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# Long term changes in the eutrophication process in a shallow Mediterranean lake ecosystem of W. Greece: Response after the reduction of external load

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## Abstract

Lake Pamvotis is a shallow Mediterranean lake located in Western Greece near the city of Ioannina. The lake has been recognized as an internationally important conservation site under European Community legislation due to its rich biodiversity. However, during the last three decades the trophic status of the lake has changed as a result of anthropogenic activity (among others irrigation and domestic sewage discharge), resulting in serious problems. Here we present data about the long-term development in eutrophication of Lake Pamvotis. Water samples were collected and analyzed (water temperature, pH, dissolved oxygen, nutrients, chlorophyll-*a*) during three monitoring periods: 1985–1989, 1998–1999, 2004–2005. The high nutrient concentrations in the lake water during the three monitoring periods, as well as its eutrophic to hypertrophic status reflect the degree of impact anthropogenic activity has had on the lake. Commencement of a restoration plan in 1995–1996, involving sewage diversion, led to a reduction in external nutrient load and consequently to lower in-lake nutrients and Chlorophyll-*a* concentrations. Orthophosphate concentration decreased by about 87%, nitrates fell below 1.20 mg/l, whilst the total reduction of inorganic N compounds showed a weaker downward trend, fluctuating between 0.39 and 1.24 mg N/l with an average value of 0.76 mg N/l. However, after a short-term recovery the eutrophic status of the lake remains eight years later (2004–2005), suggesting the importance of the internal loading process and the absence of the top-down effect of fish. This study provides evidence for the need of greater restoration efforts utilized in Mediterranean shallow lakes.

*Keywords:* Shallow lakes; Eutrophication; Nutrients; Chlorophyll-*a*; External load

## 1. Introduction

The state and evolution of freshwater ecosystems are affected by a variety of biotic and abiotic factors, as well as by natural and human-induced processes that may differ both in duration and intensity. Lake ecosystems tend to maintain a state of equilibrium but their chemical resilience depends on certain site-specific factors and processes (Carpenter et al., 1999). In contrast to deep lakes, many shallow lakes can switch quite abruptly between different stable states, representing alternative equilibria; a hypothesis developed and established over the past 20 years and summarized in Scheffer (1998). Lake eutrophication has been a major problem for decades. It involves a change in lake status from a macrophyte-dominated clear water state to a phytoplankton-dominated turbid state, with detrimental effects to the ecosystem (Portielje and Van der Molen, 1999). This "alternative states" model has been intensively investigated, whilst the need for clearer definitions in order to describe these situations has been addressed by Rojo and Alvarez-Cobelas (2003), Naselli-Flores et al. (2003).

Studies on shallow lakes from north temperate climate clearly demonstrate that they alternate between clear and turbid water states in response to some control factors. There is evidence that nutrient control may be of greater priority in eutrophicated warm shallow lakes than in

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similar lakes at higher latitudes. The influence of nutrients appears to increase southward from the north temperate regions (Nõges et al., 2003), and this was probably manifested through naturally greater annual macrophyte abundance in warmer locations as a consequence of longer plant-growing seasons (Moss et al., 2004). The eutrophication processes, as a response to nutrient loading, consist of the "tools" in understanding the ecosystem processes. In response to a period of globally intensive eutrophication, an increasing interest in freshwater restoration has taken place over the last two or three decades (Villena and Romo, 2003). According to the previously mentioned biostability model, the first step in the recovery of shallow lakes is considered to be the reduction of nutrient loading and specifically the reduction in the concentrations of orthophosphate (Scheffer et al., 1993). Previous studies concerning mostly north temperate lakes have recorded a decline in phytoplankton biomass after a reduction in phosphates (Jeppesen et al., 2000; 1998a), although this relationship is not as clear in shallow Mediterranean lakes (Villena and Romo, 2003). Recently, Gonzalez-Sagrario et al. (2005) argued that the focus should be widened to incorporate the control of both nitrogen (N) and phosphorus (P) in the restoration of eutrophic shallow lakes.

Here we present the changes in eutrophication parameters (nutrients and phytoplankton chlorophyll-*a*) for the shallow Mediterranean Lake Pamvotis, during three monitoring periods, over the last 20 years. The main questions addressed are:

(1) Are there any inter-annually changes in nutrient concentrations and chlorophyll-*a* as a part of a long-term development?
(2) What is the long-term development of eutrophication after a reduction in phosphorus, associated with sewage diversion?
(3) What are the most effective restoration measures for the recovery and conservation of lake ecosystems?

