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Nutrient Relationships of Greek Lakes: Water Eutrophication Monitoring, Assessment and Forecasting

Conides, Alexis, Dr.; Koussouris, Theodore, Dr.; Gritzalis L,; Konstantinos; Parpoura, Alkistis, Dr.; National Centre for Marine Research, Institute of Inland Waters Research, Ag. Kosmas, GR-166 04 Hellinikon, Athens, Greece;
Fotis, George, Prof. Dr., Aristotelian University of Thessaloniki, School of Veterinary Medicine, Laboratory of Ichthyology, University Box 395, GR-540 06 Thessaloniki, Greece

ABSTRACT: Previous works on lake eutrophication and assessment have recognized that comprehensive preimpoundment studies are essential but relatively few have been carried out that tend to be descriptive of lake-catchment area system without making predictions for the future conditions of such water bodies. This paper comes as a preliminary attempt to collect all available data of the Greek lakes condition, nutrient loading and morphology and correlate them either individually or using multiple regression models as an attempt to improve our current predictive capabilities in the area.

Introduction

The uniformity of a vast quantity of environmental measurements is essential for the environmental assessment and monitoring or even the forecasting of a closed reservoir condition. In many parts of the world today, a large number of water bodies undergo severe manheld alternations from domestic or industrial wastes. On the other hand, these water bodies are essential for the survival and development of the nearby human communities as water is pumped off either for industrial use (cooling etc.) or domestic needs (cleaning etc.). Unless the wastes are not treated prior to re-entering the water bodies, numerous problems will arise as most lakes are also used for water-oriented recreations (sports, fishing etc.). These problems will become important sooner or later, depending to the water body size and renewal rates (inflow and outflow). Living in an era of limited manpower and financial resources, prediction equations capable of giving significant results on several lake parameters with a limited amount of data, help fisheries managers and environmentalists understand future problems and take measures instantly (Ryder 1982; Melack 1976; Schlesinger and Regier 1982; Jenkins 1982; Hayes 1957; Dillon and Rigler 1974a, b).

Attempts were made during the past to describe accurately the environmental status of the lakes, in order to aid the assessment of these water bodies. The first step for this is to correlate the important nutrient loadings with the trophic indicators of the lakes and the production limiting factors, in order to establish knowledge on the important ramifications of these sources. In the present study an attempt was made to present for the first time relationships that describe the co-effects of the various nutrients, the abiotic factors and lake morphology for Greek lakes.

Materials and Methods

Studies on lake nutrient relationships have concentrated the interest of researchers and international organizations in the past all over the world as for Alpine European lakes, Nordic lakes, North American lakes (OECD 1982) or African lakes (Marshall 1984) not only for the eutrophication assessment of the studied water bodies but also to define and correlate the water condition with the fishery yield (Marshall 1984).

Numerous reports from Greek workers on Greek lakes exist today (Koussouris and Diapoulis 1989 a, b; Koussouris et al. 1987, 1989 a, b, 1991 a, b, 1992; Koussouris

