Greek Lakes: Limnological overview

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Abstract

The Institute of Inland Waters in Greece has investigated the physical, chemical and biological characteristics of major Greek lakes, with regard to water use, quality and trophic status. Based on this and other limnological investigations, Greek lakes can be divided into three categories: warm monomictic deep lakes, warm monomictic shallow lakes, and dimictic shallow lakes. The water quality of some Greek lakes demonstrates the presence of high concentrations of nutrients and heavy metals, with reduced concentrations of diluted oxygen. High concentrations of ammonia, nitrate and phosphate are found in many lakes, while anaerobic hypolimnia are usually found in shallow lakes. Phosphorus is the main nutrient responsible for eutrophication because it is the limiting factor in most of the lakes that were investigated.

Key words

Greece, lakes, limnology.

INTRODUCTION

Greece is located in the temperate climatic zone and its mountain ranges maintain an uneven distribution of rainfall. This produces major differences in hydrology and catchment areas, both in time and space. The morphology and land uses in the drainage area of lakes continuously reduce the availability of surface water resources (Organization for Economic Cooperation and Development (OECD) 1983). The demands for potable water and irrigation have risen many times in the past decade. However, the deterioration of Greek lakes has also accelerated during the past two decades at an enhanced rate (Koussouris *et al*. 1985, 1989a; Skoulikidis *et al*. 1998).

An important fraction of Greek terrain is mountainous, with 60% being covered by forests and shrub areas, and 35% by agricultural land. Precipitation is much more intense in western than in eastern Greece. Annually, precipitation reaches 950 mm in the north-western part of the country, 400 mm in Athens, 350 mm in the central Aegean islands, and 700 mm in the eastern Aegean islands.

The Institute of Inland Waters in Greece, one of the governmental bodies, contributes to the knowledge of water quality by providing information to authorities regarding appropriate policy and to the public regarding the information required to evaluate water quality. The present data deal with representative natural lakes that have been examined with methods that are sufficiently homogeneous to allow comparisons and evaluations. Additional data elaborated by other research groups have been evaluated and considered.

PHYSICAL CHARACTERISTICS

The important lakes of Greece, covering an area of approximately 520 km^2 and considered representative of the country, have been studied (Table 1). It is noteworthy that only 16 lakes out of approximately 40, with a total area of 610 km^2, have an area smaller than 2 km^2. There exist very few lakes, small and large, with depths greater than 50 m, while many shallow lakes are temporary. Four Greek lakes occupy crypto-depressions and lie in graben basins (Trichonis and Amvrakia) or represent coastal lakes on recent formations (Vistonis and Voulkaria).

The geographical and altitudinal distribution of the Greek lakes and their distribution show that: (i) most lakes are situated in the western and north-western part of the country, in areas with the highest rainfall (>950 mm, data averaged from the last 15 years of measurements); and (ii) most lakes (350 km^2 in area) are situated 0–200 m above sea level, with the remaining water-bodies (210 km^2) situated 400–1000 m asl (Fig. 1, Table 1). Tectonic movement is the reason for the establishment of lakes above 400 m, while erosion is the cause of the establishment of lakes below 200 m (Leontaris 1967).

The morphology of the lakes evolved from a combination

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of tectonic activity of alpine and meta-alpine orogenesis and of solution activity of meteoric water infiltrating into carbonate rocks. Most natural lakes in Greece are situated on the karstic calcareous zone running from the Alps to southern Greece, and through former Yugoslavia (Boegli 1978). Recent natural lakes belong geomorphogenetically to discrete old basins and are relics of old large lakes that occupied the country from Tertiary and Quaternary times.

