RELATIONSHIPS BETWEEN LAKE MORPHOMETRY, WATER QUALITY, AND AQUATIC MACROPHYTES, IN GREEK LAKES

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ABSTRACT

In the current study, the relationships between lake morphological characteristics, water chemistry parameters and aquatic macrophyte data of nineteen lakes of Greece were investigated. Statistical and ordination analysis was performed in order to distinguish possible correlations between lake morphology features, key water quality parameters and hydrophyte distribution. Water quality and hydrophyte data for eleven out of nineteen lakes were obtained from field surveys carried out the last five years. Water quality parameters, lake morphology and hydrophyte data published in scientific papers and reports were used as well. Several lake morphology parameters such as average depth, maximum depth, relative depth, surface area, lake catchment area, volume, Schindler's ratio and morphoedaphic index (MEI) were included in the statistical analysis. The statistical assessment of our data included Pearson correlations between the lake morphology and water quality parameters, Principal component analysis (PCA), in order to distinguish the key morphological parameters and Redundancy Analysis (RDA) in order to estimate possible associations between the hydrophyte distribution and the morphology of the lakes. The results revealed several significant correlations between the physicochemical and geomorphological variables. Most notable correlations include those between Schindler's ratio, Morphoedaphic index, Secchi depth, conductivity and chlorophyll-a. The results of PCA indicated lake volume and altitude as key variables with the strongest influence on the lake discrimination, followed by Schindler's ratio and MEI. The RDA results revealed a possible association of several hydrophyte species in shallower lakes with greater values of MEI. However, the RDA results between aquatic macrophyte and physicochemical data did not reveal any pattern of macrophyte species distribution among the studied lakes. According to our results, Schindler's ratio and relative depth are the most important morphological parameters indicating the combined influence of catchment and lake morphometry on the water quality. The MEI was associated with key physicochemical parameters and therefore could provide an additional simple and efficient tool of classification of Greek lakes in the frame of establishing a new typology.

KEYWORDS: Greek lakes, morphological parameters, water quality, water chemistry, aquatic macrophytes

1 INTRODUCTION

The morphology of lakes is one of the most important factors controlling the trophic status, physicochemistry, productivity and distribution of aquatic organisms. Lake area, lake volume, maximum and average depth are parameters that are related with nutrient cycling and water chemistry. Deeper lakes are characterized by a thicker surface layer which determines the photosynthetically available irradiance, the efficiency of nutrient cycling and the vertical distribution of organisms [1]. On the other hand smaller and shallow lakes are strongly affected by wind-induced sediment re-suspension which results to significant changes on their water chemistry and geochemical cycles. Mean depth is an important factor for controlling productivity while the size of lake is related with the depth of thermo cline [2]. Moreover the shape of the lake can be associated with bottom dynamic conditions [3]. The slope of littoral zone has a great influence on the biomass and the distribution of submerged macrophyte communities [4]. A gently sloped littoral allows the deposition of fine materials and can modulate the wave action in favor of establishment of aquatic macrophytes.

Lake Catchment is also an important element for determining the water chemistry as it affects the nutrient inputs. There are several studies demonstrating the relations between the different land uses of catchment area and water quality [5] while other studies have shown the influence of hydrology and geology in catchment on the nutrient transport capacity [6].

Morphology of lakes is used widely nowadays in order to establish a typology of European water bodies according to the requirements of the European Water Framework Directive 2000/60/EC. Typology of the lake ecosystems is based on altitude, surface area and average depth

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as obligatory typology descriptors. However, due to the complex geomorphology of Greece, uneven distribution of precipitation and different regional demands for irrigation and drinking water [7-9], the implementation of a lake typology by using only obligatory descriptors might be ineffective for Greek lakes.

Therefore, the aim of the current paper is to examine the possibility of using other morphological descriptors by investigating the relationship of these parameters and physicochemical criteria of water quality and aquatic macrophyte parameters as well. Apart from lake area, lake volume, average and maximum depth other parameters such as average depth to maximum depth ratio, relative depth, development of volume, Schindler's ratio and Morphoedaphic index were used in our analysis. These morphological parameters might provide a more detailed description of the influences of morphology on water quality.

2 MATERIALS AND METHODS

2.1. Study area

The nineteen studied lakes are located mostly at the western part of Greece (Figure 1) at latitude 20°47′- 23°20′ and longitude 38°34′- 41°21′ (Table 1). The elevation of the studied lakes varies from sea level to 853 m and the surface area varies from 0.5 km^2 for the smallest one (lake Zirou) to 266 km^2 (Lake Megali Prespa) (Table 1). Average and maximum depth, lake volume and catchment area are also presented in Table 1.