	LAKE	Area	Catchment	Volume	Z	CONDUCTIVITY	pH	Total Alkalinity	Total Hardness	SO4	Total-P	P-PO4	N-NO2	N-NO3	N-NH4	Total-N	N/P	chl-a	Secchi	MEI, Cond/Z	MEI, T.P./z	MEI, T.N./z
1	Trichonis	96,50	421,00	2927,00	30,30	277,00	8,10	2,62	111,00	24,00	18,00	9,90	6,80	28,20	14,60	49,60	13,40	1,10	10,10	9,142	0,594	1,637
2	Amvrakia	14,20	177,00	62,00	4,40	635,00	8,30	2,03	416,00	370,00	21,00	11,60	2,60	45,00	59,40	107,00	15,50	4,40	3,40	144,318	4,773	24,318
3	Lysimachia	13,50	246,00	53,00	3,90	343,00	8,10	3,40	161,00	76,50	24,00	39,00	8,00	295,00	89,00	392,00	15,20	5,20	2,60	87,949	6,154	100,513
4	Ozeros	10,10	59,00	13,00	1,60																	
5	Voulkaria	9,80		16,00	1,80																	
6	Vegoritis	53,00	1853,00	1530,00	28,90	517,00	8,20	3,48	230,00	34,00	16,00	4,10	33,30	373,00	42,50	448,80	77,10	2,60	4,10	17,889	0,554	15,529
7	m.prespa	53,00	260,00	221,00	4,10	266,00	8,20	2,46	130,00	6,00	40,00	6,20	1,40	28,00	27,70	57,10	28,30	13,30	1,70	64,878	9,756	13,927
8	M.Prespa	266,00				219,00	8,30	2,30	102,00	5,00	6,40	5,10	10,50	9,40	25,00	44,90	5,50	0,90	7,00			
9	Kastoria	30,00	304,00	144,00	4,80	239,00	8,20	2,80	121,00	6,50	63,00	21,00	5,80	15,80	22,40	44,00	5,70	18,30	1,00	49,792	13,125	9,167
10	Ioannina	22,00	330,00	120,00	5,50	308,00	8,40	2,40	138,00	15,20	67,00	11,30	2,20	24,10	27,30	53,60	13,60	28,70	0,90	56,000	12,182	9,745
11	Petron	14,40	114,00	37,00	2,60	685,00	8,50	2,10	178,00											263,462		
12	Chimaditis	12,60	229,00	15,00	1,20	480,00	8,10	3,20	160,00	40,00										400,000		
13	Zazari	2,00		3,40	1,70	370,00	8,60	1,40	95,00	12,00										217,647		
14	Volvi	68,00	220,00	940,00	13,80	980,00	8,40	4,68		24,00	37,00	30,00	2,50	22,20	26,00	50,70	21,20	7,60	1,70	71,014	2,681	3,674
15	Koronia	46,00	350,00	175,00	3,80	1170,00	8,10	7,32	133,00	62,00	107,00	27,00	13,50	34,00	25,00	72,50	15,40	64,00	0,40	307,895	28,158	19,079
16	Vistonis	40,00	3200,00	95,00	2,40	1200,00	7,80	2,62	216,00	114,00	104,00	32,70	12,40	65,90	101,40	179,70	27,10	63,00	0,40	500,000	43,333	74,875
17	Doirani	42,80	420,00	315,00	5,50	408,00	8,10	3,70	150,00	28,40	34,00	15,80	14,50	48,10	16,70	79,30	12,30	2,80	3,80	74,182	6,182	14,418
18	Mitriko	2,10		2,70	0,50																	
19	Iliki	25,00	344,00	720,00	28,80	383,00	8,20			25,00	22,80	10,30	12,00	20,60	19,00	51,60	4,00			13,299	0,792	1,792
20	Paralimni	14,20	68,00	250,00	17,60	443,00	8,20	2,70	178,00	21,00	16,30	10,60	5,00	11,30	9,00	25,30	2,00			25,170	0,926	1,438
21	Stymfalia	3,80	219,00	5,00	1,30																	
22	Moustou	0,20	0,80	1,10	3,00		7,50			975,00												
23	Polyfyto	74,00	5630,00	1174,00	26,20		7,70															
24	Kerkini	59,40	235,00	183,60	3,10	376,60	8,20		75,80	14,00	105,30	30,90	413,40	8,90	0,20	422,50	0,25	0,02	0,70	121,484	33,968	136,290

Tab 1 where: Area: lake area (km^2), Catchment: lake catchment area (km^2), volume: Lake Volume (million cub.m.), Z: mean depth (m), Conductivity.: mean annual Conductivity (μS/cm), Total Alkalinity: mean annual Total alkalinity (meq/lt), Total Hardness: mean annual Hardness ($CaCO_3$, mg/lt), SO_4: mean annaul concentration (mg/lt), Total-P:mean annual total phosphorus (μg/lt), P-PO4: mean annual phosphate phosphorus (μg/lt) $N\text{-}NO_2$: mean annual nitrate nitrogen (μg/lt), $N\text{-}NO_3$: mean annual nitrite nitrogen (μg/lt), $N\text{-}NH_4$: mean annual ammonia nitrogen (μg/lt) Total-N: mean annual total nitrogen (μg/lt), N/P: overall mean annual nitrogen to phosporus ratio, chl-a: mean annual chlorophyll -a (mg/m^3), Secchi: mean annual water transparency (m)

and Friligos 1982, 1983; Kamarianos et al. 1992 a, b, 1993; Anastasopolou 1994). This paper is based on these results on water quality for the Greek lakes which are all summarized in Tab 1. In Fig 1 the Greek territory is illustrated with the locations of the examined lakes. The known data pairs were correlated and fitted to certain mathematical models according to the least squares method.