The lakes can be classified between warm monomictic and dimictic, according to temperature and in relation to location and depth. This classification is supported by in-lake measurements from the National Centre of Marine Research (Institute of Inland Waters) or by other research groups studying the lakes. Most of the lakes exhibit summer thermal stratification, which are particularly pronounced in deep lakes (Trichonis, Megali Prespa, Volvi, Vegoritis and Amvrakia). The large and deep lakes that are not covered by ice or are covered very rarely, and the small shallow lakes that do not freeze (minimum surface temperature of >4°C and a maximum surface temperature of 25°C) are considered warm monomictic lakes with only one mixing period. Lakes Kastoria, Mikri Prespa, Ioannina and Doirani are characterized by a minimum temperature of <4°C, are covered by ice almost every 2–4 years, and can be considered as dimictic (Koussouris *et al*. 1989b).

Conductivity, in terms of seasons and depth, shows a wide range of values from a minimum of 40 μS/cm (Trichonis) to a maximum value of 11 000 μS/cm (Vistonis) because of sea water intrusion. In most of the lakes that were examined, the annual mean value falls into the range of 247–1200 μS/cm. Generally, conductivity reveals that Greek lakes fall into three categories according to geology. Lakes where metamorphic rocks dominate the catchment areas are characterized by the highest conductivity values (Volvi, Koronia and Vistonis), those where carbonate rocks dominate are characterized by intermediate conductivity values (Iliki, Doirani, Vegoritida and Amvrakia), and those in areas dominated by carbonate and igneous rocks are characterized by the lowest conductivity values (Lysimachia, Ioannina, Trichonis, Prespes and Kastoria), according to Kilikidis *et al*. (1985) (Table 2).

CHEMICAL CHARACTERISTICS

Oxygen depletion is the decisive factor affecting commercial fishery and recreational activities in Greek lakes. During summer stratification, deep and large lakes show minimum saturation values of dissolved oxygen close to the

Table 1. The main morphometric features of natural lakes in Greece

Lakes	Level (m.a.s.l.)	Lake area (km^2)	Catchment area (km^2)	Volume (10^6 m^3)	Mean depth (m)	Maximum depth (m)	Retention time (Years)
Trichonis	18	96.5	421	2927	30.3	58	9.4
Amvrakia	16	14.2	177	62	4.4	37	9.4
Lysimachia	16	13.5	246	53	3.9	9	–
Ozeros	23	10.1	59	13	1.6	2	–
Voulkaria	0.5	9.8	–	16	1.8	2.5	–
Vegoritis	524	53	1853	1530	28.9	70	9.5
Mikri Prespa	853	53	260	221	4.1	8.4	3.4
Megali Prespa	852	266	–	–	–	55	–
Kastorias	629	30	304	144	4.8	9.1	2.3
Ioanninon	470	22	330	120	5.5	11	0.8
Petron	527	14.4	114	37	2.6	5	–
Chimaditis	573	12.6	229	15	1.2	6	–
Zazari	602	2	–	3.4	1.7	5.5	–
Volvi	37	68	220	940	13.8	23	–
Koronia	75	46	350	175	3.8	9.5	–
Vistonis	0.1	40	3200	95	2.4	3.6	2.8
Doirani	145	42.8	420	315	5.5	10.4	–
Mitriko	–	2.1	–	2.7	0.5	–	–
Iliki	80	25	344	720	28.8	38.5	–
Stymfalia	600	3.8	219	5	1.3	2.3	–

bottom interface, whereas shallow lakes exhibit anoxic hypolimnia for an extended period from June to October (summer to late autumn) (Table 2). From late autumn to late spring (October to March), the water columns of most lakes are well oxygenated by wind action. In general, increased hypolimnetic oxygen depletion is the consequence of eutrophic conditions as a result of nutrient enrichment from allochthonous and autochthonous sources. The lowest oxygen conditions are found in lakes such as Vistonis, Kastorias, Ioanninon and Koronia that receive wastewater discharges and/or agricultural run-off. In lakes affected mainly by agricultural run-off, such as lakes Mikri Prespa, Amvrakia and Doirani, moderate oxygen depletion is observed. As a result of wastewater discharges, diversion and the enrichment of the lacustrine environment with fresh waters from nearby rivers have provided restorative actions in three eutrophic lakes (Kastoria, Ioannina and Koronia).