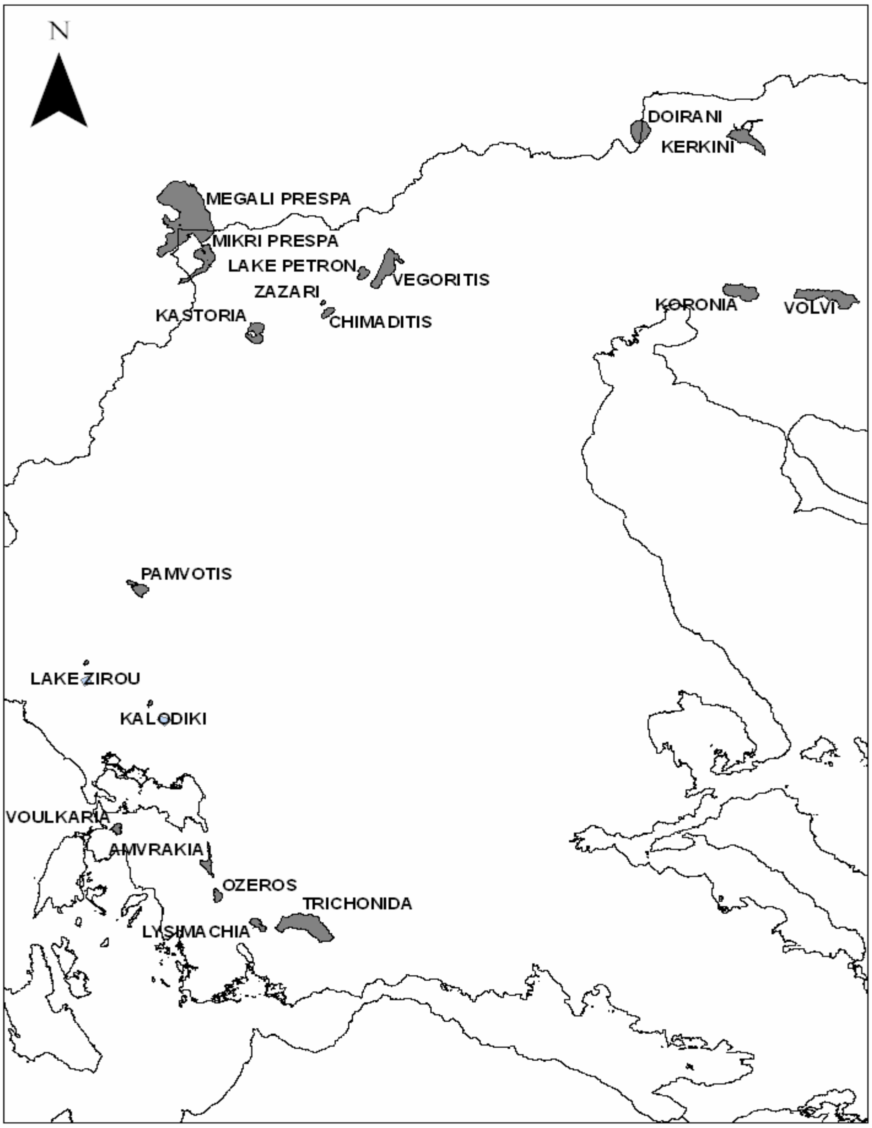

FIGURE 1 - Location of the studied lakes in NW Greece

TABLE 1 - Geographic location, altitude, and morphological descriptors of the studied lakes

Lake name	Latitude	Longitude	Altitude (m a.s.l)	Surface area (km^2)	Mean depth (m)	Max depth (m)	Volume (X 10^6 m^3)	Catchment area (km^2)
Lysimachia	21°28′	38°34′	16	13.5	3.9	9	53	246
Trichonida	21°28′	38°34′	18	96.5	30.3	58	2927	421
Ozeros	21°13′	38°39′	22	9.4	3.1	6.1	33.5	72.4
Amvrakia	21°11′	38°45′	28	14.5	30	53	278	101.4
Voulkaria	20°50′	38°52′	0	10.8	1.6	3	16	73.2
Zirou	20°50′	39°14′	49	0.5	15	70	7.5	10
Kalodiki	20°47′	39°31′	158	7.9	1.5	4.5	12	69
Pamvotis	20°53′	39°40′	470	22.0	5.5	11	120	330
Kastoria	21°18′	40°30′	629	30.0	4.8	9.1	144	304
Chimaditida	21°33′	40°37′	593	10.8	1	2.5	15	155
Zazari	21°33′	40°37′	602	2.0	1.7	5.5	3.4	228
Koronia	23°20′	40°41′	75	30	1	1	30	730.6
Volvi	23°20′	40°41′	37	68.6	13.5	23.5	940	1247
Vegoritis	21°45′	40°45′	524	53.0	28.9	70	1530	1853
Petron	21°45′	40°45′	527	14.4	2.6	5	37	114
Mikri Prespa	21°05′	40°45′	853	53.0	4.1	8.4	221	260
Megali Prespa	21°01′	40°46′	852	266.0	30	55	6000	2218
Doirani	22°47′	41°21′	150	41.5	5.5	7	200	265
Kerkini	23°07′	41°19′	34	70	3.1	6.5	170	-

