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Lake Koronia, Greece: Shift from autotrophy to heterotrophy with cultural eutrophication and progressive water-level reduction

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Abstract

Lake Koronia, a Ramsar site, is shallow, polymictic, hypertrophic and until recently was aerially the fourth largest lake in Greece. Although exceeding 5 m in the past, lake depth has declined progressively from 3.8 m in 1980 to < 1 m in 1997, reducing surface area and water volume by 50% and 80%, respectively. Specific conductivity increased from 1300 μS cm^{-1} in 1977 to >6000 μS cm^{-1} in 1991. Increased phosphate concentrations from the late 1970's (8–45 μg L^{-1}) to the late 1990's (100–1000 μg L^{-1}) document that the previously eutrophic system with a limited littoral zone switched to hypertrophy dominated by massive cyanobacteria blooms. Oxygen saturation of the water column increased progressively from about 80% in 1983 to full saturation about 1993, after which it decreased progressively to only 20% saturation in 1997. In spite of cyanobacteria dominance, community metabolism of the lake switched from progressively increasing autotrophy to rapidly advancing heterotrophy associated with progressive water-level reduction leading to fish extirpation in the lake.

Key words: Autotrophy – heterotrophy – Greek lakes – cultural eutrophication – water-level reduction

Introduction

The world is facing a fresh water crisis. What has historically been a problem of water quality is now fast becoming a double faceted problem of quality and quantity. In many areas, centers of population growth and water resources do not overlap. Semi-arid areas of the southern Balkans and eastern Mediterranean are both experiencing and poised for problems with fresh water resources, especially wetlands and shallow lakes.

The shallow lakes of this region are noted for their great age and species endemism (Petridis & Sinis 1995), especially for fish (Crivelli et al. 1997). Many are of paramount importance for migrating and overwintering bird species and have been designated as Wetlands of International Importance (Catsadorakis 1997; Frazier 1996). Local human populations, however, value lakes and wetlands primarily as water supplies to meet agricultural, domestic, and industrial needs and as a commercial fishery. Although changing recently, conservation and recreational values are of distant secondary importance (Pyrovetsi & Daoutopoulos 1989, 1997).

Both the number and magnitude of environmental perturbations to these lakes and wetlands have increased dramatically in the past two decades. Many systems have displayed progressive and profound reduction in water level and associated volume that is often accom-

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panied by enhanced cultural eutrophication (Loeffler et al. 1998), organic chemicals (Miliadis 1994) and heavy metals (Fytianos et al. 1984; Scoullos & Hatzianestis 1989). Fisheries have suffered production loss (Fotis et al. 1992), and some endemic fish species have gone extinct associated with some combination of reduced water quantity and quality, overfishing and introduction of alien fish species (Economidis et al. 1988). There is a general fear that the conservation status of many sites is endangered.

The causes for environmental decline in individual freshwater ecosystems are usually poorly understood and most assuredly are multi-faceted and additive. Most are associated with landscape alteration via deforestation, urbanization and agricultural expansion. Agricultural impacts include increased nutrient loading (Koussouris et al. 1991a), physical encroachment into fringing wetlands and hydrological alteration and diversion for irrigation and flood prevention (Psychoudakis et al. 1993; Hollis & Stevenson 1997). In-lake alterations are also important and are associated with alteration of foodweb structure, enhanced sediment resuspension and nutrient release, invasive species, and overfishing (Fotis et al. 1992; Crivelli 1995). Both landscape and in-lake alterations are overlain by regional changes in the physical environment through climate change and tectonic activity (Hollis & Stevenson 1997).

Unlike deep lakes, where progressive eutrophication usually implies changes in taxonomic dominance and biomass of phytoplankton, shallow lakes display either biomass expansion of the pre-disturbance autotrophic community (macrophytes or phytoplankton) or undergo a dominance shift between these two alternative stable states leading to long term stability (Scheffer et al. 1993). Such structural responses in shallow lakes are strongly controlled by thermal regimes and the capacity of system "memory" (sediments) to facilitate nutrient cycling. Recently, Wetzel (2001) suggested that there is an overemphasis on autotrophic production along gradients of increasing eutrophication and that most lakes are likely heterotrophic systems controlled by the overwhelming importance of allochthonous over autochthonous carbon in ecosystem metabolism.

