

Conceptual modelling of Lake Manyas, Turkey

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Abstract: Previously determined biological and physico-chemical properties of Lake Manyas are employed in modelling the sensitivity of water quality and ecosystem integrity to the (a) water residence time and (b) nutrient inputs from anthropogenic sources. In that context, simple ecological conceptual models are simulated for predicting changes in the aquatic ecosystem with respect to these driving variables. Results yield thresholds where major changes in system behaviour are expected. Based on model predictions, recommendations for the restoration of water quality and ecosystem integrity are made.

Key words: Model, lake, nutrient, monitoring, restoration

1. Introduction

Manyas is a eutrophic shallow lake first recognised by Kosswig (1938) as an important natural reserve for hundreds of migratory bird species (Karafistan and Arik-Colakoglu, 2005). Until recently, it was known to support considerable commercial fishery, especially of *Cyprinus carpio*, a common freshwater fish. The wetland is also under the protection of the European Community (EC) with an A type Diploma (1976). This represents first-class water quality applicable to bathing conditions and is renewed periodically with respect to well-established criteria. Since 1998 the whole lake has been considered under the Ramsar Convention of unique wetlands in the world. Other case studies for Lake Manyas exist (e.g., Albay and Akcaalan, 2003; Celik and Ongun, 2008).

In a previous work (Karafistan and Arik-Colakoglu, 2005) it was shown that at certain times the quality of the lake water deteriorated from the awarded Class A type to lesser degrees, due to runoff from the surrounding chemical industry, farming, and poultry wastes. Accumulation of such a nutrient load in the form of dissolved nitrate and phosphate from insufficiently treated polluting sources gives rise to the phenomenon known as eutrophication (Vollenweider, 1968; Jørgensen, 1976). When migratory bird-borne nutrients are added to the anthropogenic pressure, further degradation of the water quality can be expected in the food web. For example, the phytoplankton communities, the growth of which is limited by nitrate and phosphate availability, occupy the lowest trophic level of the food web. This was first formulated by Redfield (1958) as an N/P ratio for unicellular organisms; it remains constant in the open sea, but usually varies with respect to the productivity of each area. As a consequence, the specific plankton growth rate is limited by the local distribution of the least abundant nutrient. According to Schindler (1974), in the cases of nutrient limitation of primary productivity, phosphorus

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supply is the most regulating stressor in contrast to generally nitrogen limitation in saline water (Oviatt et al., 1995; Karafistan et al., 1998), with some exceptional cases (Krom et al., 1991; Karafistan et al., 2002). On the other hand, according to Schindler (1977), phosphorus limits primary productivity in most of the Nordic lakes in contrast to nitrogen in tropical lakes and most of the world's oceans. In estuaries, transitions from phosphorus limitation in fresh water to nitrogen limitation in saline water may occur (Doering et al., 1995). Diversity and changes in the plankton species depend, indeed, on many different biotic and abiotic aquatic factors. The most important, such as intensity and frequency of nutrient loading, and selective grazing of zooplankton and fish, have to be defined appropriately in a predictive model (Jørgensen, 1992). In restoration plans, generally auxiliary assumptions are employed and tested by means of conceptual modelling approaches (Chow-Fraser, 1998). In this respect, the regional environmental stressors with regard to monitoring and restoration purposes usually characterise conceptual ecological models. Some examples are the Sierra Nevada (Manley et al., 2000), South Florida (Ogden et al., 2005), and Lake Okeechobee (Havens and Gawlik, 2005) case studies. In a lake environment, one of the most important stressor of anthropogenic origin is nutrient enrichment, which may produce a direct impact on the phytoplankton biodiversity (Redfield et al., 1963). Nutrient enrichment, thus stimulating excessive plankton growth, was first modelled by eutrophication mechanisms where harmful algal blooms could occur as an end product (Dale et al., 1999). Conceptual models for coastal eutrophication formulated by Cloern (2001) and long-term monitoring of the Great Lakes by Gucciardo et al. (2004) followed. Such models relating to climate effects on ecosystem dynamics also exist (Blenckner, 2005).

The main purpose of this work was to assess the direct impacts of water retention on the Manyas ecosystem by conceptual modelling. First, parallel to the nature of the variable water level, the external effects of a riverine phosphate upload on the plankton dynamics are investigated by a simple eutrophication model. Further, the long-term consequences of nutrient load on plankton biodiversity are evaluated by a multi-parameter conceptual modelling approach.