The data were initially correlated according to 8 different mathematical (linear, power, reciprocal and logarithmic) models in order to check the best fit according to the estimated correlation coefficient and goodness-of-fit (ANOVA; Sokal and Rohlf 1981; Lapin 1981). After choosing the best model, the residual error (Lapin 1981) for each lake was calculated in order to define the lakes that could not be incorporated in the model and should be removed from the data set. Afterwards, the final fitting of the model was carried out. Both equations and the associated ANOVA Goodness-of-fit are presented. Additionally, multiple regression equations were estimated involving important parameters, in order to present a more complicated and accurate model of the possible interference between lake factors. The standard error of estimation (Lapin 1981) and ANOVA Goodness-of-fit of these relationships are also provided. The equations throughout the text that are marked with an asterisk are not accepted statistically according the ANOVA Goodness-of-fit performed.

Results

Total Nitrogen versus Nitrogen/Phosphorus Ratio

The initial best fit was according to the linear model that fitted the data is:

✦ $N/P = 9.041 + 0.058$ [Total-N, μg/lt],
$r = 0.469$, $n = 15$, $F = 3.73$, d.f. $= 1,13$

Calculation of the residual error for each data pair revealed that the lakes Vegoritis (+41.94) und Kerkini (−33.37) could not fit the model significantly and were removed from the set. The final model turned reciprocal and was:

$N/P = 22.84 - 525.98$ / [Total-N, μg/lt),
$r = 0.59$, $n = 13$, $F = 5.00$, d.f. $= 1,11$

$N\text{-}NH_4$ versus Total Nitrogen

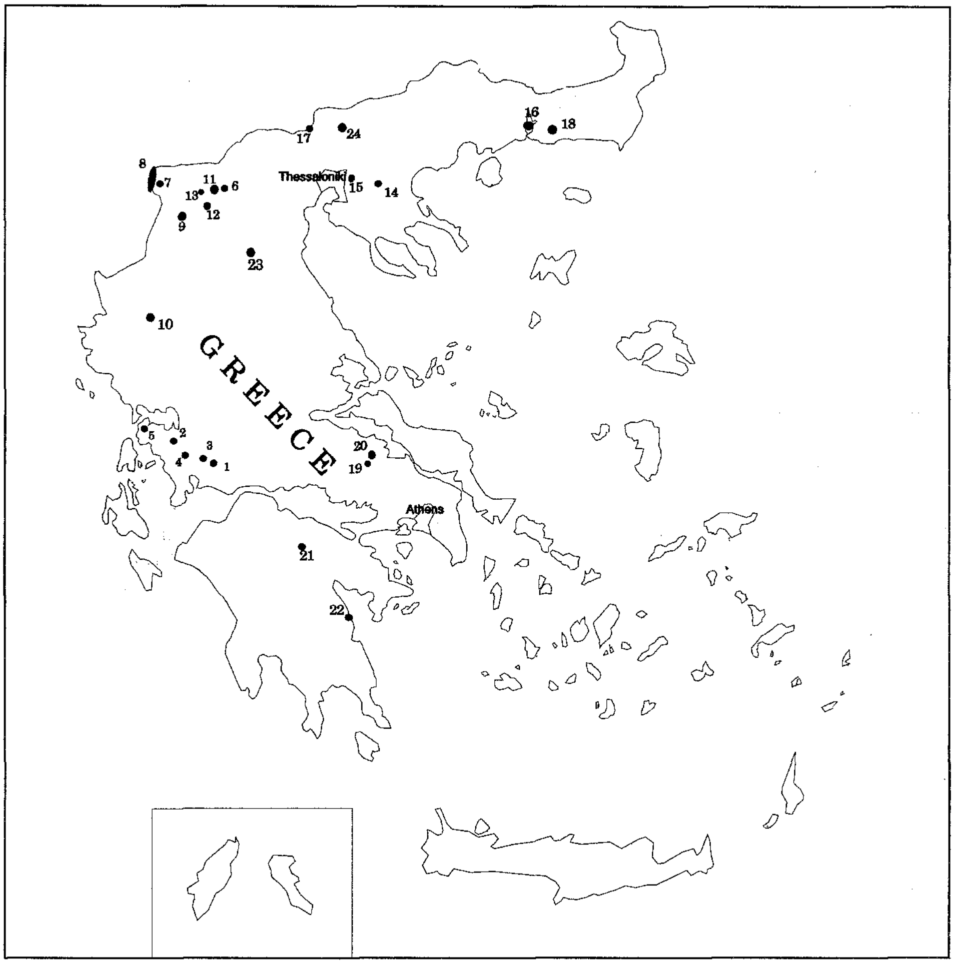
The initial best fit was according to the linear model. The model that fitted the data is:

✦ [$N\text{-}NH_4$, μg/lt] $= 28.44 + 0.053$ [Total-N, mg/lt],
$r = 0.28$, $n = 15$, $F = 1.07$, d.f. $= 1,13$

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (+39,89), Vistonis (+63,49) and Kerkini (−50,52) could not fit the model significantly and were removed from the set. The final model turned reciprocal and was:

[$N\text{-}NH_4$, μg/lt] $= 45.05 - 1036.9$ / [Total-N, μg/lt],
$r = 0.70$, $n = 13$, $F = 9{,}41$, d.f. $= 1,10$

Fig 1
Map of Greece showing the locations of the examined lakes. Note that the lakes are numbered according to Tab 1.