## 2. Materials and methods

### 2.1. Study area

Table 1
Some morphometric, hydrological, physical, chemical features of Lake Pamvotis (after Romero et al., 2002; Kagalou et al., 2003a,b)

| | |
|---|---|
| Volume ($m^3$) | $9.1 \times 10^6$ |
| Surface ($km^2$) | 22.8 |
| Catchment area ($km^2$) | 510 |
| Max/mean depth (m) | 7.5/4.3 |
| Hydraulic retention time (y range) | 0.84–0.9 |
| Summer water temp. ± St.d. (Epilimn./Hypolimn., °C) | 25 ± 0.5/20 ± 0.4 |
| Conductivity (μS/cm) | 393 |
| pH (range) | 6.70–8.94 |
| Water budget (difference between winter–summer, $m^3$) | |
| Period 1985–1988 (mean) | −31900 |
| Period 1998–1999 | −26620 |
| Period 2004–2005 | −24200 |
| Water level fluctuation range (winter–summer, m) | 0.60–1.15 |

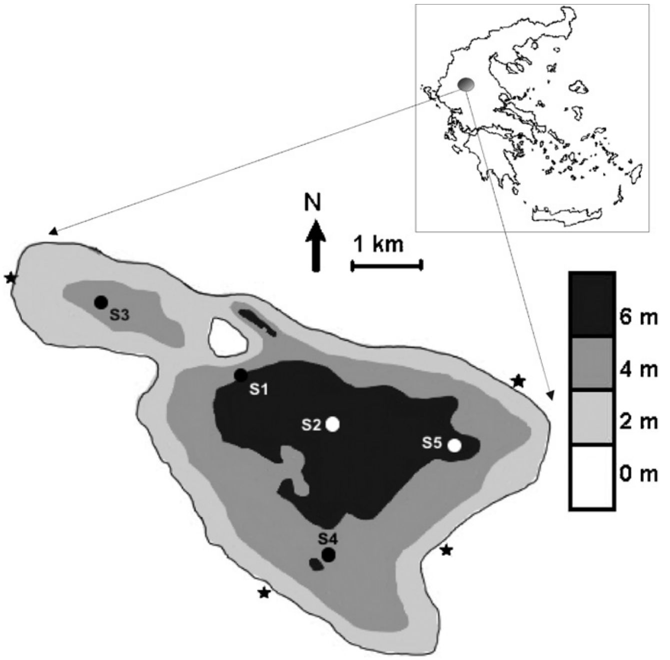

Fig. 1. Bathymetric map of the Lake Pamvotis (Greece). Dots show the sampling stations, asterisks show the inflows. Scale bar shows the different depths of the lake.

Lake Pamvotis, NW Greece (39° 40′N, 20° 53′E) is a shallow Mediterranean lake with a mean depth of 4.3 m and a maximum depth of 7.5 m. The lake occupies an area of 22.8 $km^2$ (Table 1, Fig. 1) and is situated approximately 470.25 m above the sea level. The lake is located next to the city of Ioannina (150,000 inhabitants) and 40% of the catchment is used for agriculture. It is an ancient lake ecosystem, situated in a topographically diverse landscape on the western flank of the Pindus mountain range (Tzedakis et al., 2002), and in terms of biodiversity Lake Pamvotis is of global significance (Krystufek and Reed, 2004). The basin has no naturally occurring surface outflows and is recharged by karstic springs. Drainage from the basin occurs through a system of sink holes that drain to the rivers Arachthos, Louros and Kalamas. The high topographic variability of this region provides a range of sheltered habitats. Indeed, a high-resolution pollen record from Lake Pamvotis reveals that temperate tree populations survived in this area throughout the last glacial period, owing to continued moisture availability and its varied topography, resulting in areas of relative ecological stability (Tzedakis et al., 2002). Lake Pamvotis is also a host to a number of endemic molluscan fauna (Frogley and Preece, 2004), thus enhancing the conservation value of the lake. Under the European Community Council Directive on the conservation of natural habitats and of wild fauna and flora (Habitats Directive, EC, 92/43) Lake Pamvotis is listed in the Natura Special Conservation areas as "natural eutrophic lake with *Magnopotamion* or *Hydrocharition* type vegetation". The characterization of the ecological status of lakes has become a legal imperative after the approval of the EC Water Framework Directive.