Mean annual pH values are 7.8–8.6, according to data from the last 15 years of measurements during summer (Table 2). The Secchi disk transparency in deep lakes is high, and is low in shallow lakes. High pH and low transparencies indicate increased biological activity during the productive period in the epilimnion. In fact, most lakes are eutrophic and only the deep lakes can be regarded as oligomesotrophic. Mean annual Secchi disk values range from 10.1 m (Trichonis) to 0.44 m (Koronia). The minimum value is 0.2 m (Koronia) and the maximum 15.8 m (Trichonis).

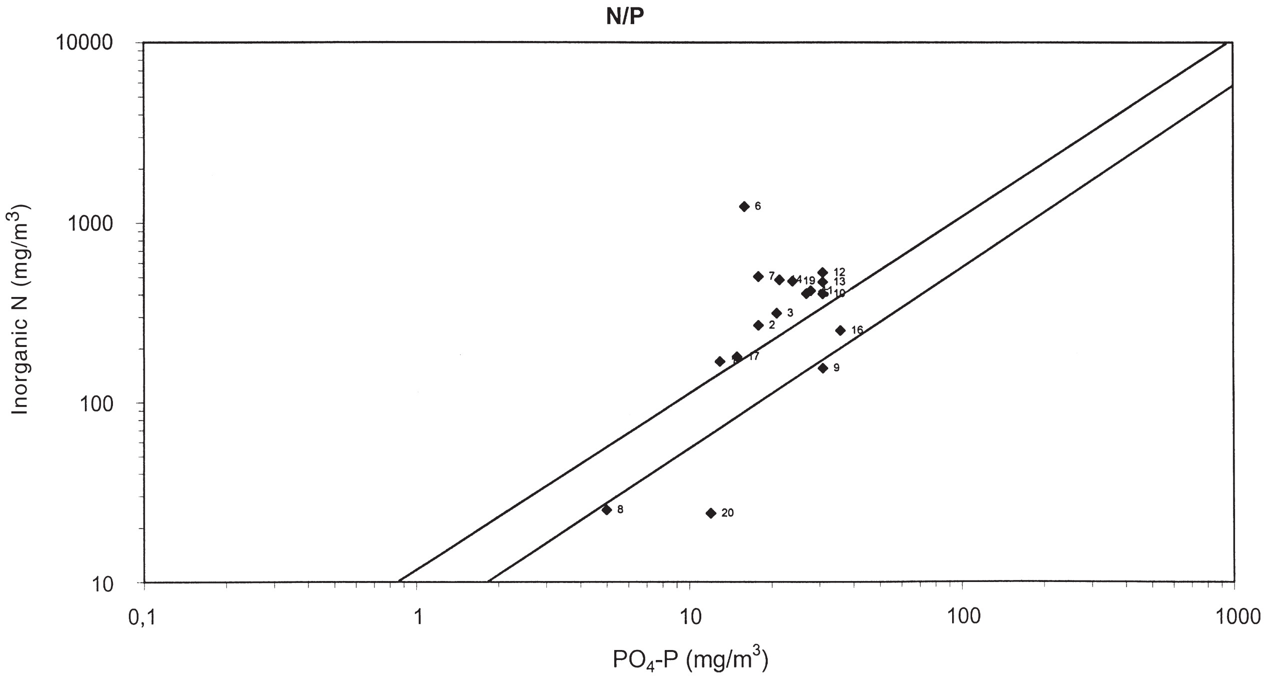

Fig. 1. The nitrogen : phosphorus ratio for Greek lakes.