N-NO_3 versus Total Nitrogen

The best fit was according to the linear model. The model that fitted the data is:

[N-NO_3, μg/lt) = −7.307 + 0.548 [Total-N, μg/lt],
$r = 0.760$, $n = 15$, $F = 17.1$, d.f. = 1,13

N-NO_2 versus Total Nitrogen

The initial best fit was according to the power model. The model that fitted the data is:

[N-NO_2, μg/lt] = 0.134 [Total-N, μg/lt]$^{0.931}$,
$r = 0.623$, $n = 15$, $F = 8.30$, d.f. = 1,13

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (−26.91) and Kerkini (+375.96) could not fit the model significantly and were removed from the set. The final model turned linear and was:

[N-NO_2, μg/lt] = 3.161 - 0.064 [Total-N, μg/lt],
$r = 0.85$, $n = 13$, $F = 27.95$, d.f. = 1,11

Total Phosphorus versus Nitrogen/Phosphorus Ratio

The initial best fit was according to the reciprocal model. The model that fitted the data is:

✦ [Total-P, μg/lt] = 39.741 + 15.13/[N/P],
$r = 0.433$, $n = 15$, $F = 3.011$, d.f. = 1,13

Calculation of the residual error for each data pair, revealed that the lakes Karonia (+66.27), Megalli Prespa (−36.09) and Vistonis (+63.7) could not fit the model significantly and were removed from the set. The final model turned linear and was:

[Total-P, μg/lt) = 30.57 + 18.137 / [NP],
$r = 0.754$, $n = 12$, $F = 13.16$, d.f. = 1,10

Total Phosphorus versus P-PO_4

The initial best fit was according to the power model. The model that fitted the data is:

[Total-P, μg/lt] = 4.341 [P-PO_4, μg/lt]$^{0.773}$
$r = 0.67$, $n = 15$, $F = 10.57$, d.f. = 1,13

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (–49.81) and Megali Prespa (–8.90) could not fit the model significantly and were removed from the set. The final model turned linear and was:

[Total-P, μg/lt] = 3.265 + 2.751 [P-PO_4 μg/lt],
r = 0.78, n = 13, F = 16.82, d.f. = 1,11

Total Nitrogenes versus Chlorophyll-a

The initial best fit was according to the reciprocal model. The model that fitted the data is:

H [Total-N, μg/lt] = 129,99 + 5.827 / [chl-a, mg/m^3],
r = 0.52, n = 13, F = 3.90, d.f. = 1,11

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (+260.89) and Vegoritis (+316.57) could not fit the model significantly and were removed from the set. The final model was:

[Total-N, μg/lt] = 71.91 + 6.99 / [chl-a, mg/m^3],
r = 0.93, n = 11, F = 59.34, d.f. = 1,9

Total Hardness versus S-SO_4

The initial best fit was according to the linear model. The model that fitted the data is:

[S-SO_4, μg/lt] = 116.19 + 0.813 [Total Hardness, mg/lt],
r = 0.91, n = 15, F = 64.41, d.f. = 1,13

Total Hardness versus Conductivity

The initial best fit was according to the power model. The model that fitted the data is:

[Conductivity, μS/cm] = 16.586 [Total Hardness, mg/lt]$^{0.652}$,
r = 0.52, n = 16, F = 5.03, d.f. = 1,14

Calculation of the residual error for each data pair, revealed that the lakes Karonia (+767.40) and Vistonis (+647.95) could not fit the model significantly and were removed from the set. The final model turned linear and was:

[Conductivity, μS/cm] = 22.549 [Total Hardness, mg/lt]$^{0.564}$,
r = 0,68, n = 14, F = 10.00, d.f. = 1,12

Total Alkalinity versus Conductivity

The initial best fit was according to the linear model. The model that fitted the data is:

[Conductivity, μS/cm] = 121.945 + 133.89 [Total Alkalinity, meq/lt],
r = 0.75, n = 15, F = 16.54, d.f. = 1,13