During the last three decades, anthropogenic activity (for example, irrigation and domestic sewage discharge) has altered the trophic status of Lake Pamvotis and caused serious problems (Stalikas et al., 1994; Kagalou et al., 2001; Kotti et al., 2000). In the 1995, sewage diversion to a treatment plant begun. During the 1970s, the submerged vegetation of Lake Pamvotis was dominated by nutrient tolerant species, with *Ceratophyllum demersum*, *Potamogeton perfoliatus*, *P. pectinatus*, and *Myriophyllum spicatum* being the most common. The floating-leaved species *Nymphaea alba*, *Nuphar lutea*, and *Nymphoides peltata* were evenly distributed and occurred in many areas of the lake (Ganiatsas, 1970). According to the testimonies of fisherman in the late 1980s, the whole bottom of the littoral zone of the lake was almost totally covered by submerged vegetation, dominated by *Myriophyllum spicatum* and *Potamogeton* species. Since 1986, the lake has been stocked with the exotic herbivorous species (*Ctenopharygodon idella*) and planktivorous species (*Hypophthalmichthus molitrix*, *Aristichthys nobilis*) in order to control the excessive vegetation and to support fishery. Common carp (*Cyprinus carpio*) has also been introduced annually. A decline in species diversity of the lake during the 1990s was found by Sarika-Xatzinikolaou (1994) and Kagalou et al. (2003a,b), the latter study reporting a decrease from 25 to 5 species of the submerged macrophytes, with low abundancies.

Land use trends around Lake Pamvotis have changed during the last 30 years. Such changes include an increase in urban areas by approximately 26% and a decrease in agricultural land but characterized as intensive productivity area. Agricultural pressures include the over abstraction of lake water for irrigation, which has a detrimental effect on the hydrological balance, the application of large amounts of fertilizers and agrochemicals in the fields causing a reduction in water quality, and problems associated with waste disposal and the expansion of cultivations, usually by fires in reed bed vegetation.

### 2.2. Methods

Limnological data collected during three different periods (1985–1988, 1998–1999, 2004–2005) were analyzed in order to evaluate the trophic state of the ecosystem during the last 20 years. Surface samples (in duplicate) were collected bi-weekly at five sampling stations using a HydroBios water sampler (2 l capacity). Key eutrophication parameters were examined, including $NO_3$–N, $NO_2$–N, $NH_4$–N, soluble reactive phosphorus (SRP) and Chlorophyll-*a*. In situ, temperature, pH, and dissolved oxygen were recorded using a WTW meter. Chemical analysis followed standard methods (APHA, 1989). Nitrates were determined spectrophotometrically by reduction to nitrite and following the method of diazotation and condensation with salicylate ($\mathrm{RSD} = 10\%$). Ammonium content was measured spectrophotometrically by the Nessler method ($\mathrm{RDS} = 10\%$). Determination of orthophosphates was made by the molybdenum blue method ($\mathrm{RDS} = 2\%$). Chlorophyll-*a* was determined spectrophotometrically, after the extraction of pigments with ethanol (Jespersen and Christoffersen, 1987). As there were no statistical differences in limnological parameters between the sampling stations, the measured values from all five stations were combined. The water level of Lake Pamvotis was recorded weekly at a marked point close to the constructed outlet of the lake. Changes in the volume of the lake (Table 1) were calculated by multiplying lake level change by lake surface area.

### 2.3. Statistical analysis

Analysis of variance (ANOVA) (Zar, 1999) after logarithmic transformation of the measurements was used in order to compare the limnological parameters within the three sampling periods. In addition, Spearmans rank correlation was used to evaluate the relationships between the physico-chemical parameters in each period.

## 3. Results

Morphometric, hydrological, physical and chemical data, as well as the water budget for the three monitoring periods are presented in Table 1.

### 3.1. Changes in nutrient level

Monthly averages of nutrients during the three periods are shown in Fig. 2. In 1985–1988 the concentration of the dissolved inorganic nitrogen (DIN) compounds fluctuated between 1.43 and 2.07 mg/l. Higher values were observed during the winter months while lowest concentrations appeared during late spring and summer. The most important form of DIN was the nitrates, contributing at the DIN pool with a percentage of 89–94%, followed by ammonia and nitrites.

Annual SRP measurements during the same period showed no clear trend and ranged between 0.72 and 2.86 mg/l, with maximum values being recorded during warm periods. The DIN/SRP ratio ranged between 1.03 and 1.23 with an average value of 1.10, suggesting a nitrogen limitation.

After the diversion of sewage (1995–1996) the external nutrient load decreased significantly, resulting in lower in-lake nutrient concentrations, as seen in the measurements during 1998–1999 (Period 2) (Fig. 3). Statistically significant differences were observed in nitrates (ANOVA,

