the water budget restoration of Lake Koronia suggested by Master Plan [2]

1	Water transfer from Axios river
2	Water transfer from Strimonas river
3	Water transfer from Aliakmon river
4	Water transfer from the wastewater treatment plant of Thessaloniki
5	Water diversion of Scholari and Lagkadikia torrents
6	Transfer of run-off water from storms from Asvestochori area
7	Water pumping from lake Volvi
8	Water pumping from the deep aquifer
9	Interventions on existed irrigation networks

Table 2
Relationship between volume and surface of the lake

Contour	Volume (mm^3)	Surface (km^2)	Type of coverage
69.5	33.8	31.31	
70	47.9	32.65	
70.5	56.5	33.48	
>71	79.9	35.71	Permanent coverage
>71.5	96.6	37.30	Seasonal coverage
>72	117	39.25	Temporary coverage
>72.5	136.7	41.13	Transient coverage
>73	156.7	43.03	Saturation
<73.5	176.7	44.94	

45 mm^3/y can be achieved by the measures presented in Table 1.

Based on the suggested measures of the Master plan several researchers carried out their works. Delimbasis et al. [26] presented a critical assessment or the Master plan of Lake Koronia. Mylopoulos [27] carried out a study for the exploitation of the deep aquifer of Lake Koronia based on measure eight of the Master plan. The study presents the development of a mathematical simulation model of the aquifer systems of the lake and its application for the study or alternative management scenarios of the aquifers. In parallel, the Institute of Geological and Mineral Exploration of Thessaloniki carried out a work to define the hydrogeology of the study area. In addition, Mylopoulos et al. [28] presented their study for the increase of water storage of the lake from additional exploitation of the deeper aquifer. According to the researchers, the measures proposed by the Master plan cannot adequately improve the water system of the lake, unless sustainable practice is used.

In 2004, following up the Master plan, the prefecture of Thessaloniki assigned to Zalidis et al. [3] the creation of a revised restoration plan of Lake Koronia. In this study, a series of actions for the gradual restoration of the functions of the lake and the reversion of the causes of degradation have been proposed. These actions are a subset of the Master Plan and focus more on solutions which will restore the lake in a sustainable way (Table 2).

This work follows up these recommendations to define the optimal mix of decisions to restore the ecosystem (lake and aquifer), while it minimises the social impact of the solution. In the past, certain measures have been disregarded based only on potential social impact without quantification. In this work, a model is created to obtain an integrated view of the basin and to quantify the impact of decisions.

3. Problem description

The literature review combined with the best practice indicates that a holistic integrated model is required to allow for the development of an efficient management model which will help to take the necessary decisions and quantify the impact. The problem is formulated as a deterministic mixed integer linear programming problem. Although deterministic, the model is dynamic or transient as it take into account the time and defines periods.

Certain elements of the model are treated as black boxes using lumped parameters to model their behaviour. These are the storage capacity and underground flow of water, which in detailed studies can only be described using distributed dynamic high order nonlinear equations. This part of work is outside the scope of the present study as it requires investment into exploring the underground watershed and it is a research area on its own merit.

The resulting MILP model is a conceptual approach of physical representation of the Lake Koronia basin and its mathematical (formal) nature introduces the quantitative element to decision-making (Table 3).

The model includes material mass equations for the lake and aquifer as an integrated system which interacts under the changing environment conditions, namely population, irrigation practice and any other decision, which may have an effect on the water resources of the basin. A number or continuous and integer variables are used.

4. Optimal management of water resources

The above problem is formulated mathematically as an MILP optimisation problem. We aim to obtain an optimal design of this system.

Table 3
Rainfall and evaporation reference data

	October	November	December	January	February	March	April	May	June	July	August	September
"Pan" coefficient	0.68	0.69	0.47	0.59	0.79	0.88	0.91	0.95	0.81	0.82	0.81	0.72
"Pan" evaporation (mm/d)												
2011	2.71	1.36	2.11	0.19	1.46	1.72	3.33	3.85	6.7	7.42	6.3	5.25
2012	3.33	2.35	1.07	0.22	1.46	2.11	3.55	4.77	7.65	9.12	6.38	4.99
2013	1.96	1.05	0.82	0.87	1.76	2.22	2.75	4.28	7.48	7.93	6.04	4.87
2014	2.81	1.2	1.04	1.56	1.96	3.25	4.57	6.27	5.68	7.43	7.05	4.61
2015	3.46	1.74	1.25	1.32	0.98	2.07	2.65	5.38	8.04	8.77	6.56	5.09
2016	2.86	1.17	0.94	1.18	1.2	1.68	4.17	5.57	7.69	8.7	7.28	5.2
2017	2.41	1.19	0.87	1.05	0.67	1.41	3.8	4.13	6.63	6.81	6.65	4.7
2018	1.65	0.84	1.03	0.84	1.35	1.6	3.11	4.77	6.84	7.38	6.73	4.86
2019	2.7	1.51	1.3	0.62	1.63	2.24	2.95	4.87	7.5	8.52	7.2	5.4
2020	2.88	1.7	0.86	1.7	2.08	2.25	3.9	4.4	7.14	8	7.8	5.3
Rainfall (mm)												
2011	126	92	66	76	11	68	49	110	38	37	44	0
2012	126	47	81	50	11	17	38	41	11	33	37	0
2013	25	74	78	22	56	68	143	40	28	36	96	30
2014	49	160	36	2	14	34	15	29	180	52	46	14
2015	19	71	106	45	63	54	86	4	22	4	22	2
2016	1	48	52	17	7	78	9	45	17	1	14	13
2017	5	153	7	132	38	42	30	104	110	29	20	11
2018	21	42	6	37	56	71	63	23	37	27	67	0
2019	29	126	61	12	55	126	46	35	19	0	3	3
2020	7	123	62	0	0	98	27	100	83	56	0	30

4.1. Notation

The notation to be used in this section is described below:

Indices/sets		
i	–	product type for agriculture
k	–	irrigation option for agriculture where applicable
t	–	time period
e	–	design option available
Parameters		
A^S	–	area of the aquifer, in m^2
A^L	–	area covered by the lake, in m^2
A_i	–	area allocated for crop i, in m^2
C_p^W	–	capacity of wastewater treatment plant for option p
CWR_i	–	crop water requirements for crop i in mm per month
$DCWR_i$	–	deficit of crop water requirements for crop i in mm per month
D_{it}^A	–	water demand for agricultural use for crop i over period t, in m^3
D_i^A	–	water demand for crop i, in mm per month as calculated
D_t^M	–	water demand for all other human use over period t, in m^3
E_t	–	evaporation mm of water per month
E_e^{AR}	–	maximum amount of water allowed to be pumped from Aliakmon River under option e over period t, in m^3
E_e^{WT}	–	maximum amount of water to be supplied by the wastewater treatment plant under option e over period t, in m^3
E^{VL}	–	maximum amount of water allowed to be pumped from Lake Volvi over period t, in m^3
f^R	–	effective rainfall coefficient
f_i^C	–	crop coefficient for crop i
H^S	–	thickness of the aquifer, in m
H^{RS}	–	thickness of the permanent reserves of the aquifer, in m
n^S	–	porosity of the aquifer that determines the amount of water can be stored
Q_t^{AI}	–	water pumped from the aquifer for industrial purposes during period t, in m^3/month
Q_t^{AM}	–	water pumped from the aquifer for domestic consumption purposes during period t, in m^3/month
Q_t^E	–	evaporation from the lake over period t, in m^3/month

(*Continued*)