Total Phosphorus versus Mean Annual Secchi Reading

The initial best fit was according to the reciprocal model. The model that fitted the data is:

[Total-P, μg/lt] = 14.287 + 41.01/[Secchi, m],
r = 0.94, n = 13, F = 83.99, d.f. = 1,11

Chlorophyll-a versus Mean Annual Secchi Reading

The initial best fit was according to the reciprocal model. The model that fitted the data is:

[chl-a, mg/m^3] = –4.67 + 24.464/[Secchi, m],
r = 0.91, n = 13, F = 49.98, d.f. = 1,11

Calculation of the residual error for each data pair, revealed that the lake Kerkini (–30.26) could not fit the model significantly and was removed from the set. The final model was:

[chl-a, mg/m^3] = –4.054 + 26.819/[Secchi, m],
r = 0.99, n = 12, F = 98.3, d.f. = 1,10

Total Phosporus versus Chlorophyll-a

The initial best fit was according to the linear model. The model that fitted the data is:

[Total-P, μg/lt] = 30.109 + 1.186 [chl-a, mg/m^3],
r = 0.734, n = 13, F = 12.91, d.f. = 1,11

Calculation of the residual error for each data pair, revealed that the lake Kerkini (+75.17) could not fit the model significantly and was removed from the set. The final model was:

[Total-P, μg/lt] = 19.794 + 1.415 [chl-a, mg/m^3],
r = 0.97, n = 12, F = 137.04, d.f. = 1,10

Total Nitrogen versus Total Phosphorus

The initial best fit was according to the power model. The model that fitted the data is:

✦ [Total-N, μg/lt] = 38.670 [Total-P, μg/lt]$^{0.236}$,
r = 0.22, n = 15, F = 0.61, d.f. = 1,13

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (+310.25), Kerkini (374.5) and Vegoritis (+306.69) could not fit the model significantly and were removed from the set. The final model was:

✦ [Total-N, μg/lt] = 21.840
[Total-P, μg/lt]$^{0.288}$,
r = 0.760, n = 15, F = 17.1, d.f. = 1,13

Total Introgen versus Secchi Disk Reading

The initial best fit was according to the reciprocal model. The model that fitted the data is:

[Total-N, μg/lt] = 1/[0.0109 + 0.0008[Secchi, m]),
r = 0.28, n = 13, F = 0.9, d.f. = 1,11

Calculation of the residual error for each data pair, revealed that the lakes Lysimachia (+313.93), Kerkini (334.66) and Vegoritis (+377.03) could not fit the model significantly and were removed from the set. The final model was:

[Total-N, μg/lt] = 1/(0.0072 + 0.0048[Secchi.m]), r = 0.79, n = 10, F = 13.0, d.f. = 1,8

Morphoedaphic Index (Total-N) versus Lake Volume

The initial best fit was according to the power model. The model that fitted the data is:

[MEI, Total-N] = 1028.263 [Volume, 10^6 m^3]$^{-0.791}$, r = 0.65, n = 14, F = 8.40, d.f. = 1,12

Calculation of the residual error for each data pair, revealed that the lake Kerkini (+119,62) could not fit the model significantly and was removed from the set. The final model turned reciprocal and was:

[MEI, Total-N] = –2.540+3957.097/[Volume, 10^6 m^3], r = 0.77, n = 13, F = 15.71, d.f. = 1,11

Morphoedaphic Index (Conductivity versus Lake Volume

The initial best fit was according to the power model. The model that fitted the data is:

[MEI, Cond.] = 1238.79 [Volume, 10^6 m^3]$^{-0.528}$, r = 0.77, n = 17, F = 16.3, d.f. = 1,15

Calculation of the residual error for each data pair, revealed that the lakes Chimaditis (+103.41), Zazari (–431.64), Koronia (+226.81) and Vistonis (+388.06) could not fit the model significantly and were removed from the set. The final model turned reciprocal and was:

[MEI, Cond.] = 22.678+7188.89/[Volume, 10^6 m^3], r = 0.85, n = 13, F = 28.82, d.f. = 1,11

Morphoedaphic Index (Conductivity) versus Lake Area

The initial best fit was according to the reciprocal model. The model that fitted the data is:

[MEI, Cond.] = 1/(0.002 + 0.0006[Area km^2]), r = 0.500, n = 17, F = 4.97, d.f. = 1,15

Calculation of the residual error for each data pair, revealed that the lakes Petron (+172.46), Chimaditis (+299.8), Koronia (+274.49) and Vistonis (+462.09) could not fit the model significantly and were removed from the set. The final model was:

[MEI, Cond.] = 48.688 + 341.43/[Area, km^2], r = 0.75, n = 13, F = 14.10, d.f. = 1,11

Morphodaphic Index (Total Phosphorus) versus Lake Volume

The initial best fit was according to the reciprocal model. The model that fitted the data is:

[MEI, Total-P] = 1/(0.146 + 0.0007[Volume, 10^6 m^3]), r = 0.80, n = 14, F = 20.4, d.f. = 1,12

Morphoedaphic Index (Total Phosphorus) versus Lake Area

The initial best fit was according to the reciprocal model. The model that fitted the data is:

✦ [MEI, Total-P] = 1/(0.146 + 0.0088[Area, km^2]), r = 0.32, n = 14, F = 1.36, d.f. = 1,12

Calculation of the residual error for each data pair, revealed that the lakes Vistonis (+41.31) and Kerkini (+32.47) could not fit the model significantly and were removed from the set. The final model was:

✦ [MEI, Total-P] = 1/(0.168+0.0105[Area, km^2]), r = 0.39, n = 12, F = 1,84, d.f. = 1,10

Considering the results that up to now have been presented on the relationships between various parameters of the Greek lakes, it is evident that in all cases, the equations obtaine after removing from the data set the lakes that show extremely high residual errors, describe the relationships accurately according to the presented ANOVA Goodness-of-fit. Only the relationships between Total Nitrogen versus Total Phosphorus and MEI [Total Phosphorus] versus Lake Area cannot describe these relationships accurately due to very disperse data sets. Additionally, the attempts to correlate all parameters individually with the Lake Catchment area (km^2) gave insignificant results (more than 95% of the variance could not be explained by the equations). As these parameters are very important, the need to incorporate them into predictive equations like the others, gave rise to predictive multiple regression equations which are presented below.

Prediction of Lake Nitrogen/Phosphorus Ratio

The [N/P] ratio shows good and acceptable correlation with the parameters: [Total-P], [Total-N], [Conductivity], [Total Hardness], [Lake Volume], [Lake Depth], [Secchi disk reading], [pH] and [Lake Area] and the models is the following:

[N/P]=–0.704 [Total-P, μg/lt]+0.011 [Total-N, μg/lt]+0.034 [Conductivity, μS/cm]+0.004 [Total Hardness, mg/lt]+ 0.0007 [Lake Volume, 10^6 m^3]+0.442 [Lake Area, km^2]+ 1.900 [Lake Depth, m]–11.891 [Secchi, m]+4.158 [pH], r^2= 0.983, n=11, F=12.808, d.f.=9,2 with standard error of the estimate = ±8.631 while the range of N/P in data = 0.25–77.1

A less complicated model is the following:

[N/P]=0.029 [Total-N, μg/lt]+0.014 [Conductivity, μS/cm]+ 0.426 [Total Hardness, mg/lt]+0.505 [Lake Depth, m] -5.524 [pH] -0,354 [S-SO_4, μg/lt], r^2=0.965, F=22.715, d.f.= 6,5 with standard error of estimation = ±7.86.

Prediction of Lake Area

Stepwise calculation of this model showed that [Lake Area] parameter correlates significantly with [Lake Depth], [Conductivity], [pH], [S-SO_4] and [Total Hardness] as follows:

[Lake Area, km^2]=1.948 [Lake Depth, m]+0.016 [Conductivity, μS/cm]+7.390 [pH]+0.177 [S-SO_4, μg/lt]–0.323 [Total Hardness], r^2=0.944, F=20.2, d.f.=5,6 with standard error of area prediction = ±15.523 km^2 while Lake Area range in data = 0.2-266 km^2.

Also, a less complicated model of [Lake Area] predictions, can be the following:
[Lake Area, km^2]=0.423 [Total-P, μg/lt]+0.003 [Total-N, μg/lt]+0.003 [Total-N, μg/lt]+1.729 [Lake Depth, m], with r^2=0.822, n=14, F=16.949, d.f.=3,11 with standard error of prediction = ±22.5 km^2.

Prediction of Total Hardness

The parameter [Total Hardness] showed significant correlation with [pH] and [S-SO_4] as follows:
[Total Hardness, mg/lt]=14.221 [pH]+0.808 [S-SO_4, μg/lt], r^2=0.970, n=11, F=143.63, d.f.=2,9 with standard error of estimation = ±37.08 mg/lt while the range of [Total Hardness] in data = 75.8-416 mg/lt.