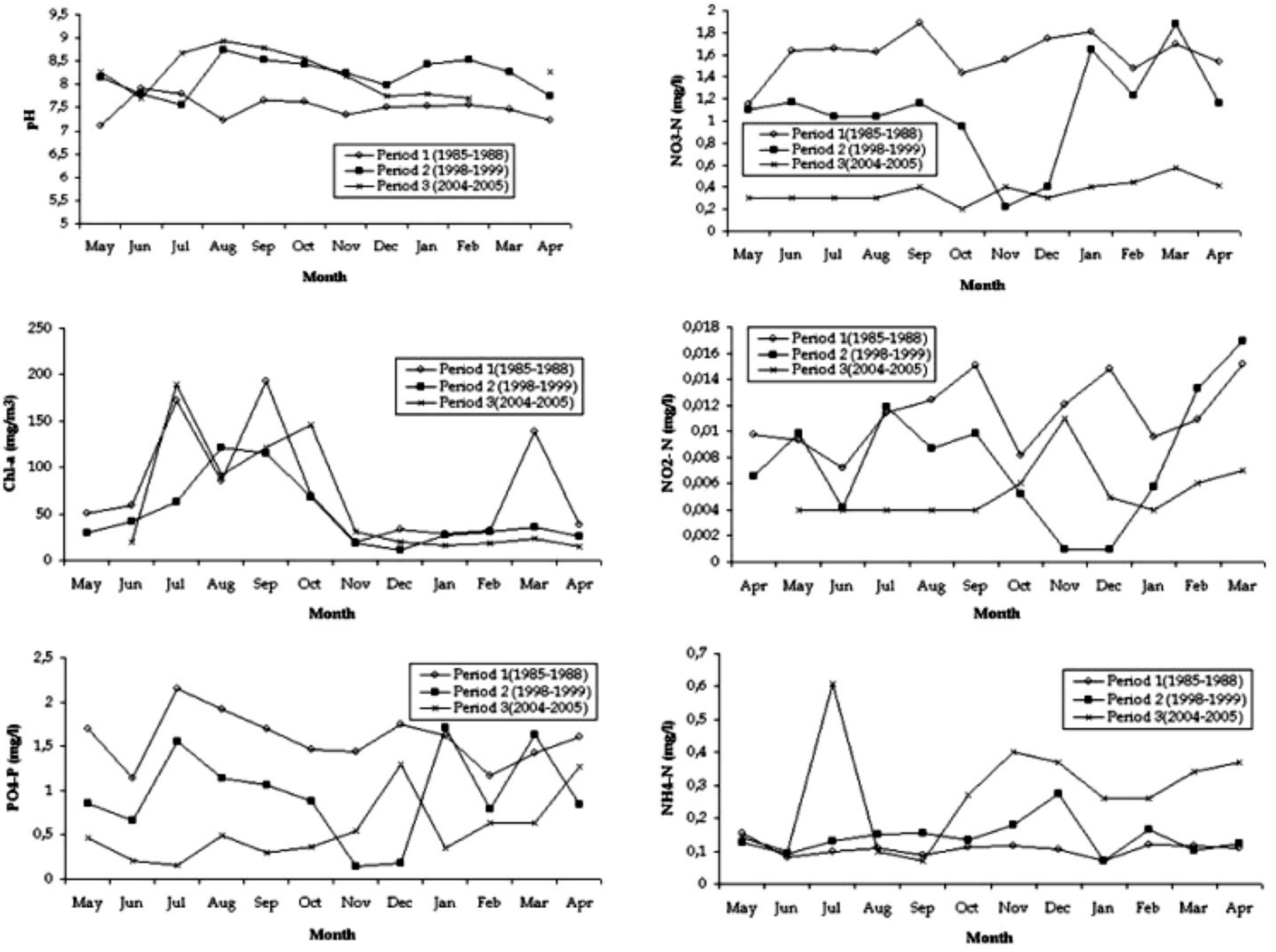

Fig. 2. Inter-annual variation of some physicochemical parameters (temperature, pH, dissolved oxygen, $NO_3$–N, $NO_2$–N, $NH_4$–N, $PO_3$–P, Chl-*a*) in the three monitoring periods.

$F = 149.97$; $P < 0.001$), nitrites ($F = 1.91$; $P < 0.1$) and phosphates ($F = 87.41$; $P < 0.001$) concentrations. Orthophosphate concentration decreased by about 87%, nitrates fell below 1.20 mg/l, whilst the total reduction of inorganic N compounds showed a weaker downward trend, fluctuating between 0.39 and 1.24 mg N/l, with an average value of 0.76 mg N/l. The annual pattern of nitrogen compounds showed similar trends as those measured in 1985–1988 (Period 1). The main DIN compound (nitrates) showed higher values during wetter months than during drier months and this may be attributed to nitrogen input from the catchment (Fig. 2). There is evidence of nitrate uptake towards the end of spring, resulting in low concentration during summer. With regard to ammonium, higher concentrations were apparent in late summer, during the warm period and during the months when the water level of the lake was high. SRP values were higher during the warm periods and during the months of high water levels (e.g. winter months). The maximum drop in water level was 1.15 m (Table 1) and occurred between spring and the end of summer. The range in the DIN/SRP ratio changed from 1.61 to 17.52 during the second monitoring period and this was due to the comparatively smaller reduction in nitrogen, leading to an increased N/P ratio.