Q_t^R	–	direct rainfall in the lake over period t, in m^3/month
Q_t^{RW}	–	reclaimed water arriving from the waste treatment plant during period t, in m^3/month
Q_t^{SL}	–	water from the lake towards the aquifer during period t, in m^3/month
$Q_t^{S,in}$	–	water entering the aquifer due to rainfall or precipitation during period t, in m^3/month
$\overline{Q}^{SW}$	–	maximum amount of water allowed to be pumped from a well in shallow aquifer, in m^3/month
$\overline{Q}^{DW}$	–	maximum amount of water allowed to be pumped from a well in deep aquifer, in m^3/month
P_{it}	–	total crop i during period t, in m^2
RF_t	–	rainfall mm of water per month
W_t^{WA}	–	agricultural waste produced during period t, in m^3/month
W_t^{WI}	–	industrial waste produced during period t, in m^3/month
W_t^{WM}	–	municipal waste produced during period t, in m^3/month
$V_t^{L,\min}$, $V_t^{L,\max}$	–	minimum and maximum volume of water in lake during period t, in m^3
$V_t^{S,\min}$, $V_t^{S,\max}$	–	minimum and maximum volume of water in aquifer during period t, in m^3
Continuous variables		
O_t	–	overflow water leaving Koronia to Lake Volvi during period t, in m^3/month
Q_t^A	–	water pumped from the lake for agricultural purposes during period t, in m^3/month
Q_t^{AA}	–	water pumped from the aquifer for agricultural purposes during period t, in m^3/month
R_t	–	run-off water collected from the plain and upland catchments areas arriving to the lake during period t, in m^3/month
S_t^{IN}	–	water arriving in the lake from other sources during period t, in m^3/month
S_t^{VL}	–	water arriving in the lake from –Lake Volvi during period t, in m^3/month
S_t^{AR}	–	water arriving in the lake from River Aliakmon sources during period t, in m^3/month
S_t^{LR}	–	water arriving in the lake from Scholari and Lagkadikia streams during period t, in m^3/month
S_t^{WT}	–	water arriving in the lake from Thessaloniki wastewater treatment plant during period t, in m^3/month

(*Continued*)

S_t^{AW}	–	water arriving in the lake from wells during period t, in m^3/month
V_t^L	–	volume of water in lake during period t, in m^3
V_t^S	–	volume of water in aquifer during period t, in m^3
Binary variables		
N_{kt}	–	1 if investment option k is operating at period t, 0 otherwise
Y_{ik}^A	–	1 if irrigation option k is selected for crop i, 0 otherwise
Y^{VL}	–	1 if transferring water from Lake Volvi is selected, 0 otherwise
Y_e^{AR}	–	1 if option e of transferring water from River Aliakmon is selected, 0 otherwise
Y_e^{WT}	–	1 if option e of supplying water from Thessaloniki wastewater treatment plant is selected, 0 otherwise
Y^{LR}	–	1 if diverting water from local streams is selected, 0 otherwise
Integer variables		
N^D	–	number of wells in operation from the deep aquifer
N^S	–	number of wells in operation from the shallow aquifer

4.2. Mathematical formulation of the deterministic problem

The mathematical model proposed for this problem is an MILP problem as described below.

4.2.1. Basin water balance

4.2.1.1. Koronia lake material balance. A water balance that includes all inflows and outflows gives the volume of the water stored in the lake during a period t. The water balance does not account for the quality or concentration of materials in the various streams, but assumes that the quality is within limits as per regulations prior to disposal to the lake. This will be ensured by the operation of appropriate treatment plants and other initiatives as described in the introduction and in the following sections. The overall water balance is:

$$V_t^L = V_{t-1}^L + (S_t^{IN} - O_t - Q_t^E + Q_t^R + R_t - Q_t^A - Q_t^{SL} + Q_t^{RW}) \cdot \Delta t, \forall t \tag{1}$$

where $\Delta t = 1$ month.

The supply of water (S_t^{IN}) into the lake from other sources which currently do not contribute towards the lake's material balance is modelled in Section 4.2.4.

During wet periods, the overflow of Lake Koronia towards Lake Volvi is modelled using variable O_t. Its value strongly depends on the requirements by other sources.

The rainfall results to direct contribution to the lake (Q_t^R) and surface flow or run-off water (R_t) from plain and upland catchments area which ends to the lake through various streams in the basin area. The evaporation parameter (Q_t^E) accounts only for direct evaporation from the lake. All other evaporation and perspiration from the ground has been taken into account while calculating the run-off water as part of the rainfall.

We use the model of Thornthwaite and Mather [29] to calculate the soil moisture which determines the amount of water withheld by the soil and allows the calculation of excess and run-off water. According to the model, the amount of water stored in the soil depends on its nature and it cannot exceed a certain limit which is based on the soil moisture capacity S_o. This parameter depends on the soil and has different values for different areas around the Koronia basin. The amount of soil moisture St each month depends on the precipitation P_t if it is higher or lower than the corresponding evapotranspiration PEi.

In the case where $P_t \geq PE_t$, the soil moisture is given by the equation:

$$S_t = \min\{(P_t - PE_t) + S_{t-1}, S_o\}, \quad P_t \geq PE_t \tag{2}$$

While in the case where $P_t < PE_t$, the soil moisture is given by the equation:

$$S_t = S_{t-1} e^{-\frac{PE_t - P_{ti}}{S_o}}, \quad P_t < PE_t \tag{3}$$

The actual evapotranspiration (AE_t) is determined based on the monthly soil moisture in comparison to the previous month's value:

$$\text{if } \Delta S = S_t - S_{t-1} < 0 \text{ then } AE_t = P_t - \Delta S_t; \tag{4}$$

$$\text{if } \Delta S = S_t - S_{t-1} > 0 \text{ then } AE_t = PE_t. \tag{5}$$

In the case where the precipitation is higher than the potential evapotranspiration and the soil moisture S_t is equal to the soil moisture capacity S_o, then the water excess is given by the equation:

$$\Delta Q_t = (P_t - PE_t) + S_{t-1} - S_o, \quad S_t \geq S_o \tag{6}$$

otherwise

$$\Delta Q_t = 0, \quad S_t < S_o \tag{7}$$

The run-off water results from the excess water as a flow on the surface of the catchment area. There is a percentage of the excess water that returns to the ground. This is modelled using a coefficient λ. Therefore, the run-off water each month is determined by the following equation:

$$R_t = (1 - \lambda)(Q_{t-1} + \Delta Q_t) \tag{8}$$

where the excess water each month is given by the equation:

$$Q_t = \lambda(Q_{t-1} + \Delta Q_t) \tag{9}$$

The value of coefficient λ used in our model is 0.65, as reported in the literature.

Although direct pumping of water from the lake for irrigation (Q_t^A) is not encouraged, it may be advisable during extremely wet periods to allow the recovery of the aquifer which is currently the main source for irrigation.

The lake also acts as a source of replenishment to the shallow aquifer (Q_t^{SL}), but the amount of water is restricted by the permeability of the bottom, examined in Section 4.2.2.

The lake is directly supplied by Bogdana River from the north, whose basin covers an area approximately 212 km^2. The streams of Kolhico and Analipsi gorge supply the lake with the run-off water of areas 86 km^2 and 53 km^2, respectively [28]. These are the main sources of water to the Lake, mainly during winter months.

Based on the recovery plan for the lake, we are targeting a maximum volume during the wet periods (winter) and a minimum volume during dry periods (summer) as per Master Plan, in order to support life and allow lake functions restoration.

$$V^{L,\min} \leq V_t^L \leq V^{L,\max} \tag{10}$$

Based on the report by Zalidis et. al. [3], the proposed restoration plan suggests for the lake to cover approximately 35,000,000 m^2 with a total volume of water of 83.8 mm^3. The plan suggests that 90% of the lake surface will be covered permanently, while seasonal coverage will exist depending on weather conditions. More specifically, using analysis of previous data the relation between volume and surface is given below.