Prediction of Lake Volume

Lake volume shows significant correlation with [N-NO_2], [N-NO_3], [Lake Depth], [Conductivity], [Total Hardness], [S-SO_4], [N-NH_4] and [P-PO_4] as follows:
[Lake volume, 10^6 m^3]=0.236 [N-NO_2, μg/lt]+0.198 [N-NO_3, μg/lt]+10.557 [N-NH_4, μg/lt]–34.395 [P-PO_4, μg/lt]+86.312 [Lake Depth, m]+0.121 [Conductivity, μS/cm]–16.733 [Total Hardness, mg/lt]+11.819 [S-SO_4 μg/lt+1965.95 with r^2= 0.961, n=12, F=9.178, d.f.=8,3 with standard error of estimation = ±326.71 10^6 while [Lake volume] range in data = 1.1-2927 10^6 m^3.

A less complicated model removing the [Conductivity] parameter and substituting the nutrient parameters with [Total-P] and [Total-N] is the following:
[Lake Volume, 10^6 m^3]=68.7 [Lake Depth, m]–3.724 [Total Hardness, mg/lt]+2.515 [S-SO_4, μg/lt]+3.071 [Total-P, μg/lt]–0.404 [Total-N,μg/lt], r^2=0.995, F=153,88, d.f.=6,5 with standard error of prediction = ±109.70 10^6 m^3.

Prediction of Lake Catchment Area

Lake catchment area showed a good correlation with all parameters together ie [N-NO_2], [N-NO_3], [Lake Depth], [Conductivity], [Total Hardness], [S-SO_4], N-NH_4] and [P-PO_4] and gave the following equation:
[Lake Catchment, km^2]=4.311 [N-NO_2, μg/lt]–1.548 [N-NO_3, μg/lt]+38.972 [N-NH_4, μg/lt]–63.412 [P-PO_4, μg/lt]+14.281 [Lake Depth, m]+1.570 [Conductivity, μS/cm]–1.664 [Total Hardness, mg/lt]–4.583 [S-SO_4], r^2=0.909, n= 12, F=5.011, d.f.=8,4 with standard error of estimation = ±574.83 km^2 while [Lake Catchment] range in data = 0.8-5630 km^2.

Prediction of Secchi Disk Readings

The Secchi disk readings of the lakes showed good correlation with [Lake Depth], [pH], [Total Hardness], [S-SO_4], [pH], [Total-P], [Total-N] and [Lake Catchment] as follows:
[Secchi, m]=0.187 [Lake Depth, m]+0.001 [Lake Catchment, km^2]+1.272 [pH]–0.056 [Total Hardness, mg/lt]+0.045 [S-SO_4, μg/lt]–0.056 [Total-P, μg/lt]–0.003 [Total-N, μg/lt], r^2= 0.984, F=35.9, d.f.=7,4 with standard error of prediction = ±0.78 m while [Secchi] range in data = 0.4-10.1 m.

A less complicated model with sufficiently significant correlation may be the following: [Secchi, m] = –0.027 [Chl-a, mg/m^3]–0.002 [Total-N, μg/lt]+0.0146 [Total-P, μg/lt]+ 0.252 [Lake Depth, m] r^2=0.800, F=8,0, d.f.=4,8 with standard error of the estimation = ±2.0 m.

Prediction of Total Phosphorus

Total phosphorus seems well correlated with all parameters except [Lake Depth], [Chl-a] and [Total-N] as follows:
[Total-P, μg/lt]=0.504 [Lake Area, km^2]–9.561 [Secchi, m]+ 0.025 [Conductivity, μS/cm]+12.222 [pH]–0.502 [Total Hardness, mg/lt]+0.362 [S-SO_4 μg/lt]+0.010 [Lake Catchment, km^2], r^2=0.983, F=32.957, d.f.=7,4 with standard error of prediction = ±14.03μg/lt.

Prediction of Total Nitrogen

Total nitrogen correlates with all parameters together significantly well as follows:
[Total-N, μg/lt]=–3.289 [Lake Area, km^2]–117.119 [Secchi, m]+24.199 [Lake Depth, m]+0.612 [Conductivity, μS/cm]+ 168.799 [pH]–7.170 [Total Hardness, mg/lt]+4.790 [S-SO_4, μg/lt]–11.444 [Chl-a, mg/m^3]–5.321 [Total-P, μg/lt]+0.164 [Lake Catchment, km^2], r^2=0.992, F=12.27, d.f.=10,1 with standard error of prediction = ±69.602 μg/lt.