Most of the 60 Greek lakes (Zalidis & Mantzavelas 1994) have been altered to some degree, most commonly via hydrological changes and/or cultural eutrophication. Except for nine, Greek lakes are on the mainland, shallow (70%) and <1,000 ha in area. Most work on ecosystem responses to progressive eutrophication has been done in regions lacking either pronounced wet-dry seasons or long term progressive reduction in water level (Wetzel 2001). The purpose of this paper is to examine how progressive eutrophication and water level reduction over the past 30 years have affected the metabolism (autotrophy vs heterotrophy) of Lake Koronia, Greece without a shift in autotrophic stable state and its implications for lake management.

Methods

Site description

Lake Koronia is located in northern Greece (40′41″ N., 23′09″ E.) (Mourkides et al. 1978), at approximately 75 m a.s.l. The watershed population of about 45,000 is mostly concentrated in the city of Langadas on the western shore of the lake. The area of the watershed, which comprises the western part of the Mygdonia Basin, is about 350 km^2, and the lake drains eastward into Lake Volvi (Hellenic Ministry of Environment 1996; European Commission 1998).

Lake Koronia is one of 11 Greek Ramsar sites (Frazier 1996) and has undergone severe human impact. Based on the first available data, it was eutrophic as early as 1977 (Mourkides et al. 1978). Currently, it is hypertrophic, and its surface area has gradually declined from 47 km^2 in 1970 to 30 km^2 in 1995 (Papakonstantinou & Katirtjoglou 1995). During the same period, water volume contracted from 150–200 × 10^6 m^3 to 30 × 10^6 m^3 (Papakonstantinou et al. 1996), and by 2001 it was <10 × 10^6 m^3. In 1980, maximum depth was >5 m with a mean depth of 3.9 m (Mourkides & Tsikritsis 1988). Mean depth in 2001 was <1 m. In August 1995, the lake experienced an extensive fish-kill resulting in fish extirpation and significant waterfowl deaths (Grammatikopoulou et al. 1996).

Climate of the region is transitional between Mediterranean and temperate. Annual precipitation at Thessaloniki, 15 km to the west, during the last century was 262–722 mm, with a mean annual value of 455.8 mm. Precipitation displays a primary peak in December and a secondary one in June. Minimum monthly rainfall occurs during August (Sector of Meteorology and Climatology, Department of Geology, Aristotle University of Thessaloniki; European Commission 1998).

Lake Koronia is adversely affected by both agricultural and industrial operations. The local economy was based on agriculture until the twentieth century with little change in cultivation techniques until the late 1940's. Total cultivated area has been relatively stable since 1968 at about 30,420 ha (National Statistical Service of Greece), and agriculture affects the lake via fertilizer application since the mid 1970's and groundwater extraction for irrigation. Tsiouris et al. (1993) reported nutrient concentrations in watershed runoff at 0.05 to 14.08 mg L^{-1} for NO_3^-, 4 to 1993 mg L^{-1} for NO_2^-, 1.66 to 11.4 mg L^{-1} for NH_4^+ and 0.1 to 0.96 mg L^{-1} for P. Irrigated area increased progressively from 2,730 ha (9.6% of the total cultivated area) in 1968 to 6,106 ha (20% of the total) in 1991 (National Statistical Service of Greece). All irrigated areas are adjacent to the lake.