Based on given values in the literature, we calculate using linear extrapolation the volume of the lake as shown in Fig. 3.

4.2.1.2. Agricultural use. The water used for irrigation and other agricultural activities for each geographical area may come from the lake (Q_t^A) during extremely wet periods or the aquifer (Q_t^{AA}).

The demand of water strongly depends on the actual crops in terms of surface and their requirements of water per surface unit they occupy, which are season and more specifically monthly dependent:

$$Q_t^A + Q_t^{AA} \leq \sum_i P_{it} D_{it}^A, \ \forall t \tag{11}$$

Each crop has a different profile of water requirements which depend on the type of crop used in the area.

In addition, the irrigation method used for each results in higher or lower demand as given in the equations below:

$$D_{it}^A \leq \sum_k D_{ik}^A Y_{ik}^A, \ \forall i, t \tag{12}$$

$$\sum_k Y_{ik}^A \leq 1, \ \forall i \tag{13}$$

The model will determine the best irrigation option based on water demand and cost. Not all available irrigation options are suitable for all crops, therefore variable Y_{ik}^A will be set to zero for the option that is not suited for that crop. This does not limit the model as any new technological development that might become available for use can be activated.

In order to define the requirements of the crops for watering, the model considers the water deficit resulting from the rainfall on that period and the calculated evaporatranspiration for the same period. The requirements are different for each crop which results in different total requirements based on the crop mix.

In order to quantify the impact of land use changes on the hydrology of Lake Koronia, a simple model is constructed as follows, to account for changes in vegetation (crops), due to the different crop water requirements (CWRs). The demand is:

$$D_{it} = \mathrm{DCWR}_i \cdot A_i, \ \forall i, t \tag{14}$$

where i = crop and A_i = the area allocated for each crop. To accurately calculate the actual requirements, the model needs to incorporate the evaporatranspiration, rainfall and evaporation to determine the deficit that needs to be covered by other resources.

The method to calculate the deficit uses an effective rainfall coefficient which adjusts the rainfall and compares with the actual evaporatranspiration for the month to determine the deficit. There is also a crop coefficient which is used to adjust the water requirements of the crop as part of the CWRs $\mathrm{CWR}_i = f_i^C \cdot E_t$.

This coefficient depends on the crop and the month as well as the stage of the crop's maturity.

$$\text{If } f^R \cdot \mathrm{RF}_t - \mathrm{CWR}_i > 0 \text{ then } \mathrm{DCWR}_i = 0 \text{ otherwise } \mathrm{DCWR}_i = \mathrm{CWR}_i - f^R \cdot \mathrm{RF}_t$$

The wastewater produced is mainly from animal farming activities and is considered similar to municipal waste and needs to be treated or disposed according to the regulations.

4.2.1.3. Industrial use. The water used for industrial purposes (Q_t^{AI}) needs to be of high quality due to specific production requirements of the industry. Water used for the food industry needs to have high quality standards, therefore only potable water can be used. In order to minimise the environmental impact of industrial operations, the wastewater requires extensive treatment. This can potentially be a source of water to the lake once treated and had all toxic or other substances removed.

The demand of water for each industry is given based on their capacity, which effectively determines the amount of wastewater produced. The capacity of the plants is considered to be constant for this study and no variation is expected except seasonal variation due to the nature of some operations.

4.2.1.4. Domestic use. The water used for domestic purposes (Q_t^{AM}) needs to be of high quality due to the health restrictions applying to the use of water by humans. Furthermore, the municipal wastewater produced need to be treated in order to minimise the impact on the environment, due to its contents in organic material. The population variation in the area is very small which means that consumption requirements are constant over time. The only variation expected in consumption is between summer and winter months. Based on studies, there is an increase of water consumption during summer months of approximately 25–40% [30]. This will be reflected in the annual demand profile.

4.2.2. Modelling of aquifer water reserves

The hydrological basin of Lake Koronia as modelled in Fig. 2 needs to account for the water flow from the lake to the aquifer and vice versa. This has been done in detail using simplified Darcy equations taking into account all the parameters affecting the water balance.

It is important to understand the connection that exists between the amount of the water in the aquifer and the amount of water in the lake as the reservoirs are considered as an interconnected system.

The confined aquifer is supplied directly by rainfall and by surface streams. In many cases, the shallow and confined aquifers are united as the clay layers disappear.

In the case of Lake Koronia, hydrogeologically there are two water-bearing systems [2]:

(a) A shallow unconfined aquifer (from the lake's surface until 40–50 m down) consists of thick elastic material, mainly of gravels and sands with intermediate small clay unions. The aquifer is expanded to 269 km^2 into the catchment. Its hydraulic conductivity ranges from 5.1×10^{-2} to 9.2×10^{-2} $\mathrm{m}^2/\mathrm{sec}$ and the storage coefficient ranges from 1.2×10^{-2} to 6.1×10^{-3}. The system is hydrologically connected with the Lake Koronia that provides to the aquifer through its surface exposures a water volume of 30 mm^3/y. The slack underground water table is charged by rainfall percolation and by a number of surface streams that are crossing the catchment area.

(b) A deep confined aquifer is developed 60–500 m down from the lake surface. It consists of sandstone, slack conglomerates, deposits, etc. with intermediate clay–sand layers. These formations are supplied with water from the rocks that are located at the edging of a tectonic crack and they communicate hydrologically through rifts and gaps. It was found from hydrological and isotope tests that the age of the water is not more than 50 years old and it is not significantly affected by the shallow water table.

Based on those, we can calculate the volume of the aquifer using average values as presented in section

4.2.2.1. Aquifer water balance. The amount of water pumped from the aquifer is mainly used for public and industrial use and irrigation. The contributions to the aquifer are directly from the lake and other sources as run-off water.

$$V_t^S = V_{t-1}^S + (Q_t^{S,in} + Q_t^{SL} - Q_t^{AM} - Q_t^{AA} - Q_t^{AI}) \cdot \Delta t, \ \forall t \quad (15)$$

where $\Delta t = 1$ month.

The aquifer has a depth between 40 and 60 m and covers an area of approximately 270 km^2. Again its capacity is limited. Based on the recovery plan for the area, current wells are not allowed to pump any deeper; therefore, a minimum quantity will exist even during draught periods.

$$V^{S,\min} \le V_t^S \le V^{S,\max} \quad (16)$$

4.2.2.2. Calculating the aquifer bounds. Not all the water in the aquifer is available. The water available for use will be characterised as regulating reserves, while the minimum water is characterised as permanent reserves and depends on the depth of the well, which is usually a few metres within the depth of the aquifer:

$$V^{S,\min} = A^S(H^S - H^{RS})n^s \quad (17)$$

The amount of water strongly depends on the permeability of the aquifer. In this work, we are not going to model in detail the physical phenomena taking place and we will use approximate values from the literature.

4.2.2.3. Calculating the aquifer inflow. Both shallow and deep aquifers are being replenished annually at a rate which depends on the hydrological conditions of the year.

The shallow aquifer of the basin is directly replenished by the catchment area around the lake and directly from the lake. In order to calculate the amount of water entering the aquifer, the percolation theory is used, where a different coefficient is applied for each of the distinct catchment areas around the lake.

For the discharge to the shallow aquifer from the lake, we use Darcy's theory and a simple calculation based on hydraulic conductivity K and corresponding area A:

$$Q_t^{SL} = K \cdot A \quad (18)$$

The replenishment of the deep aquifer is more difficult as the water quantities reaching, there are much smaller than those reaching the shallow aquifer. These are calculated using Darcy's theory based on experiments performed in the area.