The results are discussed with mention of sustainable monitoring and restoration plans for Lake Manyas.

2. Study area and data

The sampling area, presented in Figure 1, covered about 16.8 ha, with a variable outflow controlled since 1992 by 2 regulators. Before water retention, water depth was known to fluctuate naturally between 14.5 and 17.5 m, reaching its highest level in spring. The most important water supply to the lake is via the Manyas Creek, with an average inflow rate $19.5 \text{ m}^3/\text{s}$. The monthly water budget regulated by the Water Works Department (Turkish abbreviation DSI) for the period 2002–2003 is reproduced from the relevant TÜBİTAK reports in the Table.

Table. Monthly water budget (m^3/s) of Lake Manyas (2002–2003) from DSI.

		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Aug	Jul
2002	Kocaçay Input	0.34	1.27	130.0	57.4	17.8	26.9	42.8	7.00	3.20	1.20	1.00
	Ergili Output	0.00	0.00	7.24	49.00	47.00	24.50	40.60	34.30	35.00	9.48	16.60
2003	Kocaçay Input	2.07	7.07	11.40	25.10	119.0	64.80	46.90	12.80	3.20	0.46	1.35
	Ergili Output	6.6	8.20	7.70	3.88	24.10	38.30	41.00	39.40	35.00	11.00	17.00

Field data relevant to the physico-chemical and biological aspects of water quality contained 36 bi-monthly successive measurements recorded in 2002–2003 as explained in Karafistan and Arik-Colakoglu (2005).

For clarity in the present work seasonal variations in temperature, Secchi transparency, and lake depth are reproduced in Figure 2. It is observed that an extreme temperature of 30 °C is reached in July–August, whereas sometimes 2 °C can be recorded in December. The deepest water level measured was variable and found to be around 4 m, falling to below 1 m at the coastal stations 1 and 2, situated in the northern part. As expected for a turbid lake like Manyas, the highest Secchi transparency reached about 1 m at Station 4, which is located in the southern part.

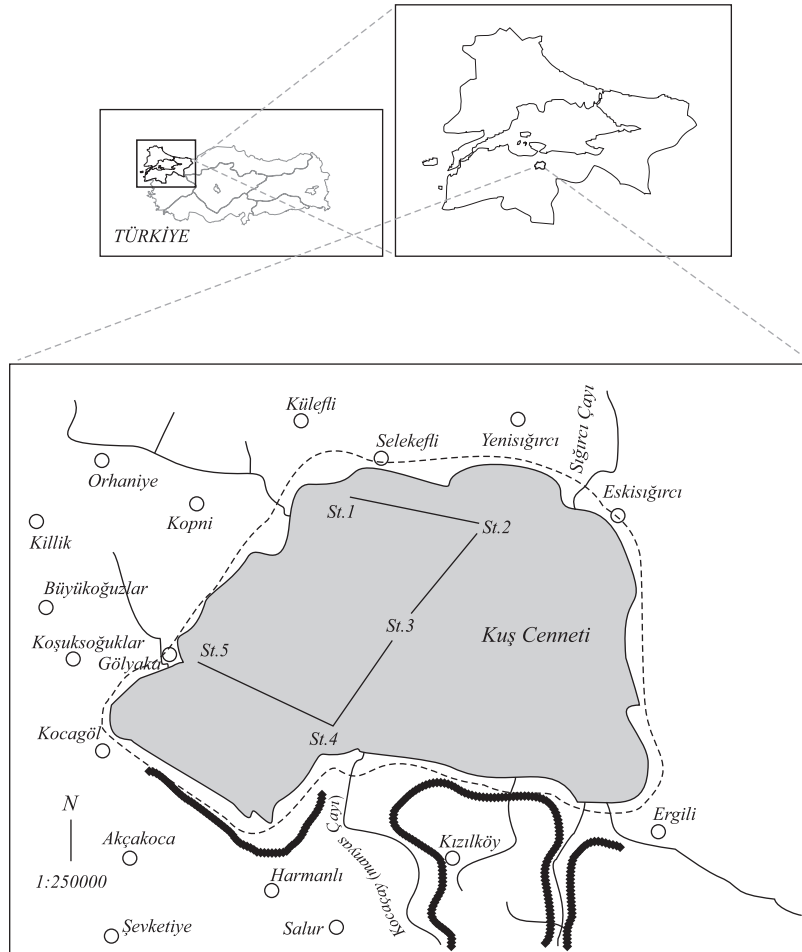


Figure 1. Map of Lake Manyas, with hatched lines indicating the water regulation area.