Industrial production affects Lake Koronia via wastewater discharge and alteration of the hydrologic budget of the watershed through groundwater pumping. Current industrial operations in the Mygdonia Basin are diverse (fabric making/dying, food products, and clothing manufacturing) with 80% located close to the lake (Tsagkarlis 1998; Hellenic Ministry of Environment 1996). The most water-demanding and potentially the most polluting are fabric dying and dairy operations. The first dying industries were established in the early 1980's (Tsagkarlis 1998), with the remainder starting during the mid 1980's. Several expanded their operations in the early 1990's (Hellenic Ministry of Environment 1996). Despite recent intensification of industrial and municipal wastewater treatment, they rarely meet current water quality standards, which are among the strictest in Europe (Hellenic Ministry of Environment 1996; Tsagkalis 1998).

Database

The Hellenic Ministry of Agriculture, Directorate of Land Reclamation (2001) provided the longest series of approximately monthly water level and limnological data for Lake Koronia. Water level was measured at a permanent staff gauge in the lake. Limnological data from this study were supplemented by additional sources to provide a historical perspective on trophic state change of the lake since the mid 1970's including Mourkides et al. (1978), Mourkides & Tsiouris (1984), Kilikidis et al. (1984), Mourkides & Tsikritsis (1988), Bobori (1996), Chatzikirkou & Kalousi (1997), Ministry of Macedonia-Thrace (1996, 1997), Growth Agency of Thessaloniki (1995) and the European Commission (1999). Where possible data for mid-lake stations were utilized, and if multiple investigations were sampled for a given month, data were expressed as a mean for that month.

Because of differences in methodology between studies, only three conservative parameters were utilized in this study: specific conductivity, total phosphorus and dissolved oxygen. Use of these data focused on determining broad temporal patterns in trophic state and likely response to altered lake level.

Results and Discussion

Lake level changes

Although the database is rather sparse prior to 1986, it is clear that water level in Lake Koronia has declined progressively from > 4 m during the mid 1980's (Fig. 1).

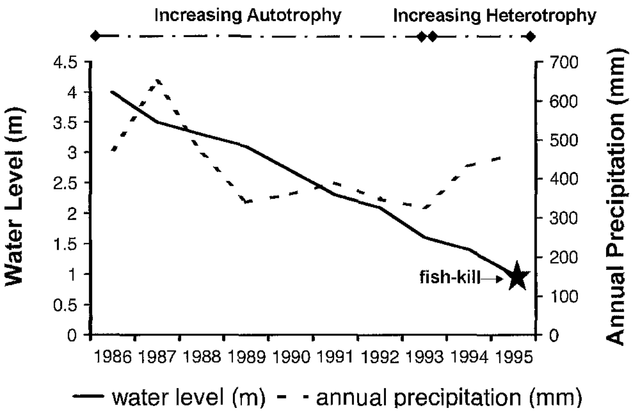

Fig. 1. Annual mean lake level (m) and annual mean precipitation (mm) for the period 1986–1997.

After the prolonged drought of 1989–1994, water depth reached about 1.0 m in 1995. By 2001, depth declined further to approximately 0.8 m with a lake volume approximately 10% of that calculated when water depth was > 4 m in the mid 1980s (Papakonstantinou & Katirtjoglou 1995).

For the period 1986–1995, mean annual rainfall in the area dropped from a high of > 600 mm to > 300 mm between 1989 and 1993, after which it increased to > 400 mm (Fig. 1). The progressive drop in lake level from at least 1986 to 1995 and beyond to 2001 therefore can not be ascribed principally to climatic factors. The influence of a major earthquake in 1978, epicentered approximately 10 km east of Lake Koronia, is unknown, but earthquake induced changes in the hydrology of Lake Prespa in western Greece have been documented (Hollis & Stevenson 1997).

Agricultural and industrial activities appear to have had a significant effect on lake level of Lake Koronia. Groundwater levels of the shallow aquifer (0–50 m) in the western part of the watershed dropped progressively during 1969–1981 when the area of irrigated agriculture increased from about 3,000 ha to 5,000 ha and eventually to > 6,000 ha by the mid 1980's (Dimitris Megas, person. commun.). This is also the location of extensive groundwater extracting industries including fabric-dying operations that were established and expanded in the mid 1980's. The European Commission (1998) estimated that groundwater pumping by agriculture (40 × 10^6 m^3) greatly exceeds that of industry (12 × 10^6 m^3). While agriculture affects the entire basin, industry exerts a strong local water demand.