4.2.3. Management of wells

One of the biggest impacts on the resources is the use of wells which draw water from the aquifer for irrigation purposes, affecting the water balance. This creates a negative water balance as pointed out by many studies.

As pointed out by the Master Plan, a combined use of the deep and shallow aquifer can improve the water balance and help restore the ecosystem to a sustainable state.

The number of wells in the shallow aquifer in operation will be optimised to satisfy the needs for agriculture as part of the overall management of water resources. This might require the upgrade of certain facilities to allow supply of irrigation networks rather than individuals.

$$Q_t^{AA} \le N^S \overline{Q}^{SW}, \ \forall t \quad (19)$$

The number of wells in operation pumping from the deep aquifer should be sufficient to cover the demand to supply the lake if that restoration option is selected and to cover the demand by the population and industry. Again this assumes that necessary measures will be taken to ensure that water use is maximised and sustainable usage is practiced.

$$Q_t^{AM} + Q_t^{AI} + S_t^{AW} \le N^D \ \overline{Q}^{DW}, \ \forall t \quad (20)$$

Based on the Master Plan, the total amount should not exceed an upper limit as defined by the capacity of the aquifer.

$$\sum_t (Q_t^{AM} + Q_t^{AI} + S_t^{AW}) \le \overline{SQ}^{DW} \quad (21)$$

4.2.4. Transferring water from other sources

One of the options suggested by the original plan in order to restore the amount of water in the lake is to transfer water from other nearby sources. They are Lake Volvi, River Aliakmon, local streams Scholari and Lagkadikia and wastewater treatment plants of Thessaloniki.

$$S_t^{IN} = S_t^{VL} + S_t^{AR} + S_t^{LR} + S_t^{WT} + S_t^{AW}, \ \forall t \quad (22)$$

We will examine the options and limitations of each of the suggested solutions next. The best option or combination of options will be decided based on cost and sustainability of the solution and taking into account the constraints imposed.

4.2.4.1. Transferring water from Lake Volvi. Lake Volvi is much larger than Lake Koronia and holds approximately 940 mm^3 compared with Koronia that currently holds 58 mm^3. The amount that will be used will be bounded to 2% of the total volume.

In order to implement this solution, the following should be made available:

- Pumping station;
- Piping network; and
- Discharge facilities.

The amount of the water transferred will be bounded by the capacity of the pumping station and installations as per the constraint given below:

$$S_t^{VL} \leq E^{VL} Y^{VL}, \forall t \quad (23)$$

Also we need to mention that the operation of this solution will be available only during wet seasons when Volvi is saturated.

4.2.4.2. Transferring water from River Aliakmon. The case of transferring water from Aliakmon was suggested, taking into account that the river already supplies with water the city of Thessaloniki. There are two alternative options for this case, use existing infrastructure with the necessary upgrades and modifications to allow higher volume of water through the network or construct a completely new independent network that will accommodate the needs of the plan.

The amount of the water transferred will be bounded by the capacity of the pumping station and installations as per constraint below, depending on the option selected:

$$S_t^{AR} \leq \sum_{e \in R^{AR}} E_e^{AR} Y_e^{AR}, \forall t \quad (24)$$

$$\sum_{e \in R^{AR}} Y_e^{AR} \leq 1 \quad (25)$$

Although both options are of similar nature, the infrastructure and the operational costs are different and this needs to be taken into account in the overall model. We need to highlight that the operation of this scheme is seasonal and strongly depends on the meteorological conditions.

4.2.4.3. Transferring water from Streams Lagkadikia and Scholari. Both streams end up in the area between Lakes Koronia and Volvi and due to the morphology of the area end up in Volvi. They cover an area of 144 and 137 km^2, respectively, and they collect approximately 44.6 mm^3 of water on average. After losses to aquifers and evaporation, 50% ends up as surface water flowing towards Lake Volvi. With necessary modifications of the existing canal between Koronia and Volvi, part of the water can be diverted to Koronia. The amount of the water is limited by the technical characteristics of the canal.

$$S_t^{LR} \leq E^{LR} Y^{LR}, \forall t \quad (26)$$

In our approach, we do not use the annual average amounts, but we use the approach described in Section 4.2.1.1 to calculate the monthly flow.

The environmental impact of such a solution is small and the impact to Lake Volvi by reducing the amount of water flowing is not significant with respect to its hydrology if the scheme is operated for a limited period of time. Its operation strongly depends on each season and the amount of rain, therefore subject to high uncertainty.

4.2.4.4. Transferring water from the wastewater treatment plant of Thessaloniki. One option considered would be to use the effluents from the treatment plants to support the water balance towards the restoration of the ecosystem. Current practice in areas with arid conditions allows the use of treated effluents for irrigation. The wastewater treatment plant in the area should be capable of processing 300,000 m^3/day within strict quality criteria. Due to the configuration of the processing plant and the area of disposal, direct pumping will not meet the restrictions for irrigation and disposal to the lake. Therefore, modifications are required to further treat the effluent to reduce its salinity and bring it within the acceptable limits.

In order to implement this solution the following should be made available:

- Additional treatment using a desalination plant;
- Pumping stations to allow the transfer of water through altitude;
- Pipe network;
- Canal to allow discharge in Kavalari stream with the necessary facilities; and
- Works to avoid flooding due to additional water load.

The amount of the water transferred will be bounded by the capacity of the pumping station and installations as per the constraint below:

$$S_t^{WT} \leq \sum_{e \in R^{WT}} E_e^{WT} Y_e^{WT}, \ \forall t \tag{27}$$

$$\sum_{e \in R^{WT}} Y_e^{WT} \leq 1 \tag{28}$$

As the effluent is currently disposed to the sea by river, the environmental impact of the solution is minimal. This solution will guarantee a constant flow of water to the Lake during all periods.

4.2.5. Objective function

The objective is to restore Lake Koronia to a sustainable situation within 5–10 years from present, while the investment is kept to a minimum with respect to its hydrological balance. Therefore, the optimisation problem is defined as a minimisation cost problem for the investment and operational costs required to restore the lake and achieve a sustainable state while the water usage is rationalised and managed effectively.

4.2.5.1. Agriculture costs. In order to minimise the cost of waste it is suggested to charge for both operating a well and watering the crops. The price charged will be determined by other factors which will be analysed separately.

There should be two basic charges for the water used. One will be a licence to operate a well and will be charged per area and well. This is given by:

$$C^{AW,fixed} N^S$$

The second contributing cost is the charge per unit of water used irrelevant where it comes from. This will be enforced by using metres on every pump in operation (electric or diesel).

$$C^{AW} \sum_t (Q_t^A + Q_t^{AA})$$

4.2.5.3. Transferring water from Volvi. There is the infrastructure cost which has been annualised based on certain investment criteria. Maintenance and other fixed costs are included here, since they will occur, if the idea materialises.

$$C^{VL} Y^{VL}$$

The operational costs are related to the operation of the equipment which is directly related to the actual flow. Therefore, the costs are calculated as euro/m^3 and apply whenever the plant is in operation:

$$\sum_t O^{VL} S_t^{VL}$$

4.2.5.3. Transferring water from Aliakmon River. In a similar fashion, there is the infrastructure cost which has been annualised based on certain investment criteria. Maintenance and other fixed costs are included here since they will occur, if the idea materialises.

$$\sum_{e \in E^A} C_e^{AR} Y_e^{AR}$$

The operational costs are related to the operation of the equipment, which is directly related to the actual flow and the option selected.