In Figure 3a the seasonal distributions of surface phytoplankton populations, *Chlorophyceae* and *Cyanophyceae*, are given. They are most abundant in summer and decline in number when all the nutrients are depleted (Figure 3b). Their predators, which are the herbivorous and omnivorous zooplankton, are represented in Figure 3c only for Station 2, which is situated next to the National Park. First, an increase in the number of the herbivorous zooplankton (e.g., amoeba) feeding on these populations follows from June to November at Station 2. The omnivorous zooplankton peak occurs with a phase lag next spring, starting in April 2003.

In the present work, the data presented in the Table and Figures 2 and 3 were introduced as stressors to different conceptual models. The results served as predictive tools for the management and restoration of the lake ecosystem.

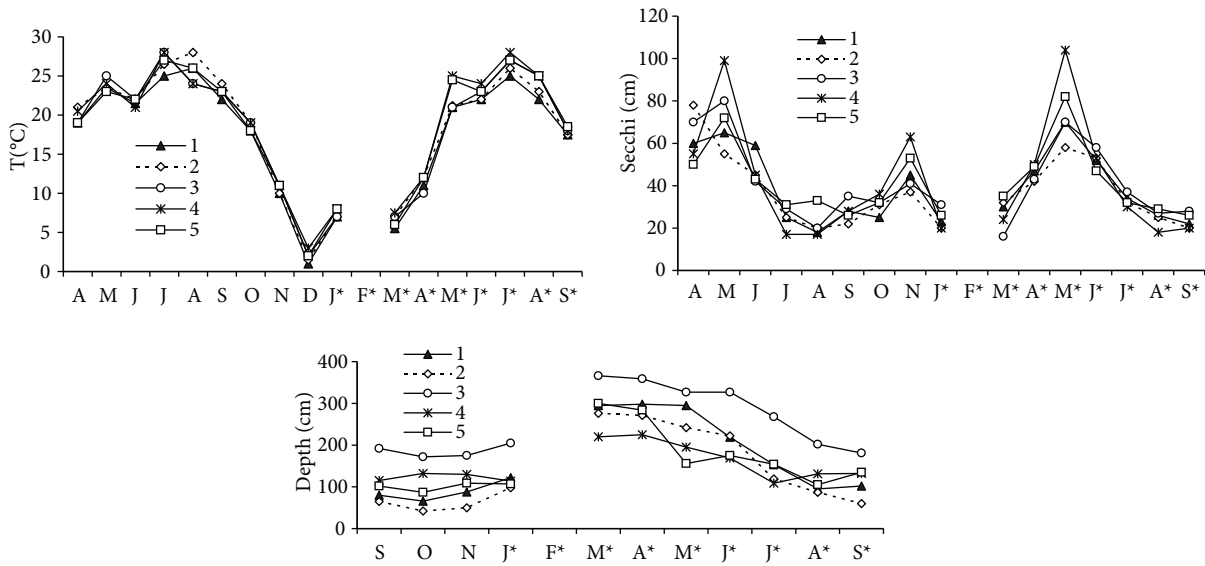


Figure 2. Distributions of temperature, Secchi transparency, and depth from April 2002 to September 2003 (*). Measurements in February 2002 are missing due to weather conditions.