Trophic state changes

Reduced Secchi transparency (0.55–0.65 m) and frequent blooms of cyanobacteria (*Anabaena* and *Aphanizomenon*) (Ananiadis 1977) suggest that Lake Koronia

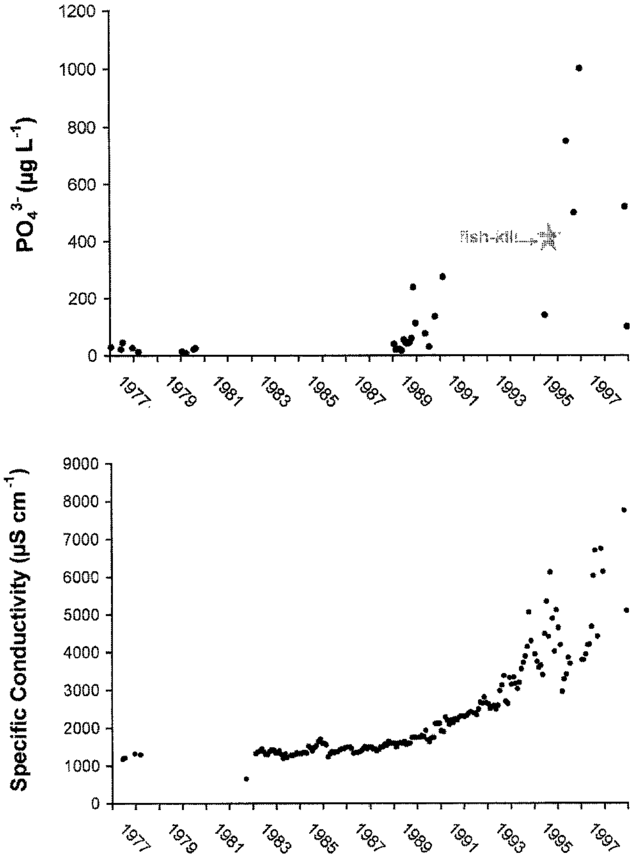

Fig. 2. Monthly mean PO_4^{3-} concentrations (µg L^{-1}) and monthly mean specific conductivity (µS cm^{-1}) for the period 1977–1997.

has been eutrophic since at least 1950. Since then, Secchi has remained <1.0 m, and chlorophyll *a* values >36 µg L^{-1} have been reported. The lake became hypertrophic during the late 1980's and early 1990's. PO_4^{3-} values increased rapidly from 8–45 µg L^{-1} in the late 1970's to 15–274 µg L^{-1} in 1989–1991 and 100–1,000 µg L^{-1} in the late 1990's (Fig. 2). During 1977–1997, specific conductivity remained relatively stable at 1,300 µS cm^{-1} from 1977 until 1991, after which it increased rapidly to >6,000 µS cm^{-1} by 1993–1994 and a maximum of 7,700 µS cm^{-1} in 1997 (Fig. 2). Finally, pH increased from the late 1940's (7.7–8.2) through the 1980's (8.5–9.3) to the early 1990's (>9.0 mostly) and often exceeded 10.0 in the late 1990's.

While lowering of lake level likely contributed somewhat, the rapid increase of conductivity in Lake Koronia in the late 1980's is clearly associated with agricultural and especially industrial activities. PAPAKONSTANTINOU et al. (1996) noted that specific conductivity of two tributaries draining the industrial area was 5–6 times greater than that of groundwater. Wastewaters from both fabric dying and diary product operations display high conductivity, 2,800–9,100 and 1,600–1,700 µS cm^{-1}, respectively (TSAGKARLIS 1998; Growth Agency of Thessaloniki 1995). By contrast, concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- in agricultural runoff decreased significantly during the growing season and were not affected by the degree of active management (TSIOURIS et al. 2002). Thus, industrial operations are significant point sources of cations/anions in Lake Koronia, and agriculture serves mainly as a non-point source of nutrients through increased fertilizer use over the past three decades.