$$O^{AR} = \sum_e O_e^{AR} Y_e^{AR}$$

The costs are calculated as euro/m^3 and apply whenever the plant is in operation:

$$\sum_t O^{AR} S_t^{AR}$$

4.2.5.4. Transferring water from Streams Lagkadikia and Scholari. As in the case of transferring water from Volvi, there is an infrastructure cost which has been annualised based on certain investment criteria. Maintenance and other fixed costs are included here since they will occur, if the idea materialises.

$$C^{LR} Y^{LR}$$

The operational costs are related to the operation of the equipment which is directly related to the actual flow. Therefore, the costs are calculated as euro/m^3 and apply whenever the plant is in operation:

$$\sum_t O^{LR} S_t^{LR}$$

4.2.5.5. Transferring water from the wastewater treatment plant of Thessaloniki. As in the case of transferring water from Volvi, there is an infrastructure cost which has been annualised based on certain investment criteria. Maintenance and other fixed costs are included here since they will occur, if the idea materialises.

$$C^{WT} Y^{WT}$$

The operational costs are related to the operation of the equipment which is directly related to the actual flow. Therefore, the costs are calculated as euro/m^3 and apply whenever the plant is in operation:

$$\sum_t O^{WT} S_t^{WT}$$

4.2.5.6. Supplying the Lake from the Aquifer. As an alternative to the method of supplying from rivers or diverting the flow of other sources, the use of wells from the deep aquifer is suggested for a limited period.

There are two basic costs, should this option is used. One will be an investment cost to modernise existing wells or will be to create a new well. This is given by:

$$C^{DW,fixed} N^D$$

The second contributing cost is the annual operation cost per unit of water produced.

$$C^{DW} \sum_t S_t^{AW}$$

4.2.5.7. Overall objective function. The overall objective function is to minimise the investment and operating cost while maximising the amount of water in the lake.

min

$$\begin{aligned} & C^{AW,fixed} N^S + C^{AW} \sum_t (Q_t^A + Q_t^{AA}) + C^{VL} Y^{VL} \\ & + \sum_t O^{VL} S_t^{VL} + \sum_{e \in E^A} C_e^{AR} Y_e^{AR} + \sum_t O^{AR} S_t^{AR} \\ & + C^{LR} Y^{LR} + \sum_t O^{LR} S_t^{LR} + C^{WT} Y^{WT} + \sum_t O^{WT} S_t^{WT} \\ & + C^{DW,fixed} N^D + C^{DW} \sum_t S_t^{AW} \end{aligned} \quad (29)$$

5. Creating a policy to restore Lake Koronia

The proposed model was developed specifically for the case of Lake Koronia and uses some of the proposals of the Master Plan and its later revisions to arrive to a sustainable situation.

The Master Plan completed in 1998 with its major revision completed in 2004 and approved in 2005. The plan was to bring the lake to an acceptable state within 5 years, but both failed to materialise. In our problem definition, we start from 2011 (hypothetical year) and we aim by 2015 to bring the lake into a self-sustainable state with no additional intervention and no additional investment. We are going to look into 10 years in the future aiming to have the basin operating under a sustainable water balance. This approach does not examine the biological aspects, but assumes that any sources of water to the lake are treated and managed accordingly to minimise any biological disturbances.

The model looks into a discrete representation of time at monthly intervals. This results in a MILP with 120 time periods.

In this problem, the options of transferring water from Thessaloniki wastewater treatment plant to Volvi will not be included as the data available is not sufficient and further studies are pending. This will be part of future work.

5.1. Data description

5.1.1. Hydrological data

There have been many studies on the hydrological basin of Lake Koronia which cover many areas, such as geothermal and seismic activity, hydrology and hydrogeology mapping of the area.

The height of rainfall, as it is recorded in the station of Lagkada, is used for the purposes of this study. If the total height of rainfall per year is plotted in a graph (see Fig. 4), we can see that there is a considerable variation and only one extreme dry period over 20 years and two extreme wet periods, while the rest range from 450 to 650 mm per annum.

Based on Fig. 5, the evaporation rate presents a reasonable periodic value that will allow projection of those values in the future without major error. The data are based on the measurements of the average evaporation rate (mm/d) in an area close to the basin.

Table 3 presents the data will be used for our planning model. The height of rainfall is in mm per month, while the evaporation is in mm/day.

Using the above values for evaporation and rainfall, we can calculate the direct evaporation and rainfall to the lake. The planned area to be permanently covered by water as per restoration plan is approximately 35,000,000 m^2. Based on this and the height of rain and pan evaporation per month (30 days), the monthly volume of direct rainfall and evaporation can be calculated. The basic assumption of the model is that the lake will have a permanent coverage that corresponds to 83 mm^3 of water volume and a surface of approximately 35 km^2.

For the evaporation, we use the "pan" coefficient to adjust the observed evaporation rate.

In order to calculate the run-off water (Table 4) from the catchment area (see Table 5) to the lake, the method outlined in Section 4.2.1.1 is used. We distinguish three main catchment areas as per Table 5.

The percolation coefficient for the north upland is 0.04, the south upland is 0.005 and the lowlands is 0.07. Based on those the amount of water entering the aquifer can be calculated.

The effective porosity value for the aquifer is 0.08 [31].

The hydraulic conductivity of the layer between lake and aquifer has been calculated to be $K = 10^{-9}$ m/s [28]. This is in line with observations on clay beds. Based on an average coverage of 35,000,000 m^2, it results to a monthly flow between the Lake and the aquifer of approximately 91,000 m^3 and annually 1,092,000 m^3.

This is in addition to the replenishment happening as part of the percolation which is given in Table 6.

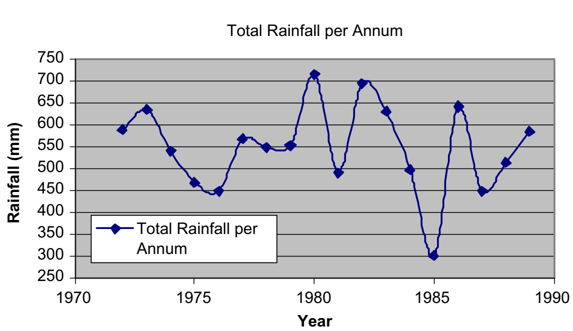

Fig. 4. Graph for the rainfall for the period 1972–1989.

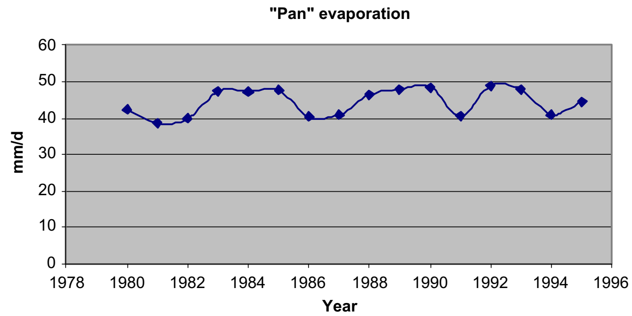

Fig. 5. Graph of average (mm/d) "Pan" evaporation data at Sindo for the period 1980–1995.

5.1.2. Agriculture use

Amount of water used for agriculture is calculated based on the deficit for each of the crops selected for the specific year. The water requirements for irrigation per period are given in Table 7. For reasons of economy of space certain data is not provided here, but is available upon request.

5.1.3. Industrial use

The amount of water used by the industry is relatively constant as a total demand, but the profile of water requirements is different per industry and month. As some of the companies operate seasonally and especially during summer and autumn months an average annual profile will not provide a true reflection on the strain posed to the water resources of ecosystem and the requirements to support these demands. For this case there is no sufficient data to use, therefore it is omitted from the study. In any case the volume is relatively small compared to other uses. The annual consumption by the industry was 1 mm^3. This is now significantly smaller, as many of the production units are now shut-down.