The measurements taken in 2004–2005 (Period 3), eight years after the sewage diversion, show that nitrates undergo a further decrease (Fig. 3), although the inter-annual pattern is quite stable with an accumulation tendency during the winter months. Ammonium concentration seems to increase during the summer months (Fig. 2). In winter the lake DIN was largely $NO_3$–N and in summer largely $NH_4$–N. In-lake orthophosphates concentrations appeared to increase significantly with an average value of 0.19 mg/l whilst the minimum concentration was recorded in May 2004 (0.08 mg/l). DIN/SRP decreased (average 2.12), and this is due to the increase in the concentration of phosphates.

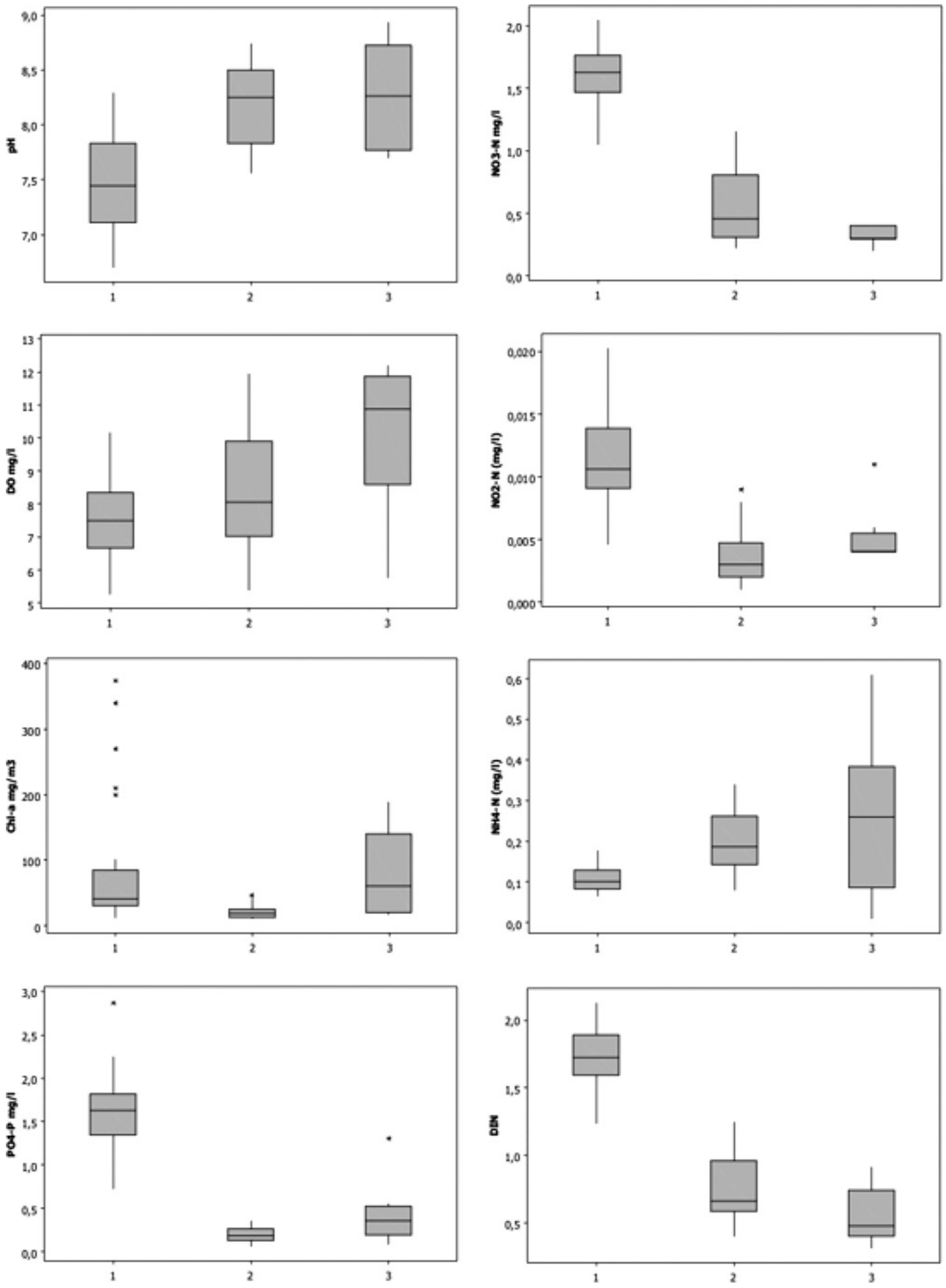

Fig. 3. Box plot of long term limnological features in Lake Pamvotis.