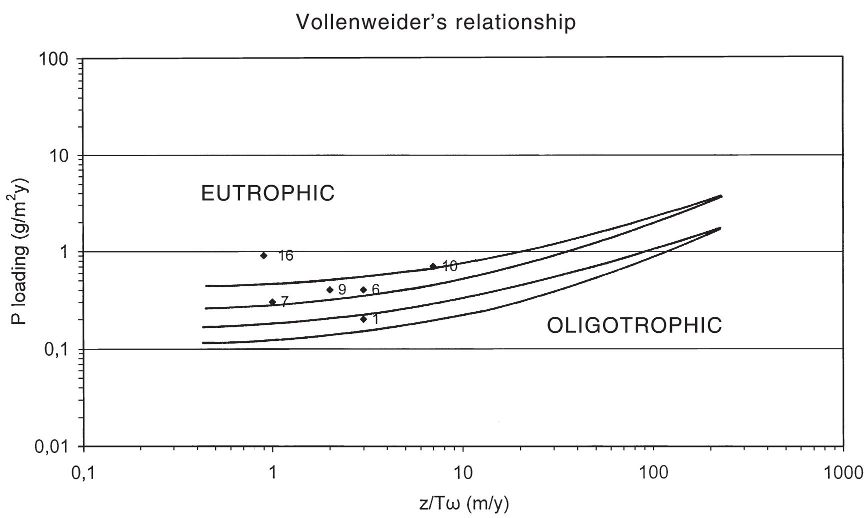

Fig. 2. Vollenweider's relationship applied to some Greek lakes.

Table 2. Physico-chemical parameters for the main Greek lakes

Lakes	T (°C)	DO (mg/L)	C (μS/cm)	pH	Secchi (m)	TA (mval/L)	SO_4 (mval/L)	Cl (mval/L)	Chl-a (mg/m^3)	TP (μg/L)	$P\text{-}PO_4$ (μg/L)	$N\text{-}NO_2$ (μg/L)	$N\text{-}NO_3$ (μg/L)	$N\text{-}NH_4$ (μg/L)	N/P
Trichonis															
Mean	30	9	247	8.1	8.5	2.6	0.48	0.51	2.3	17	13.2	6.8	28.2	14.6	13.4
Max		11	380	8.7	13	3	1.68	0.75	4.3		24.6	24	232	62	
Volvi															
Mean	29	8	980	7.9	0.7	4.7	0.48	3.36	7.6	30	23	2.5	22.2	26	21.2
Max			13	1320	9.3	2	5.4	0.5	3.93	86		56	4	405	630
Vegoritis															
Mean	26	8.4	517	8.2	3.3	3.5	0.68	0.87	2.6	24	16.7	33.3	373	42.5	77.1
Max			12.5	1012	9.1	5.5	4	1.58	2.43	15		28.2	98	1310	110
Mikri Prespa															
Mean	28	7	266	8.3	1.2	2.5	0.12	0.21	13.3	28	18.7	1.4	38	27.7	28.3
Max			8.5	520	8.8	1.6	3	0.16	1.14	45		28.1	140	745	372
Koronia															
Mean	28	8	1170	8.1	0.4	7.3	1.24	4.38	64	42	27	13.5	34	25	15.4
Max			11.3	1660	9.2	0.8	8.8	1.7	5.07	206		45	92	48	268
Vistonis															
Mean	28	8.5	1200	7.8	0.4	2.6	2.3	9.72	63	42	36	12.4	65.9	101	27.1
Max			12.5	11000	9.2	1.1	3.6	9.6	10.8	214		67.8	21	116	228
Megali Prespa															
Mean	22	7.5	219	8.3	6.2	2.1	0.1	0.18	0.9	6.4	5.1	10.5	9.4	25	5.5
Max			8.5	260	8.9	7.5	2.3	0.16	0.66	1.6		9	30	19	73
Kastorias															
Mean	22	8.2	239	8.2	1.2	2.8	0.13	0.36	27	39	31.3	5.8	15.8	22.4	5.7
Max			12.2	310	9.5	2.3	3	0.2	1.2	280		62.5	19	1011	288
Ioanninon															
Mean	28	6	308	8.4	0.4	2.4	0.32	1.35	28	38	31.7	2.2	24.1	27.3	13.6
Max			11.5	560	9.8	0.8	3.1	0.72	6.75	190		91	65.3	926	62.8
Doirani															
Mean	28	7.3	408	8.1	0.9	3.7	0.56	0.42	2.8	26	15.8	14.5	48.1	16.7	12.3
Max			12.8	630	9.3	1.4	4.6	0.66	0.66	8.9		28.6	26.4	216	38