5.1.4. Municipal use

Water usage by general population is estimated to be 250,000 m^3 per month for the period October to April and 325,000 m^3 per month for the rest of the year. The increase during the summer months is based on research performed internationally. The amount of 250,000 m^3 per month is based on an average consumption of 108 m^3/year per person. Total population is assumed to be 27,834. This results to an approximate 3,275,000 mm^3 per year.

Table 4
Run-off water to Lake Koronia from the catchment area (m^3/month)

	October	November	December	January	February	March	April	May	June	July	August	September
2011	0	4,005,265	7,345,265	10,581,807	6,878,174	1,973,997	1,283,098	2,656,112	1,726,473	0	0	0
2012	0	0	6,010,485	7,157,100	4,652,115	0	0	0	0	0	0	0
2013	0	0	0	175,885	3,229,027	5,312,570	11,973,510	7,782,782	0	0	0	0
2014	0	3,639,385	4,156,943	2,702,013	0	0	0	0	0	0	0	0
2015	0	0	3,528,918	5,052,332	7,087,167	6,443,461	7,102,639	4,616,716	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0	0
2017	0	1,404,327	912,812	10,301,216	8,040,192	5,882,727	3,823,773	444,508	288,930	0	0	0
2018	0	0	0	0	0	0	418,281	271,882	0	0	0	0
2019	0	0	3,405,713	2,213,713	2,539,414	10,568,621	6,869,604	0	0	0	0	0
2020	0	0	2,848,285	1,851,385	0	2,738,246	1,779,860	0	0	0	0	0

Table 5
Catchment area analysis

a/a	Catchment area	Area (Km^2)	Mean absolute elevation (m)	Soil moisture capacity S_o (mm)
A	*Lowlands*			
A_1	Plain part	269	117	
A_2	Hilly area of Drymos	13	140	
	Sum (A)	282		210.3
B	*North Upland*			
B_1	Bogdanas river	178	471	
B_2	Kolchiko river	86	484	
B_3	Analipsis river	53	480	
	Sum (B)	317		150.2
C	South Upland	147	300	
	Sum (C)	147		118.0
Total	(A + B + C)	746		

Table 6
Estimated percolation to the aquifer (m^3/month)

	October	November	December	January	February	March	April	May	June	July	August	September
2011	5,011,020	3,658,840	2,624,820	3,022,520	437,470	2,704,360	1,948,730	4,374,700	1,511,260	1,471,490	1,749,880	0
2012	5,011,020	1,869,190	3,221,370	1,988,500	437,470	676,090	1,511,260	1,630,570	437,470	1,312,410	1,471,490	0
2013	994,250	2,942,980	3,102,060	874,940	2,227,120	2,704,360	5,687,110	1,590,800	1,113,560	1,431,720	3,817,920	1,193,100
2014	1,948,730	6,363,200	1,431,720	79,540	556,780	1,352,180	596,550	1,153,330	7,158,600	2,068,040	1,829,420	556,780
2015	755,630	2,823,670	4,215,620	1,789,650	2,505,510	2,147,580	3,420,220	159,080	874,940	159,080	874,940	79,540
2016	39,770	1,908,960	2,068,040	676,090	278,390	3,102,060	357,930	1,789,650	676,090	39,770	556,780	517,010
2017	198,850	6,084,810	278,390	5,249,640	1,511,260	1,670,340	1,193,100	4,136,080	4,374,700	1,153,330	795,400	437,470
2018	835,170	1,670,340	238,620	1,471,490	2,227,120	2,823,670	2,505,510	914,710	1,471,490	1,073,790	2,664,590	0
2019	1,153,330	5,011,020	2,425,970	477,240	2,187,350	5,011,020	1,829,420	1,391,950	755,630	0	119,310	119,310
2020	140,210	2,463,690	1,241,860	0	0	1,962,940	540,810	2,003,000	1,662,490	1,121,680	0	600,900

Table 7
Agriculture demands (m^3/month)

	October	November	December	January	February	March	April	May	June	July	August	September
2011	0	0	0	0	805,532	0	1,647,602	495,488	7,447,092	8,648,924	5,686,927	4,232,698
2012	0	266,601	0	0	805,532	1,321,714	0	0	10,046,959	11,227,361	6,112,875	4,023,079
2013	597,203	0	0	0	0	0	0	4,230,307	9,001,652	9,412,887	2,933,758	2,954,394
2014	485,180	0	0	840,099	1,104,065	1,804,899	4,663,198	7,608,143	0	7,945,396	6,515,478	3,263,141
2015	1,356,648	0	0	0	0	1,243,898	1,607,931	8,799,891	6,800,300	10,241,617	7,638,628	3,651,916
2016	1,618,036	0	0	127,263	311,984	0	4,039,424	3,777,767	8,351,429	9,514,546	7,521,200	3,368,100
2017	1,499,175	0	196,115	0	0	45,735	3,060,196	1,057,595	3,918,127	8,175,084	7,240,412	3,432,895
2018	504,109	0	296,343	0	0	0	974,090	5,743,308	7,688,224	9,071,136	5,139,273	3,918,269
2019	984,287	0	0	23,033	0	0	1,353,855	5,314,660	9,458,319	11,963,511	8,712,218	4,256,439
2020	1,761,090	0	0	979,890	1,610,648	0	3,317,430	1,606,214	5,909,970	8,554,420	9,590,330	3,301,072

5.1.5. Aliakmon River

Water supply from Aliakmon if selected as one of the options can start only after 2 years when the necessary works are completed. This will supply the lake with a maximum of 2,592,000 m^3 per month only during the wet period, when the water levels are high and is not required upstream for irrigation or other uses.

As per Master Plan [2], there are three options for the construction and operation of the necessary infrastructure to provide this water supply. The three options have a fixed cost of investment of €1.37, €1.73 and €1.77 m, while their operational costs are €1.80, €2.45 and €1.80 m, respectively.

These figures are calculated for the maximum available capacity.

5.1.6. Diversion of Scholari and Lagkadikia streams

Another option to support the restoration of Lake Koronia is the partial diversion of streams Scholari and Lagkadikia [2] for a period of time. Currently, the water collected by those two streams runs-off to Lake Volvi. The proposal is for a limited diversion of their water till Lake Koronia reaches a sustainable state. The volume of the water collected is summarised in Table 8. The method to calculate the run-off water is the same as the one used for the streams currently supplying Lake Koronia.

As the infrastructure already exists there are only operational costs estimated to be €24 k. The cost is significantly lower due to lack of pumping stations as the canal connecting Koronia to Volvi and gravity will be used.

5.1.7. Management of wells and irrigation methods

In addition to the diversion of rivers or streams, a measure to support the restoration of Lake Koronia is the use of underground water resources, using either existing wells or by constructing new ones [2] that will pump water from a depth of approximately 150 m depth. During extremely dry periods between May and October, the use of wells to top-up the water balance of the lake is suggested. Currently, there are more than 1,000 wells mainly tapping the shallow aquifer and used for irrigation purposes. The suggestion is to use 110 wells to supply a maximum of 40,000,000 m^3 annually to support the Lake's water balance during the dry season. This is for a maximum period of 4 years to avoid irreplaceable damage to the aquifer and allow its partial replenishment.