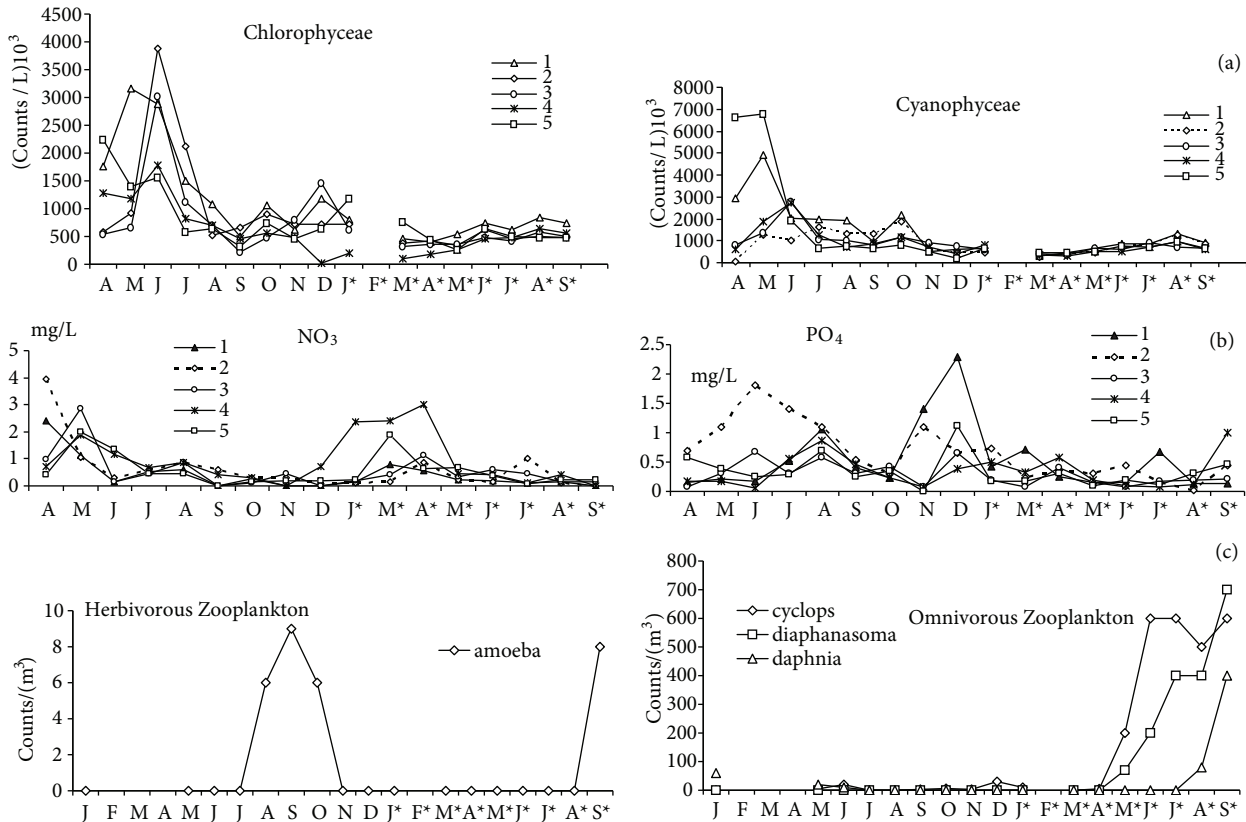


Figure 3. (a) Seasonal distribution of *Chlorophyceae* and *Cyanophyceae* representing dominant small phytoplankton populations measured in 2002–2003 at 5 different stations. (b) Seasonal distribution of nitrates and phosphates for different stations (2002–2003). (c) Seasonal counts (in ppm) of herbivorous and omnivorous zooplankton observed at Station 2 in 2002–2003.

3. Conceptual modelling

From the field measurements of 2002–2003 it was observed that, water quality of Lake Manyas varied in space and time, due to many stressors. For modelling purposes, water level variations could be considered as one parameter and the nutrient load as another. For short-term and urgent restoration of water quality, the conceptual ecological modelling approach was found to be useful.

3.1. Case I: 3-parameter variable flow model

Starting from the assumption of an artificially variable water flow rate, a 3-parameter eutrophication model (Model I) was constructed. Effects of water level fluctuations on the continuity of the population dynamics were modelled as schematised in Figure 4.

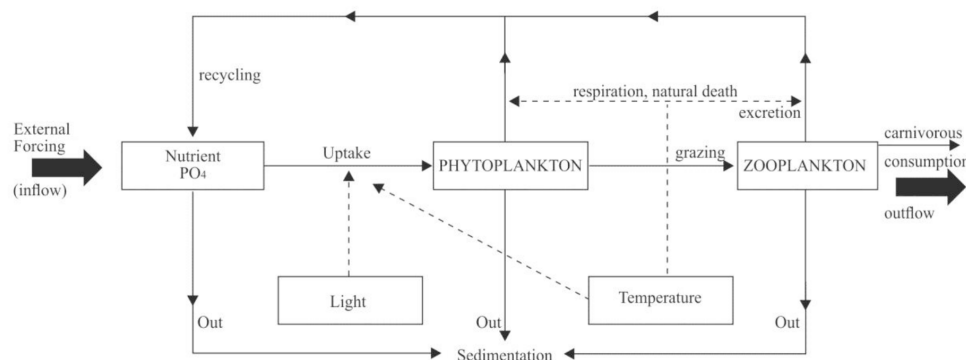


Figure 4. Simple phosphorus limited conceptual model adapted from Chahuneau (1979).