Table 2. (continued)

Lakes	T (°C)	DO (mg/L)	C (μS/cm)	pH	Secchi (m)	TA (mval/L)	SO_4 (mval/L)	Cl (mval/L)	Chl-a (mg/m^3)	TP (μg/L)	P-PO_4 (μg/L)	N-NO_2 (μg/L)	N-NO_3 (μg/L)	N-NH_4 (μg/L)	N/P
Amvrakia															
Mean	26	7.1	550	8.3	0.8	2	7.4	1.44	4.4	37	18.4	2.6	45	59.4	15.5
Max			12.5	1100	8.9	1.5	2.6	13	2.25	66		32.6	30	290	590
Lysimachia															
Mean	30	7.2	343	8.1	0.9	3.4	1.54	0.66	5.2	23	21.4	8	295	89	15.2
Max			12.1	460	8.7	1.8	4.1	1.62	1.11	74		65	12	566	143
Iliki															
Mean	28	7.8	368	8.2	2.5		0.46	0.36	0.8	14	10.3	12	20.6	19	4
Max			12.8	577	8.8	6.7		0.80	1.41	2.1		22.3	18	790	60
Chimaditis															
Mean	29	7	480	8.1	1.2	3.2	0.8	0.6	7	36	31.7	9.5	226	63.2	16.3
Max			11.2	910	9.5	2.1	3.6	2.4	0.9	11		67.2	16.8	437	630
Petron															
Mean	30	7.1	685	8.5	0.6	2.1	2.74	0.99	11	38	28.6	8.6	285	57.8	15.8
Max			11.4	1430	9.3	0.9	5.8	3.2	1.29	18		43.8	14.6	442	586
Zazari															
Mean	28	7.2	370	8.6	0.7	1.4	0.2	0.29	11	34	31.7	8.7	312	71.4	16.7
Max			11	520	9.6	1.6	2.1	0.4	1.42	17		67.1	14.8	491	663

T, temperature; C, conductivity; DO, dissolved oxygen; TA, total alkalinity; TP, total phosphorus; Chl-a, chlorophyll-a.

Mean annual total alkalinity varies between 1.4 and 7.3 mval/L. Minimum values (1.4–2.6 mval/L) are found in most lakes. Moderate values (3.2–3.7 mval/L) occur in lakes Vegoritis, Doirani, Lysimachia and Chimaditis, while maximum values occur in lakes Volvi and Koronia (4.7 and 7.3 mval/L, respectively). Low alkalinity values indicate photosynthetically induced carbonate dissolution following CO_2 inputs from respiration.

It has been shown that phosphate chemisorbs on calcite particles (Kuo & Lotse 1972). In addition, calcium forms several insoluble solid phases with phosphates (Stumm & Morgan 1970). In arid soils, most phosphorus is held on the surface of $CaCO_3$ or precipitated as calcium phosphate (Lajtha & Schlessinger 1988). In lakes, when phosphorus concentrations in the overlying waters are high, Fe, Mn and Ca minerals in the sediments absorb phosphorus even in anaerobic conditions (Patrick & Khalid 1974). In addition, the process of autochthonous calcite precipitation in hard-water lakes (due to enhanced photosynthesis) can result in significant phosphorus removal (Danen-Louwerse *et al.* 1995). As the particulate matter show high content in carbonates in soils, sediments and streams in Greece (Skoulikidis 1990), and Greek lakes are of a karstic origin with hard and eutrophicated waters, it seems that a portion of phosphate is stored in the sediments. This fact explains the low phosphate concentrations in Greek lakes.