### 3.2. *Temperature, pH and dissolved oxygen trends*

The changes in the water temperature of Lake Pamvotis during the three monitoring periods followed the typical seasonal pattern of a Mediterranean shallow lake (Fig. 2). Summer epilimnetic values varied between 22 and 32 °C, whilst during winter the range was 4.2 to 8.0 °C. Statistically significant differences were observed among pH values between the first monitoring period (1985–1988) and the two other monitoring periods (1998–1999 and 2004–2005) (ANOVA $F = 21.54$; $P < 0.001$), indicating that there is a shift to more alkaline conditions. Typical annual dissolved oxygen (DO) patterns were also encountered, with lower DO concentrations recorded towards the end of summer and higher values recorded during the winter months. No statistical differences were found between the periods studied.

### 3.3. *Response of phytoplankton Chlorophyll-a to nutrient changes*

Period 1 (1985–1988) Chl-*a* monthly averages are shown in the Fig. 2. The annual mean concentration was 76.91 mg/m$^3$ and the highest values were recorded during the warm periods. The values of Chl-*a* demonstrate that the trophic classification of the lake is eutrophic to hypertrophic (OECD, 1982). In Period 2 (1998–1999) a sharp decline in chlorophyll-*a*, associated with a reduction in nutrient input, follows the diversion of sewage, with an annual mean Chl-*a* level of 21.21 mg/m$^3$ being reached. Increased Chl-*a* concentrations (up to 20 mg/m$^3$) were recorded during the end of summer, reaching a peak of 45.9 mg/m$^3$ in October. Chl-*a* concentrations measured in 2004–2005 (Period 3) were significantly higher (ANOVA $F = 2.51$; $P = 0.09$) with a mean value of 79.23 mg/m$^3$. Even higher concentrations were observed during the warmer months of this period, with concentrations fluctuating between 91 and 189 mg/m$^3$, indicating a return of strong hypertrophic conditions.

Spearman rank correlation analysis revealed a significant positive relationship ($R = 0.706$; $P = 0.010$) between Chl-*a* and SRP during the second monitoring period (1998–1999), whilst no significant relationships were found concerning the above variables during the other two periods.

## 4. Discussion

### 4.1. Phosphorus budget

Many lakes are highly eutrophic because of high nutrient loads from sewage and agricultural activities in their catchments. During the last decades many efforts have been made to reduce and control the input of nutrients, mostly P, through sewage diversion. According to Cullen and Forsberg (1988) there are three responses in lake water quality parameters after the reduction of external nutrient loads. The relationship between the external nutrient loading and in-lake nutrient concentrations depends on processes occurring within the lake and thus on physical, chemical and biological parameters and variables (Portielje and Van der Molen, 1999). Most external P-reduction studies in shallow lakes have shown a long recovery hysteresis (Jeppesen et al., 1991; Villena and Romo, 2003; Beklioglu et al., 1999). Moreover the response time can be highly variable in shallow lakes due to internal loading, the magnitude of the former external loading and the hydraulic retention time (Jeppesen et al., 1991; Sondergaard et al., 1993). However, there are also case studies demonstrating an almost immediate response after nutrient reduction (Chen et al., 2003).