A complete description of differential equations of the 3-parameter eutrophication model of Chahuneau (1979) is given in the Appendix. External and internal forcing on the variables (Figure 4) was adapted to the specific phytoplankton and zooplankton dynamics of Lake Manyas summarised in Figures 2 and 3. Model I represents a simple food-chain model consisting of phosphate (PO_4) as a nutrient, with phytoplankton and zooplankton populations. For a shallow lake like Manyas, the dissolved phosphate PO_4 and phyto- and zooplankton abundances were modelled for the completely mixed water column, by means of a Lotka–Volterra (Lotka, 1925) type predator–prey model.

In the model equations given in the Appendix, transfer of flux between 3 compartments was evaluated for the case of a variable PO_4 load. The biological flux for the phytoplankton was calculated from the primary productivity, with the growth rate being controlled by external forcing functions such as temperature and nutrients. As a nutrient, uptake of orthophosphate by the phytoplankton in the form of P-PO_4 , was formulated by a typical Michaelis–Menten or a Monod type expression first introduced by Dugdale (1967) and later used by Steele (1972). For comparison purposes, different residence times of water (inversely proportional to the difference of the in–out flow rates) were used in the numerical simulations, starting from a few months up to several years. In the numerical simulations, the necessary initial conditions were selected as $10 \mu\text{mol L}^{-1}$ for phosphate, and 1 and 0.01 individuals per litre for the phyto- and zooplankton, respectively. A fourth Runge–Kutta method was used for the modelling of the plankton population dynamics. It was found that a residence time of about 4 years could maintain the seasonal population dynamics in a stable situation. Employing this flow rate as external forcing in Model I, seasonal population dynamics were predicted numerically from FORTRAN simulations.

3.2. Model I results

In the 3-parameter model simulations with a suitable water residence (minimum 4 years), favourable conditions occurred around 10 April, where abrupt phosphate depletion was followed successively by the phytoplankton and zooplankton peaks. The 2-year population dynamics cycle thus obtained is given in Figure 5. The maximal values reached were $27.7 \mu\text{mol}$ of phosphate, and 18 for phytoplankton and 0.04 zooplankton counts per litre, which seemed realistic for this lake. These cycles repeated at the same amplitudes for 2 years. If the retention time of water was shortened, the population dynamics did not reveal the expected seasonal peaks; neither reproduced a periodicity. Simple conceptual model simulations based on 3 parameters and a variable water flow indicated that intervention in the water level might affect the overall ecosystem dynamics and the seasonal population dynamics.

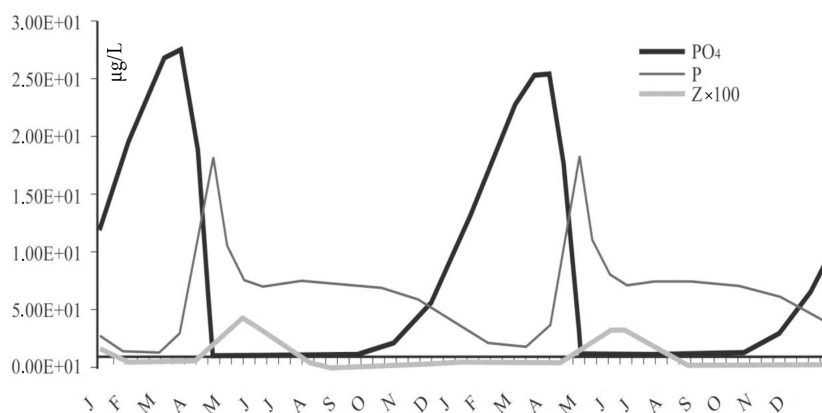


Figure 5. The 3-parameter model simulation results for phosphate, phytoplankton, and zooplankton (in $\mu\text{g L}^{-1}$) for 2 consecutive years with a water residence time of 4 years.