With respect to hardness, most lakes fall in the range of 100–200 mg/L of $CaCO_3$, that is, the range characteristic of waters with moderate mineral content. Minimum values occur seasonally in lakes Koronia (50 mg/L) and Doirani (70 mg/L), and maximum values in lakes Amvrakia (464 mg/L) and Vistonis (430 mg/L).

The highest sulphate concetration is observed in Lake Amvrakia and originate from the weathering of Triassic gypsum deposits. In Lake Vistonis, sulphate is derived primarily from sea water intrusion and secondarily from anthropogenic sources. Lake Petron is enriched with sulphate from irrigation return flows, while Lake Lysimachia receives sulphate ions from both Triassic breccias (remnants of weathered gypsum) and anthropogenic sources (agricultural run-off and sewage wastes from the town of Agrinio).

Nutrient levels are of interest because of their role in eutrophication. The northern Greek lakes (Ioanninon, Kastorias, Vegoritis, Petron, Chimaditis, Zazari, Koronia and Vistonis) exhibit the highest nutrient concentrations. In most lakes, total phosphorus concentration exceeds 20 μg/L, thereby indicating an anthropogenic influence on the lake catchments (Stanner & Bourdeau 1995). In contrast, average total inorganic nitrogen levels exceed 0.5 mg/L, which is taken to be the cut-off value for unpolluted lake water, in only two lakes (Vegoritis and Petron). Agricultural run-off and untreated sewage discharges are perceived as the most significant causes of nutrient enrichment. Lake

Table 3. Mean heavy metals concentrations in the Greek lakes (parts per billion)

Lakes	Pb	Zn	Cu	Ni	Co	Cr	Cd	Hg	As
Trichonis		47.8	18.9						2.1
Volvi		5.9	4.8						30.2
Vegoritis	24.2	92	15.2	8.2		0.5	1.4	0.08	
	1.2	16.3	0.7						
Mikri Prespa	0.2	23.6	14.4	2.5			0.1		2
		1.2	0.4						
Koronia	36.8	115.5	3.7			15.3	1.8	0.46	53.7
		121	21.8						
Vistonis	58.4	83.7	43.2		4	38.9	5	0.16	
Kastoria	31.1	32.8	6.6				0.7	0.25	11.1
		81.2	19.4						
Ioannina		33.1	5.2				1.6		1.9
Doirani	22.3	40	9.6					0.04	43.3
		62.5	12.4						
Stymfalia		22.8	9.7						2.2
Near pristine natural waters*		<5 g	<2–5				<1		

*Near pristine natural waters are waters that are hydrochemically not directly affected by point or non-point pollution sources. These waters are termed as near pristine because they are possibly affected by atmospheric pollution from remote areas.

Vegoritis, in particular, has a high concentration of inorganic nitrogen compounds as a result of wastewater discharges from a local fertilizer factory. Lakes Kastorias and Ioanninon are enriched with nutrients as a result of domestic wastewater inputs and from their bottom sediments. Other lakes are enriched with nutrients mainly from agricultural run-off and local point sources of pollution (Gianakopoulou 1989). For most lakes, the N:P ratio is >12 during the spring overturn. This indicates that the limiting nutrient for algal growth is phosphorus. Only lakes Megali Prespa, Kastorias and Iliki, with N:P ratios of <7, appear to be nitrogen-limited (Fig. 2).

Heavy metals reach high concentration levels in some lakes (Table 3). However, analytical procedures were variable with results showing differences of over one order of magnitude; therefore, caution is required in their interpretation. According to some results, it can be concluded that the most polluted lakes are Koronia, Vegoritis, Vistonis and Kastorias. The main sources of cadmium, copper, lead and zinc are fertilizer and pesticide residues. In the case of Lake Vistonis, high heavy metals levels are additionally caused by wastewater from food processing industries (Zacharias 1993).