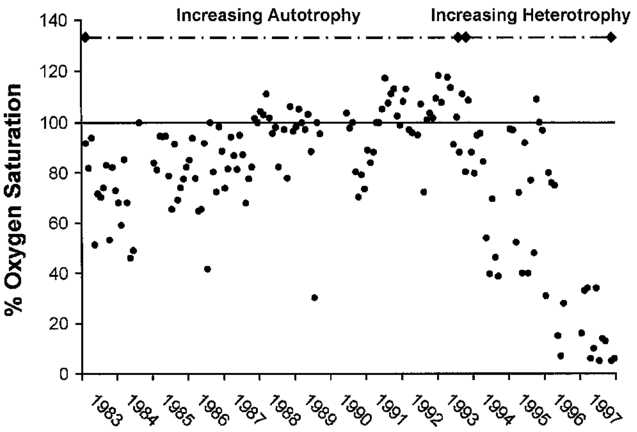

Fig. 3. Monthly mean oxygen saturation in Lake Koronia for the period 1983–1997.

Balance of autotrophy to heterotrophy along a gradient of trophic state and hydrologic change

Dissolved oxygen and temperature data were collected concurrently from 0.5 meters below the surface of Lake Koronia at a fixed station approximately monthly and always between 9 and 11 am from 1983 through 1997 by the Hellenic Ministry of Agriculture, Directorate of Land Reclamation (2001). Monthly oxygen data were converted to percent saturation for the temperature of collection to establish a general trend of the balance between autrophy and heterotrophy for the lake over time (Fig. 3). Although expected variation among temporally close data was evident reflecting time of collection and weather conditions, a clear trend is evident. Oxygen saturation increased progressively from approximately 50% in 1983 to exceed 100% for the first time at the end of 1987 and beginning of 1988 when the lake began the shift from eutrophy to hypertrophy as evidenced by rapidly increasing phosphorus concentrations thereafter. The 1983 to 1988 period also corresponded to a drop in lake level from 4 to <3.5 meters. With some exceptions, especially during early 1991, oxygen saturation for the most part remained >100% until the final quarter of 1993, after which it began a steep decline to reach hypoxia and anoxia by the end of 1997. The progressive drop in lake level had reached 1.5 meters by the end of

1993 and <1 meter by at least August 1995, the time of a massive fish kill, waterfowl deaths and eventual fish extirpation from the lake (GRAMMATIKOPOULOU et al. 1996).

Oxygen saturation in the water column of Lake Koronia paralleled increasing trophic state from 1983 until 1993, approximately five years after the lake shifted from eutrophic to hypertrophic. Submersed macrophytes were never of great importance in the lake, and the trophic state change largely reflected variation in phytoplankton biomass and composition leading to complete dominance during the hypertrophic period by massive surface blooms of cyanobacteria. Progressively increasing phosphorus concentrations in the water column of the lake during the period of record reflect increased external nutrient loading from agricultural and industrial sources combined with internal nutrient loading from sediments facilitated by declining lake level. The latter is inversely related to the depth of shallow lakes (LUETTICH & HARLMAN 1990; REDDY et al. 1996).

Although the lake remained hypertrophic and dominated by extensive scums of floating cyanobacteria, oxygen saturation in the water column reversed its trend after lake level dropped to 1.5 meters (1993) and began a steep, progressive decline to hypoxia and anoxia by 1997, when lake depth was <1 meter. This is likely a function of two factors. First, phytoplankton productivity shifted to the lake surface as decreasing water level facilitated resuspension of highly flocculent sediments produced by cyanobacterial dominance to increase water column turbidity and nutrient availability (SCHEFFER et al. 1993). The increased flocculence of recently deposited sediments from the hypertrophic period is clear from our preliminary examination of sediment cores of the lake. Coupled with reduced gaseous exchange through the water surface due to extensive cyanobacterial scums and increased light limitation of water column phytoplankton due to sediment resuspension and shading from surface algae, the positive contribution to oxygen in water column when the lake became hypertrophic was minimized. On the other hand, benthic respiration either remained unchanged during this period or increased through the presence of unconsolidated sediments, and pelagic respiration increased through sediment resuspension. Even small incremental changes in lake level, as evident in Koronia since 1990, can increase sediment resuspension significantly (SCHEFFER 1998). Decreasing lake level reduced the positive influence of phytoplankton on oxygen, while water column and sediment respiration were facilitated. Thus, the overall ability of the water column to counterbalance or dilute sediment respiration was diminished, and water-column oxygen concentrations reflected more closely sediment respiration than pelagic production.