3.3. Case II: multi-parameter ecological model

The 3-parameter plankton succession model was extended to 8 parameters (hereafter Model II), by distinguishing plankton diversity with respect to their nutritional needs, as well as the predator–prey relations. Thus, Model II was based on the diversity of the phyto- and zooplankton populations, with respect to their growth-limiting nutrient. The assimilation rates were taken as Michaelis–Menten type (Droop, 1975), and the plankton mortality was assumed to depend directly on the availability of the most limiting nutrient. Zooplankton was divided into 3 groups (herbivorous, omnivorous, and carnivorous) as schematised in Figure 6, by conceptual diagrams connecting these 8 variables. Interactions between different groups were expressed as a function of the limiting nutrients. Taking into account competition between species as well, evolution of population dynamics was expressed by 8 equations for the 8 unknown state variables. They were solved numerically in the same way as for case I.

3.4. Model II results

From the simulation results given in Figure 7, it is seen that the population dynamics of the smaller phytoplankton followed that of diatoms. If the initial simulation time was started again on 10 April, a conceptual similarity between measurements and model results was established on a short seasonal scale and between species, but this did not continue for a longer timescale.

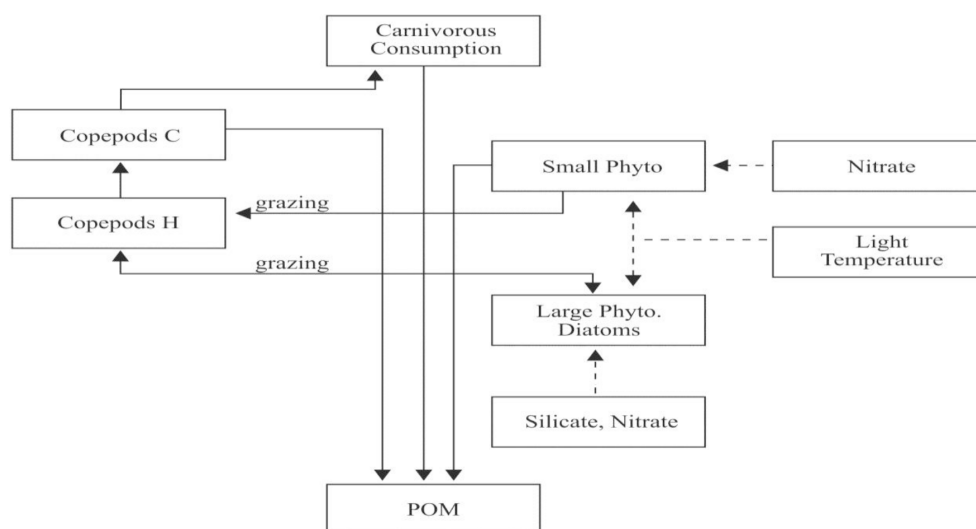


Figure 6. Multi-parameter nitrogen limited conceptual model with 8 components. Arrows indicate flow and interaction directions between compartments, where POM is the particulate organic matter.

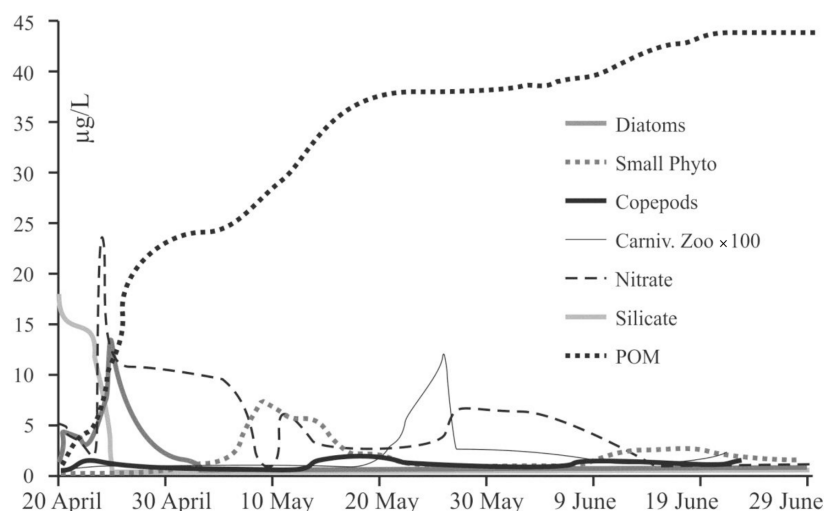


Figure 7. Eighty-day simulation results of the population dynamics obtained from Model II, where abundances are expressed as $\mu\text{g L}^{-1}$. Days are counted from the beginning of the year where day 100 corresponds to 10 April.