Lake Pamvotis has a long eutrophication history (Anagnostidis and Economou, 1980; Albanis et al., 1986; Stalikas et al., 1994; Kagalou et al., 2001, 2003a,b) due to the heavy point and non-point loading of nutrients, with cyanophyte blooms occurring since 1978 (Anagnostidis and Economou, 1980). Reduction of external P-loading from 1.07 g P/m$^2$ y during the period 1985–1988 (Koussouris et al., 1989) to 0.75 g P/m$^2$ y after sewage diversion (Romero et al., 2002) resulted in a major decline in in-lake SRP concentrations, which was followed by a reduction of Chl-*a*, even though the reduced concentration was still high enough to maintain eutrophic conditions. Sediment accumulation of P in Lake Pamvotis has been observed (Romero et al., 2002; Kotti et al., 2000) although there is no evidence concerning the net internal loading rate, except the high near-bottom water SRP values during the warmer months (Kagalou et al., 2003a). Thus it is not possible to test the hypothesis directly. The importance of internal loading process in Lake Pamvotis is confirmed by the fact that SRP concentrations increase during summer months, exceeding winter concentrations by up to 200–300% with a winter–summer water level fluctuation, ranging from 80 to 120 cm. According to Jeppesen et al. (1997) and Sondergaard et al. (1999), this increase can only be the result of internal process. In addition, information derived from previous studies (Romero et al., 2002) highlights the internal loading processes. Firstly, Lake Pamvotis experiences periodic wind-induced resuspension of its bottom sediments and lake currents are substantially important in driving resuspension (Romero et al., 2002) and thus phosphorus release (Ekholm et al., 1997; Jones and Welch, 1990; Fan et al., 2001). Secondly, many of the stocked fish are plankti-benthivorous, bottom dwelling cyprinids, which will enhance the internal loading process (Tartrai and Istvanovits, 1986; Jeppesen et al., 1990; Sondergraad et al., 1990) and affect predatory control. Furthermore the disappearance of submerged macrophytes (Kagalou et al., 2003a), probably due to the introduction of large herbivorous species, and thus the loss of habitat complexity may enhance the internal loading process (Graneli and Solander, 1988; Gonzalez et al., 1988). Thus, in terms of P concentrations, the arrest in the recovery of Lake Pamvotis observed during the last monitoring period (five years after the recorded SRP decline) may be explained by the intense internal loading processes, since internal loading is the dominant factor explaining the variation in P concentrations of lakes after a reduction in external loading (Diederik and van der Molen, 1994). According to Portielje and Van der Molen (1999), after an increase in the ratio $C_{\mathrm{lake}}/C_{\mathrm{in}}$ (where $C_{\mathrm{lake}}$ is the in-lake nutrient concentration and $C_{\mathrm{in}}$ the nutrient concentration of the incoming water) following a reduction of external load, a decrease in $C_{\mathrm{lake}}/C_{\mathrm{in}}$ may be expected again after some years when the P-content in the top sediment layer has moved towards equilibrium with the concentrations in the overlying water column. The time needed for this recovery can vary largely between lakes, and may in some cases take decades (Jeppesen et al., 1990). The present average SRP in-lake concentration is 0.19 mg/l for Lake Pamvotis, far from the recently suggested threshold of $<0.05$ mg/l needed to avoid algal turbid states in Mediterranean shallow lakes (Romo et al., 2004). The extremely high abundance of the planktivores (mainly silver carp, bighead carp and YOY common carp) (Kagalou et al., 2003a) also contribute to the increase in internal P loading. Many studies have demonstrated a significant internal P reduction after fish removal, followed by chlorophyll-*a* reduction (Jeppesen et al., 1990, 1991). Concerning the role of planktivores on P dynamics, Romo et al. (2004) found a slight, significant, direct effect of planktivorous fish on SRP in-lake concentration when macrophytes covered the bottom. Moreover, the removal of carps substantially reduced total phosphorus availability in the water column in the Turkish lake Eymir (Beklioglu et al., 2003). Planktivory markedly influences zooplankton community, changing nutrient availability and also nutrients recycling rate (Fernández-Aláez et al., 2004). In addition plankti-benthivorous fish contribute to the re-loading of the water column with "new" nutrients from outside the nutrient cycle, also diminishing the P-accumulation rate in the sediment (Karjalainen et al., 1999). An intense annual fish re-stocking of Lake Pamvotis has occurred over the last decade in order to meet the requirements of local fishermen. Additionally, the absence of an adequate predator results in high phytoplankton biomass, through minimizing the top-down control effects (Sondergraad et al., 1993).

### 4.2. Dissolved inorganic nitrogen concentration

Many shallow eutrophic lakes studies have shown a rapid decrease in nitrogen after a reduction of external N loading. In-lake DIN concentrations can be affected by catchment characteristics, terrestrial N-retention, denitrification and direct atmospheric DIN deposition (Kopacek et al., 2005). After the diversion of sewage Lake Pamvotis responded to N-reduction with a slight decline in the concentration of DIN, which persisted until the final monitoring period. A higher reduction in DIN might have been expected, but a significant ammonium loading was observed in DIN pool during the last warm months of Period 3. This late increase in the concentration of ammonium may also have been a critical point in the enhancement of eutrophic conditions (Gonzalez-Sagrario et al., 2005; Landkildehus, 2005). During summer periods, low lake levels in Mediterranean shallow lakes, including Lake Pamvotis, lead to a higher plant biomass and a greater denitrification effect (Ozen et al., 2005) in the presence of nutrient loading and high temperature. Changes in temperature may explain the inter-annual variability observed in nitrate concentrations, and temperature changes may also contribute to the long-term nitrate concentration changes. Climate studies for this region and for the Mediterranean region as a whole have reported that Greece entered a warm period after 1997, in parallel with the abrupt climatic warming which occurred in the North Hemisphere since 1994 (Feidas et al., 2004). The increase of the annual average temperature in relation to biogeochemical processes might be a critical factor affecting in-lake nitrogen dynamics, in addition to the intense agricultural activities in the catchment. On the other hand, the intense carp stocking that took place during last period may also be enhancing dissolved nitrogen levels and needs to be corrected (Jeppesen et al., 1998b).