Table 8
Water supplied to the basin by rivers Scholari kai Lagkadikia (m^3/month)

	October	November	December	January	February	March	April	May	June	July	August	September
2011	0	4,005,265	7,345,265	10,581,807	6,878,174	1,973,997	1,283,098	2,656,112	1,726,473	0	0	0
2012	0	0	6,010,485	7,157,100	4,652,115	0	0	0	0	0	0	0
2013	0	0	0	175,885	3,229,027	5,312,570	11,973,510	7,782,782	0	0	0	0
2014	0	3,639,385	4,156,943	2,702,013	0	0	0	0	0	0	0	0
2015	0	0	3,528,918	5,052,332	7,087,167	6,443,461	7,102,639	4,616,716	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0	0
2017	0	1,404,327	912,812	10,301,216	8,040,192	5,882,727	3,823,773	444,508	288,930	0	0	0
2018	0	0	0	0	0	0	418,281	271,882	0	0	0	0
2019	0	0	3,405,713	2,213,713	2,539,414	10,568,621	6,869,604	0	0	0	0	0
2020	0	0	2,848,285	1,851,385	0	2,738,246	1,779,860	0	0	0	0	0

This, together with improvement in irrigation methods, can reduce the water consumption.

The cost to deliver is estimated at €3.23 m to repair or construct a total of 110 wells capable of producing 1,000 m^3/day each.

Assuming effective uniform porosity of the aquifer 0.08 and 50% recoverable water assets, the volume is estimated at 1,656 mm^3. Other studies set the porosity higher to 0.09.

5.2. Results

The results suggest that a combination of measures is the preferable way forward with the leading intervention to be the diversion of water from river Aliakmon during extremely dry conditions. This will assist the Lake to maintain its volume and support the local irrigation network. Additional water may be supplied easily by partial diversion of local streams Lagkadikia and Scholari. As the diversion exists the operation of the canal depends strongly on the climate conditions.

Fig. 6 shows the volume profile of the lake over the total horizon. Assuming an initial volume of approximately 56 mm^3 and taking advantage of normal to wet weather conditions, the lake can recover within a few years to a sustainable position assuming that water is not pumped from the lake for irrigation or if it is pumped is strictly monitored. Significantly high amounts of water mean that there is an outflow to Lake Volvi, but this is not maintained as excess water is used for agriculture.

The model also takes into account the water levels of the aquifer and tries to maintain them above a safety level which ensures that the volume can be replenished as shown in Fig. 7. The initial volume of the aquifer is calculated to be 1,661,700,000 m^3.

One of the complimentary measures suggested by the model is the reduction of water usage for irrigation by introducing certain irrigation technologies for the crops that can use them. Table 9 shows the water demand for irrigation if new techniques are adopted and an integrated approach for management of water resources is in place. Irrigation will be supported using networks of canals which translate to a reduction of the wells operated within the basin to a much smaller number of the current 1,000. It is estimated

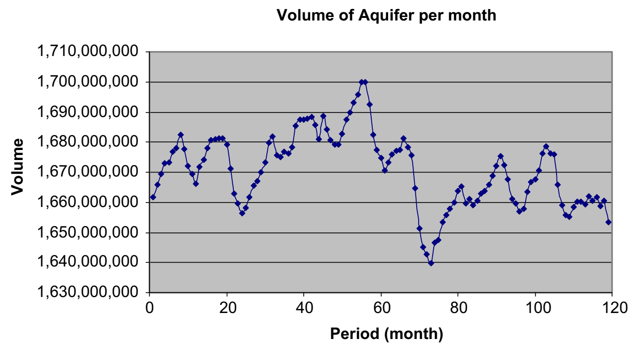

Fig. 7. Volume of aquifer per month in m^3.

Table 9
Agriculture demand (m^3)

	Net Agriculture requirements	Water supplied by aquifer	Water supplied by Lake
2011	25,920,000	25,920,000	
2012	36,641,880	36,641,880	
2013	25,942,120	15,660,000	10,282,120
2014	29,992,960	29,460,000	532,960
2015	38,102,990	31,907,180	6,195,810
2016	41,766,610	41,733,530	33,080
2017	25,254,980	15,910,190	9,344,790
2018	29,550,600	27,540,000	2,010,600
2019	37,323,380	29,024,410	8,298,970
2020	32,253,850	23,460,000	8,793,850

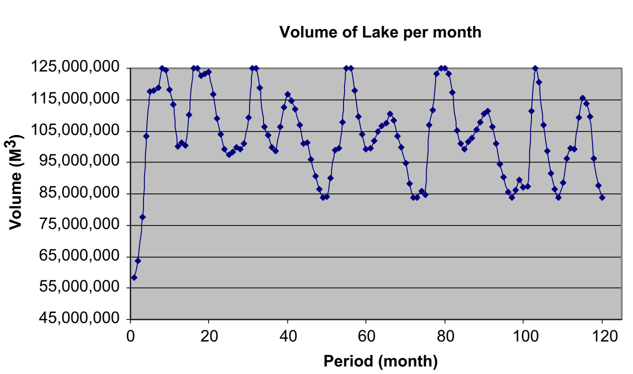

Fig. 6. Volume of Lake Koronia.

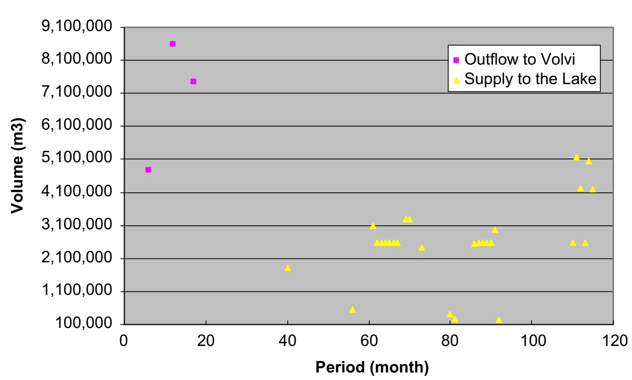

Fig. 8. Ouflow to Lake Volvi and supply to the Lake from other sources.

that the number of active wells may be reduced by half at least, so that the necessary modifications to agriculture practices take place.

From Figure 8, it is clear that the lake will require support to respond to the dry conditions expected as part of the water cycle.

6. Conclusions

The proposed model in general has been adopted specifically for the case of the basin of Lake Koronia and examines the proposals of the Master Plan and its later revisions to arrive to a sustainable state for the Lake. The inputs to the model are various hydrological data such as forecasted rainfall in the area, evaporation, current water balance which is not at steady-state, estimates of water usage, technical innovations regarding irrigation, investment and operational cost associated with the measures and others. These can be modified to capture the initial state without an impact to the model structure. Thus, the results presented here are not marketed as the only solution, but as an indication of the capabilities that this approach offers to the decision and policy-makers.

The initial results suggest that the optimal mix of solutions is diversion of the local rivers Scholari and Lagkadikia for short periods of time to support the volume of the water arriving to the lake and use of deep wells to supply water for extremely dry weather and periodical diversion of Aliakmon River during wet periods. In addition, the investment on better irrigation methods to reduce the water consumption significantly is recommended. The model aims to restore the lake to a sustainable water balance within 5 years as seen on the graph below. The volume of the Lake follows the hydrological pattern of the area. Initially, the Lake will need the support of measures taken to bring it at a steady-state. After the period of 5 years and with the measures enabled the Lake will need support only during extreme dry periods. The restoration of the Lake is beneficial to the area and the basin as excessive water during wet periods can be used to support the local economy (irrigation). Critical to say that such a model may be used on monthly basis to derive a short-term policy of water usage combined with a strategic sustainable view.

As per the volume of the lake reaches the desired level of 83.8 mm^3 within the first year, but due to weather conditions and lack of support, as most of the measures require at least 1–2 years before they are complete, the permanent coverage required is only sustained after 5 years.