Considering the high variability of the N/P ratios in both space and time, in Model II we have investigated the role of nutrient availability in the distribution of diverse plankton populations close to the Natural Park (Station 2). In this selection not only the external P-loading but also the internal nitrogen cycling was considered in a conceptual modelling framework. Here, the phytoplankton growth was limited by the least abundant nutrient, the uptake of which was formulated in the form of a ratio depending on species composition (Andersen and Nival, 1989). Results thus obtained can be compared with the measurements presented in Figure 3c for Station 2. Since the units are not the same they cannot be compared directly but on a short seasonal scale the trends in the population dynamics are parallel. Model II results obtained for organic matter can be compared with the high sedimentation rates measured by Leroy et al. (2002). This implies that the external pressure of nutrient input and water level variations should be completely minimised as a restoration plan.

4. Discussion

For the shallow and eutrophic Lake Manyas, succession of the plankton dynamics in a variable water column was represented by means of conceptual modelling. Consequences of an increasing nutrient load, and water retention for land use, were investigated. In the first case, by means of a 3-parameter eutrophication model the seasonal overall plankton dynamics was adequately represented as a function of the phosphate availability (starting from $10 \mu\text{mol L}^{-1}$). It is demonstrated that, for a water residence of about 4 years, corresponding to a minimum water level of 4 m, the growth cycle of the total phyto- and zooplankton populations could be maintained and reproduced seasonally. For the extreme case of water levels lower than 1 m (which we have encountered in certain coastal areas), seasonality of the population dynamics could not be reproduced anymore. This simple model clearly indicated that the plankton dynamics, as a whole, is more sensitive to the hydrological water management than the availability of the specific nutrient in water. Our results also implied conceptually that nutrient availability might affect plankton diversity with respect to the individual needs of each species at certain periods, especially in spring. Further, if the outflow rate is controlled for water use, all the plankton population dynamics cannot be stabilised as a short-term response in the seasonal succession. Conceptual modelling results, based on the measurements covering several seasonal cycles, revealed that Lake Manyas is facing potential external threats for the whole ecosystem. Similar to other degraded wetlands, with the same marsh and turbid features such as the Cootes Paradise (Havens and Gawlik, 2005), long-term changes in habitats can be expected to occur (Chow-Fraser, 1998), affecting the upper level of the food web, including birds and fishing on a longer time scale. For example, from the study of long-term dynamics of phytoplankton in a shallow lake in China, Chen et al. (2003) also conclude that biomass dynamics are affected considerably by the variability in nutrient levels. In our case, by-products of nitrogen, modelled as POM, are expected to accumulate more with respect to decreasing water level. However, unlike some degraded shallow lakes, removal of mud is not a practical restoration process for Manyas, which is mostly occupied by macrophytes (Brouwer and Roelofs, 2001).

5. Conclusions

The initial aim of this research work was to provide the in situ physico-chemical water quality level by means of regular measurements. The second aim was the prediction of the aquatic ecosystem dynamics by means of ecological modelling of field measurements. The last and ultimate goal was the monitoring and restoration of the EC protected area. With these aims in mind, the most important water quality indicators relevant to the aquatic ecosystem were chosen with respect to the dynamics of the physico-chemical and biological (such as the plankton biomass) aspects of the data. Composed of 36 bi-monthly measurements at 5 pre-selected stations, these data served as initial values for the conceptual modelling of the lake ecosystem presented in this work. Based on model predictions a 2-fold restoration plan was suggested to the local authorities; maintenance of the water fluctuations should be brought to the natural level with no external input of organic load or nutrients. Such a control and purification scheme can be applied over a longer time scale, where the input of organic load from bird-borne sources (Kitchell et al., 1999) and the inner nitrogen cycle are important. Similar to the work by Gaines et al. (2007), response of birds to changes in water quality on longer time scales can be investigated by bird counting. Further, the effects of low N/P ratios on the phytoplankton communities of such shallow eutrophic lakes or lagoons (e.g., Aralar et al., 2004) can be studied conceptually by modelling nutrient availability at different trophic levels, including birds and fish.