Prediction of Lake Conductivity

Lake conductivity correlates with all parameters together significantly well as follows:
[Conductivity, μS/cm]=5.198 [Lake Area, km^2]+174.057 [Secchi, m]–35.950 [Lake Depth, m]+1.495 [Total-N, μg/lt]–252,918 [pH]–10.745 [Total Hardness, mg/lt]–7.046 [S-SO_4, μg/lt]+17.908 [Chl-a, mg/m^3]+8.074 [Total-P, μg/lt]–0.240 [Lake Catchment, km^2], r^2=0.997, F=35.448, d.f.=10,1 with standard error of prediction = ±108.759 μS/cm.

Discussion

Studying the presented equations, it is evident that statistically the data may be correlated and predictions may be calculated with significant accuracy. The correlation coefficients vary between 0.6 to 0.99 and are considered sufficient compared to other similar reports (OECD 1982). In most cases, both equations provided are acceptable from the statistical point of view. However, even in those cases, lakes were removed from the data set (according to their residual error) in order to present these lakes that have even the slightest problem in fitting with the others and calculate the final equation with the highest accuracy possible. Between [Total Phosphorus, μg/lt] and [Total Nitrogen, μg/lt], the former was found to correlate better with the rest of parameters as [N/P ratio], [Chlorophyll-a, mg/m^3] and [Secchi disk reading, m] while the relation between them shows very low correlation ($r < 0.5$). However, these two parameters, are involved in the predictions of all parameters using multiple regressions depicting the synergistic influence of these nutrients to the lake condition. Total phosphorus is shown to correlate well with [Chlorophyll-a, mg/m^3] and [Secchi disk reading, m] depicting the major influence of the former to the lake productivity. Finally, lake morphometry, through MEI indices (calculated from total nitrogen, total phosphorus and conductivity), correlates significantly with the lake morphological characteristics, indicating that the surrounding area and lake dimensions contribute significantly to the annual profiles of nitrogen and phosphorus as well as the final nutrient condition of the lake which can be indirectly studied from conductivity measurements. The [Total Hardness, mg/lt] is evident that it is influenced mainly by [S-SO_4, μg/lt] rather than other salts as can be seen from the correlation with [Conductivity, μS/cm].

From the simple expression between parameters that were presented in this study, it was clearly seen that among the 24 lakes examined only Vegoritis, Kerkini, Lysimachia, Vistonis, Koronia, Megali Prespa, Petron and Chimaditis in combinations could not be incorporated in various models and were removed from the data. In particular (numbers in bracket from Fig 1), Kerkini [24], Vegoritis [6] and Lysimachia [3] cannot be introduced in the models that involve [Total Nitrogen, μg/lt] with [N/P], [Total Phosphorus, μg/lt] and [Chlorophyll-a, mg/m^3]. This deviation can be explained from the value of [Total Nitrogen, μg/lt] (Tab 1) which are the highest among the others. On the other hand, these values may be influenced by the low depths of Kerkini and Lysimachia while for Vegoritis, they may influenced by the fact that it belongs to a large group of 7 adjacent lakes that are both interconnected and share the same catchment areas and therefor, nitrogen concentrations cannot be directly predicted by simple expressions rather than complicated ones incorporating more than one parameters.

Lakes Megali Prespsa [8], Vistonis [16] and Koronia [15] cannot be fitted in the model that describe the relationship between [N/P] and [Total Phosphorus, μg/lt]. For Megali Prespa, it is very difficult to explain any kind of deviations because this lake is shared by 3 countries (Greece, FYROM[1] and Albania) and therefore, knowledge of the shoreline exploitation does not exist. For Koronia lake, it should be noted that it is located in an industrial area near Thessaloniki (Fig 1) and therefore, nutrients as nitrogen and especially phosphorus may fluctuate sharply throughout the year and give these overall results. Lake Vistonis [16] is located adjacent to the seashore and is connected with the sea via man-made channels and therefore, exhibits both lake and lagoon characteristics. These interferences affect mainly the nitrogen and phosphorus nutrients and their relationship [N/P] which explains these deviations.

Finally for lakes Petron [11], Vistonis [16], Koronia [15] and Kerkini [24] the MEI (Conductivity/depth) and MEI [Total-P/depth] show low correlation with [Lake Area, km^2]. From Tab 1 can be seen that these lakes exhibit much different areas but also have similar depths (2–4 m) and volumes ($<200\ 10^6\ m^3$). Therefore, such deviation between MEI and lake area may be attributed to the catchment area exploitation (nutrient inflow) rather than lake morphology.

The provided multiple regression equations with their significant accuracy help the use of all parameters without allowing these problems to interfere, and therefore they are more accurate for prediction and lake modelling.

[1] Makedone (not acknowledged by Greece)

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