The model proposed is deterministic but can be easily turned into a stochastic scenario-based model to allow simultaneous study of multiple options under a weighted average model. Climate conditions in terms of rainfall and evaporation directly connected to temperature have been statistically analysed to improve on missing or distorted data.

The results presented here are not conclusive and further analysis and fine tuning is required to extract valuable information from the model. The next steps are to validate all data used for input and statistically verify any disturbances, review and refine cost parameters and add more social factors to the model to drive the decision-making.

The most important reason for the low-quality data available in hydrological and limnological studies in Greece is unambiguously the non-existence of central planning and administration at the watershed level. Recently, the Greek Government adopted this kind of management scheme and there is a huge effort at the central and local scale to establish such initiatives. In addition, it is now widely admitted that water management is better achieved by the combination of skills from many disciplines with similar interest [32,33].

References

[1] C. Mitraki, T.L. Crisman, G. Zalidis, Lake Koronia: Shift from autotrophy to heterotrophy with cultural eutrophication and progressive water-level reduction, Limnologica. 34 (2004) 110–116.

[2] Karavokyris and Partners, Knight Piesold, Anelixi, Agrisystems, Environmental restoration of Lake Koronia. Final report submitted to European Commission, DG XVII, 1998.

[3] G.C. Zalidis, V. Takabakoglou, T. Alexandridis, Revised Restoration Plan of Lake Koronia, Aristotle University of Thessaloniki, Department of Agronomy, Laboratory of Applied Soil Science, Thessaloniki, 2004, Pages 236+Annexes (In Greek, English summary).

[4] C. Tzimopoulos, A. Zeibeki, P. Ginidi, E. Evangelides, Water resources management in the watershed of Volvi lake, Global NEST J. 7 (2005) 379–385.

[5] C. Tzimopoulos, D. Pliatsika, Water management of Koronia lake watershed, in: Proceedings of Heleco 05, Athens, TEE, 2005.

[6] N. Gantidis, M. Pervolarakis, K. Fytianos, Assessment of the quality characteristics of two lakes (Koronia and Volvi) of N. Greece, Environ. Monit. Assess. 125 (2007) 175–181.

[7] WWF Ελλάς, Ελληνική Ορνιθολογική Εταιρία & ΕΛΛΗΝΙΚΗ ΕΤΑΙΡΕΙΑ Περιβάλλοντος και Πολιτισμού. Ελληνικοί Υγρότοποι Ραμσάρ: Αξιολόγηση Προστασίας και Διαχείρισης. Αθήνα. Φεβρουάριος 2009 [Greece, Greek ornithological society and Greek society of environment and culture. Greek ramsar wetlands: Protection and management assessment. Athens, February 2009].

[8] A. Kaiserli, D. Voutsa, C. Samara, Phosporous fractionation in lake sediments- Lakes Volvi and Koronia, N. Greece, Chemosphere 46 (2002) 1147–1155.

[9] A.A. Psilovikos, Paleogeographic development of lake Mygdonia (Lagada-Volvi) and the catchment [Doctorate Thesis]. Aristotle University; 1977.

[10] R.A. Vollenweider, Eutrophication: Conventional and non-conventional considerations and comments on selected topics, in: R. de Bernardi, G. Giussani, and L. Barbanti (Eds.), Scientific Perspectives in Theoretical and Applied Limnology. Mem. Ist. Ital. Idrobiol. 47 (1990) 77-134.
[11] T. Garmaeva, Lake Baikal: Model for sustainable development of the territory, Lakes Reserv. Res. Manage. 6 (2001) 253–257.
[12] B. Saragih, S. Sunito, Lake Toba: Need for an integrated management system, Lakes Reserv. Res. Manage. 6 (2001) 247–251.
[13] Z. Spirkovski, O. Avramovski, A. Kodzoman, Watershed management in the lake Ohrid region of Albania and Macedonia, Lakes Reserv. Res. Manage. 6 (2001) 237–242.
[14] UN-WWAP (United Nations-World Water Assessment Programme), Water for People, Water for Life: The United Nations World Water Development Report, UNESCO and Berghahn Books, Paris, 2003.
[15] L. Borre, D.R. Barker, L.E. Duker, Institutional arrangements for managing the great lakes of the world: Results of a workshop on implementing the watershed approach, Lakes Reserv. Res. Manage. 6 (2001) 199–209.
[16] US Environmental Protection Agency, Watershed Approach Framework, Office of Water, Washington, DC,. EPA-840-S-96-001 1996.
[17] G. Premazzi, A. Dalmiglio, A.C. Cardoso, G. Chiaudani, Lake management in Italy: The implications of the water framework directive, Lakes Reserv. Res. Manage. 8 (2003) 41–59.
[18] S.E. Jørgensen, (Ed.), Fundamentals of Ecological Modelling, second ed., Elsevier, Amsterdam,. p. 628 1994.
[19] J.W. Haefner, (Ed.), Modeling Biological Systems. Principles and Applications, Chapman & Hall, New York, NY, 1996, p. 437.
[20] S.E. Jørgensen, Handbook of Environmental and Ecological Modelling, CRC, Florida, FL, 1995, p. 688.
[21] V. Krivtsov, C. Goldspink, D.C. Sigee, E.G. Bellinger, Expansion of the model "Rostherne" for fish and zooplankton: Role of top-down effects in modifying the prevailing pattern of ecosystem functioning, Ecol. Model. 138 (2001) 153–171.
[22] T.C. Winter, Hydrological processes and the water budget of lakes, In: A. Lerman, D.M. Imboden, J.R. Gat (Eds.), Physics and Chemistry of Lakes, Springer-Verlag, Berlin, pp. 37–62, 1995.
[23] B.S. Piper, T. Plinston, J.V. Sutcliffe, The water balance of lake Victoria, Hydrol. Sci. J. 31 (1986) 25–37.
[24] C.W. Thornthwaite, An approach toward a rational classification of climate, Geogr. Rev. 38 (1948) 55–94.
[25] C.W. Thornthwaite, F.K. Hare, The loss of water to the air, American Meteorological Society, Boston, MA, 1965.
[26] K. Delimbasis, K. Katsifarakis, I. Mylopoulos, G. Oikonomidis, Assessment of the Measures Proposed by the Master Plan for Environmental Rehabilitation of Lake Koronia, Technical Chamber of Greece, Branch of central Greece, Thessaloniki,1998, p. 9 (in Greek).
[27] I. Mylopoulos, Enrichment of Lake Koronia from the Deeper Aquifer—A Simulation Model, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece,. p. 145 (in Greek) 2001.
[28] N. Mylopoulos, Y. Mylopoulos, E. Kolokytha, D. Tolikas, Integrated water management plans for the restoration of lake Koronia, Greece, Water Int. 32 (S1) (2007) 720–738.
[29] C.W. Thornthwaite, J.R. Mather, "The water balance", publications, Climatology. VIII(1) (1955) 1–104, Drexel Institute of Climatology, Centerton, NJ.
[30] A.F. Garcia, A.M. Valinas Garcia, R. Espineria-Martinez, The Literature on the Estimation of Residential Water Demand, Elsevier Science, Amsterdam, 2001.
[31] N. Veranis, K. Katirtzoglou, Drill Inventory in Koronia Catchment—Prefecture of Thessaloniki, Institute of Geological and Mineral Research of Thessaloniki, Greece,. p. 137 (in Greek) 2001.
[32] The Chemical Engineer, IChemE "Water a Liquid Asset", 2005.
[33] The Chemical Engineer, IChemE "Desalination, Wastewater, Modelling", 2008.