Inclusion of climatic influences (e.g., Kosten et al., 2009) on the ecosystem dynamics can also be proposed

as a modelling parameter. However, this would require rather long time series measurements, which is not applicable here.

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Appendix

Description of Model I equations

Model I is described by means of the differential equations given below:

$$\frac{dP}{dt} = G(X, Y, Z, W) = Z \times \mu \times \theta^{T-20} \times \frac{I}{KI+I} \times \frac{Y}{KPO+Y} - Z \times \text{RESP} \times \theta^{T-20} - Z \times \text{SED} - W \times \text{GRAZ} \times \frac{Z}{KP+Z} - \text{FOUTP}$$

$$\frac{dZ}{dt} = Q(X, Y, Z, W) = W \times \text{GRAZ} \times \frac{Z}{KP+Z} \times \text{ASS} - W \times \text{RESP} \times \theta^{T-20} - W \times \text{CARN} - \text{FOUTZ}$$

P, Z : Phyto- and zooplankton densities ($\mu\text{g L}^{-1}$)

Meaning of all parameters is given below:

Constants, coefficients:

μ = Constant related to the use of phosphate by phytoplankton

Ass = Assimilation constant

Timret = Retention time of phytoplankton in water

Flowin = Input of phosphate (related to water inflow)

Flowot = System output

Frcycp = Phosphate recycling

Frcycz = Phosphate regeneration

Carn = Carnivorous zooplankton

$G_p = \mu \times \theta^{T-20} \times \frac{I}{KI+I} \times \frac{Y}{KPO+Y}$ (Phytoplankton growth rate with respect to temperature (T),

Light (I) and phosphate (PO) as nutrient)

$K_p(T) = \mu \times \theta^{T-20}$ (T: temperature dependence)

$R(I) = I / I_{opt} \times e^{1-I/I_{opt}}$ (I: light dependence)

$D_p = \text{Resp} \times \theta^{T-20} + \text{Sed} + Z \times \text{Graz} \times \frac{I}{KP+P}$

(1)

(2)

(3)

(1): phytoplankton respiration

(2): phytoplankton sedimentation

(3): growth of zooplankton and phytoplankton with respect to nutrients

Graz: Grazing of phytoplankton by zooplankton

$D_z = \text{Resp} \times \theta^{T-20} + \text{Carnivor}$

(Zooplankton respiration with respect to temperature, natural death and grazing by carnivores)

$\Rightarrow F_1 = \text{Flowin} - \text{Conv} \times Z \times \mu \times \theta^{T-20} \times \frac{I}{KI+I} \times \frac{PO}{KPO+PO} - \text{FLOWOT} + \text{FRCYCP} + \text{FRCYCZ}$

$I = 0.2 \times (K1 - K2 \times \cos(2 \times \text{PI} \times (t + 15) / 365))$

$\text{FLOWOT} = 1 / \text{TIMRET}$

$\text{TIMRET} = 200$

$\text{FRCYCP} = \text{CONV} \times P \times \text{RESP} \times \theta^{T-20}$

$\text{FRCYCZ} = \text{CONV} \times Z \times \text{RESP} \times \theta^{T-20}$

$G(t, P, Z) = P \times \mu \times \theta^{T-20} \times \frac{I}{KI+I} \times \frac{PO}{KPO+PO} - P \times \text{RESP} \times \theta^{T-20} - P \times \text{SED}$

$\Rightarrow -Z \times \text{GRAZ} \times \frac{P}{KP+P} - \text{FOUTP}$

$\text{FOUTP} = \frac{P}{\text{TIMRET}}$

$$Q(t, P, Z) = Z \times \text{GRAZ} \times \frac{P}{K_P + P} \times \text{ASS} - Z \times \text{RESP} \times \theta^{T-20} - Z \times \text{CARN} - \text{FOUTZ}$$

$$\text{FOUTZ} = \frac{Z}{\text{TIMRET}}$$

$$T = \text{KK3} - \text{KK4} \times \cos(2\pi(t - 30) / 365)$$

Solutions of the 3-parameter model (Model I) given above are obtained by means of numerical integration in Fortran 90 language as $Y(P)$, $Z(W)$ varying with respect to time $X(t)$ in the program.