### 4.3. Stoichiometry

After the first N-limited period, DIN/SRP ratio became greater than 10:1 (Havens et al., 2003), suggesting a P-limitation, whilst a nitrogen limitation is briefly evident during summer and winter months. As revealed from measurements taken during 2004–2005 (Period 3), overall nutrient concentrations in the lake did not reach sufficiently low levels to directly limit phytoplankton growth. A decrease in DIN/SRP occurred because phosphorus created a surplus supply and nitrogen became relative scarce. A nitrogen limitation is apparent during the last monitoring period.

As a consequence, cyanobacteria are predicted to become the most widespread phytoplankton group (Smith, 1983). According to Havens et al. (2003) and Smith et al. (1995), DIN/SRP ratios of less than 10:1 or TN/TP below 29:1 by mass (Smith, 1983) are considered to indicate strong nitrogen-limiting conditions, which favor the growth and proliferation of $N_2$-fixing cyanobacteria. Cyanobacteria blooms also occur in Lake Pamvotis, affecting the aquatic life of the lake (Gkelis et al., 2005; Papadimitriou et al., 2005). The temporary decline of Chlorophyll-*a* values was insufficient to change the trophic category of Lake Pamvotis, which maintained its eutrophic status. The results presented here agree with the observations from several Mediterranean shallow lakes, where a long turbid phase (80–100 μg/l Chl-*a*) corresponds well with in-lake P concentrations >0.1 mg/l (Romo et al., 2004; Temponeras et al., 2000; Mitraki et al., 2003). The Lake Pamvotis system became more eutrophic after a return of higher SRP values, with an apparent hypertrophication tendency and frequent cyanobacterial blooms occurring during warm months (unpublished data). Downing et al. (2001) estimate that average summer TP concentrations above 70 μg/l in lakes will provide an 80% probability of phytoplankton dominated by cyanobacteria. In Lake Pamvotis the soluble part of phosphorus alone is higher than 70 μg/l. During the second monitoring period (1998–1999) phytoplankton biomass coincided with SRP concentration. After a long time of excessive P loads it is possible that the capacity of a lake to assimilate P will decrease (Havens and Schelske, 2001) and thus the accumulated P favors a P-surplus and a long nitrogen limitation. Further research is needed to improve our understanding of all possible parameters involved (for example, light climate, metabolic processes, species composition, coverage of macrophytes) especially for Mediterranean shallow lakes.

## 5. Conclusions

The research on Lake Pamvotis serves as a further example of the valuable insight provided by developing a two-tiered approach to lake classification and assessment. The lake can be considered as a shallow eutrophic Mediterranean lake located at a high altitude and influenced by changes in climate.

The long-term eutrophication of Lake Pamvotis confirms that eutrophic to hypertrophic conditions have existed at least since the 1980s. Lake restoration efforts were traditionally focused on reducing the external phosphorus loading, leading to a significant decrease of in-lake phosphorus, even though the in-lake concentration was still high enough to maintain eutrophic conditions. Internal P-loading is expected to enhance the eutrophication and to reduce the lake's response time to external reductions in P load by a decade or longer. Besides the further reduction in external P-loading, the removal of some P-rich sediments may allow a more effective response and recovery. This approach must be very carefully considered due to the shallowness of the lake and issues concerning sediment resuspension. Concerning the top-down control, the abundance of detritivorous and the absence of piscivorous species cannot contribute to the cascading effects of fish. The possible introduction of a piscivorous species might have unknown consequences for the endangered endemic species *Phoxinellus epiroticus* and *Barbus albanicus.*

It seems that a future significant decline in P and a substantial removal of carps could act as a 'reverse switch' for the recovery of Lake Pamvotis and the re-establishment of the submerged vegetation. Fish removal may lead in a consequence of changes in the nutrient levels, as it has happened in many other cases, and thus in the improving of the water clarity. Although the fact that each lake is unique and that the response may be different in this warm Mediterranean lake compared to a cold-temperate one the general re-oligotrophication response pattern might be, more or less, the same. The degree of influence of these restoration measures needs to be assessed and monitored as part of an effective management plan for the lake. Whether the present activities associated with Lake Pamvotis (e.g. fishery, irrigation, navigation, agriculture) will sustain or constrain a recovery process is open to discussion. Moreover, the effect of climate changes for this Mediterranean lake may be greater than the environmental impacts already considered; something which is difficult to predict. Because Lake Pamvotis now falls under EC Habitats Directive, there is a requirement to maintain and restore the lake to a "favorable conservation status". This status will be achieved when specific structure and functions necessary for its long-term maintenance exist and which are likely to continue into the future.

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