TROPHIC STATUS

The trophic level that a lake reaches in relation to morphometric features and edaphic factors depends on the natural characteristics of the drainage area. The natural background loading based on the ratio between alkalinity or conductivity to mean depth has been examined for a widely distributed group of Greek lakes (Vighi & Chiaudani 1985). In Table 2, we can see that without any anthropogenic influence, the natural background loading for TP would be ~42 μg/L for Lake Koronia, 38 μg/L for Lake Ioannina and 39 μg/L for Lake Kastoria. These concentrations mean that 70–38 μg/L of total phosphorus enter these lakes from other sources, thus causing an alteration in natural concentrations (Goulandris 1994). Low effects have been observed for lakes Mikri Prespa (28 μg/L), Volvi (30 μg/L) and Doirani (26 μg/L), while even lower effects have been observed for lakes Amvrakia (23 μg/L) and Trichonis (17 μg/L).

A significant gap still exists in the knowledge of hydrological features of some of the lakes. Particularly scarce are data on the theoretical hydraulic residence time of most lakes mainly as a result of their anomalous regime. The available data, requiring confirmation from time to time, indicate that residence time is high for lakes Trichonis and Vegoritis (9.4 and 9.5 years), moderate for Lake Mikri Prespa (3.4 years), Vistonis (2.8 years) and Kastoria (2.3 years), and low for Lake Ioannina (0.8 years; Zacharias 1998).

The phosphorus retention coefficient, based on Vollenweider's (1975) relationships, was calculated using data from lakes Trichonis, Vegoritis, Mikri Prespa, Vistonis and Ioannina. It ranges from ~0.6 in lakes Ioannina and Vistonis to 0.88 in Lake Mikri Prespa, indicating that 60–88% of the incoming phosphorus is being retained by the lake sediments. Using the Dillon & Rigler (1974) model, and following the back-calculation procedure described by Nikolaidis *et al.* (1985), the phosphorus loading to these lakes is 0.153, 0.293, 0.281, 0.870 and 0.645 g/m^2 per year for Trichonis, Vegoritis, Mikri Prespa, Vistonis and Ioannina, respectively. Based on Vollenweider's (1975) critical loading relationships of phosphorus limits in Greek lakes, the critical loading is exceeded in lakes Mikri Prespa (0.16 g/m^2 per year), Vistonis (0.176 g/m^2 per year) and Ioannina (0.248 g/m^2 per year), while Lake Trichonis is the only lake at the permissible level. Lakes Mikri Prespa, Vistonis and Ioannina are shallow, and during summer, the mean temperature is high. This causes the reduction of oxygen in the water column and the increase of phosphorus in the water coming from the sediments. The entire situation results in the eutrophication of these lakes. Lake Trichonis is the deepest lake in Greece and this phenomenon is uncommon.

CONCLUSIONS

The Institute of Inland Waters in Greece has provided information on the physical, chemical and biological characteristics of major Greek lakes with regard to water use, water quality and trophic status. Based on this and other limnological investigations, Greek lakes can be divided into three categories: (i) warm monomictic and deep lakes with oligotrophic to oligomesotrophic and mesoeutrophic conditions, which are mainly affected by non-point sources of pollution of nutrients; (ii) warm monomictic and shallow lakes with eutrophic to hypertrophic conditions, resulting mainly from agricultural run-off and point source pollution; and (iii) dimictic and shallow lakes with eutrophic to hypertrophic conditions as a result of sewage discharges directly into the basin, and oligomesotrophic conditions with natural and agricultural enrichment of their waters.

The water quality of some Greek lakes demonstrates the presence of high concentrations of nutrients and heavy metals, with reduced concentrations of diluted oxygen often occurring. High concentrations of ammonia, nitrate and phosphate are found in many lakes, while anaerobic hypolimnia are usually found in the shallow lakes. Phosphorus is the main nutrient responsible for eutrophication because it is the limiting factor in most of the lakes that were investigated. The phosphorus retention coefficient, loading and its permissible level have been also calculated for most of the lakes. These indicate that the run-offs from agricultural activities are having an increasing effect on water quality and water, such as irrigation, fisheries etc. It becomes clear that many problems are a result of a lack of knowledge and are therefore in need of appropriate research in order to be solved.

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