Implications for lake management

From the beginning of intellectual focus on eutrophication as a process (National Academy of Sciences 1969; LIKENS 1972), emphasis has been on aspects of autotrophic production, as popularized by the "algal bowl" concept of VALLENTYNE (1974). SCHEFFER et al. (1993) recognized that eutrophic shallow lakes are dominated by either phytoplankton or macrophytes (alternative stable states) that exhibit long term stability unless the ecosystem undergoes major perturbation in either the food web or external and/or internal nutrient loading. The role of hydrological alterations in such relationships is poorly understood.

WETZEL (2001) suggested that there is an overemphasis on autotrophic production along gradients of increasing eutrophication, while ignoring ecosystem metabolism and the overwhelming importance of allochthonous over autochthonous carbon in freshwater ecosystems. He suggested that lakes are really heterotrophic "detrital bowls" not autotrophic "algal bowls".

Lake Koronia provides a unique opportunity to observe interactions among hydrology, trophic state and ecosystem metabolism during long-term progressive lake level decline. While dissolved oxygen was inverse to declining lake level during the first 13 years of limnological monitoring, five years after the lake became hypertrophic water level reached an inflection point beyond which water column processes were no longer able to counterbalance sediment respiration and pelagic dissolved oxygen values paralleled the additional progressive loss of water level. Thus, while there was no change in autotrophic stable state, system metabolism shifted and became increasingly heterotrophic under the control of water level.

Water levels in many Greek lakes, including Mikri Prespa (HOLLIS & STEVENSON 1997), have declined drastically recently as a result of drainage, water-course diversion and irrigation schemes to promote intensive agriculture. Many are undergoing cultural eutrophication from sewage discharge (KOUSSOURIS et al. 1991a) or a combination of sewage, industrial wastes and agricultural runoff (KOUSSOURIS et al. 1991b; NIKOLAIDIS et al. 1996). A similar situation exists throughout the Balkans, Turkey (BEKLIOGLU & MOSS 1996; GREEN et al. 1996), Armenia (HOVHANISSIAN & GABRIELYAN 2000; LEGOVICH et al. 1973) and the Middle East (GOPHEN 2000). In light of ever increasing demands on a finite water resource, it is critical to determine the minimum water volume and level and the required timing and duration needed for lakes and wetlands for maintenance of ecosystem structure and function. There are unlikely sufficient fresh water resources to return regional lakes to pre-impact conditions. Clear objectives for lake management in light of decreasing water resources must be established.

The example of Lake Koronia demonstrates that basing lake management more on manipulating the balance of ecosystem autotrophy to heterotrophy than on radical alteration of autotrophic stable states (phytoplankton versus macrophytes) or the overall productivity of either not only recognizes the reality of limited water availability for ecosystem management, but it can be tailored to meet specific management goals. It appears, for example, that raising lake-level from the current <1.0 m to about 2.5 m would alter the autotrophy to heterotrophy balance sufficiently to ensure adequate oxygen availability for a fish community. On the other hand, setting a management goal of reducing trophic state or shifting autotrophic stable state from phytoplankton to macrophytes may be relatively unobtainable considering the extremely flocculent sediments and volume of water necessary to reduce their wind-induced resuspension and associated nutrient release. Such an approach offers a reasonable means for establishing minimum permissible lake levels for specific management goals.

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