TABLE 2 - Physicochemical parameters and literature sources used for each lake.

Lake	TP (mg/L)	Chl-a (μg/L)	DIN (mg/L)	Cond. (μS/cm)	pH	Secchi depth (m)	Source
Lysimachia	0.151	3.9	1.045	332	7.8	0.8	[10]
Trichonida	0.146	1.9	0.421	320	8.1	5	[10]
Ozeros	0.04	n/a	0.45	450	8	0.6	[11]
Amvrakia	0.037	1	0.07	950	7.5	5	[11]
Voulkaria	0.08	n/a	0.505	1800	7.8	n/a	[11]
Zirou	0.058	1.2	0.359	333	8.18	6	[12]
Kalodiki	0.05	12.2	0.153	321	7.95	0.83	[13]
Pamvotis	0.14	19	0.303	353	8.21	0.4	[14]
Kastoria	0.201	15.9	0.267	325	8	0.43	[10]
Chimaditida	0.04	7	0.3	815	8	0.6	[11]
Zazari	0.094	40	1	177	7.5	0.3	[10]
Koronia	0.362	64	0.209	5720	8.9	0.3	[11], [15]
Volvi	0.155	7.6	0.126	1040	8.5	0.7	[11], [15]
Vegoritis	0.202	3.4	0.467	718	7.6	5	[10]
Petron	0.115	22.6	0.412	804	6.9	0.4	[10]
Mikri Prespa	0.252	11.6	0.363	293	7.8	0.77	[10]
Megali Prespa	0.252	4.2	0.348	220	8.5	5	[10]
Doirani	0.034	2.8	0.1	450	8	0.6	[11], [15]
Kerkini	0.1	0.02	0.422	500	8.3	0.7	[16]

Hydrophyte presence/ absence data used in our analysis consist of a total of twenty one taxa where seventeen taxa are documented at species level and four taxa are represented by the genera of *Chara, Ceratophyllum, Myriophyllum* and *Najas.*

2.2. Water quality and aquatic macrophytes

The collection of information used in the current study is based mostly on field measurements and samplings carried out during 2004 and 2008 and literature sources including research projects and national monitoring programs (Table 2). Water quality parameters include pH, conductivity, total phosphorus, dissolved inorganic nitrogen, chlorophyll-a and secchi depth (Table 2).

2.3. Lake Morphometry

Lake Morphometry parameters, such as average and maximum depth, lake area and volume and catchment area, were obtained by literature sources. Other morphology parameters such as Relative Depth and Development of Volume were calculated. Additionally Schindler's ratio and the Morphoedaphic Index were calculated. Specifically, Relative depth was calculated according to [17] as:

$$Zr = \frac{50 \times Zmean \times \sqrt{\pi}}{\sqrt{Area}}$$

Development of volume (Dv) as a measure of the departure of the shape of the lake from that of a cone [18] was calculated according to Hutchinson [19] as:

$$Dv = \frac{3 \times Zmean}{Z\max}$$

Schindler's ratio was used as a measure of the intensity of the catchment area impact upon the lake [20] and is expressed as the ratio of catchment area plus surface and lake volume.

$$\text{Schindler's ratio} = \frac{\text{Catchment area} + \text{Lake area}}{\text{Lake volume}}$$

Morphoedaphic index (MEI) was originally used as a tool for estimating fish biomass in lakes [21]. Later, MEI was used as a predictor of phosphorus concentration in lakes [22] and now has a wide use of applications in limnology. For the purposes of this research MEI was calculated by using conductivity values:

$$MEIconductiviy = \frac{\text{conductivity } (\mu S \times cm^{-1})}{\text{Mean depth (m)}}$$

2.4. Statistical analysis

Statistical analysis included Pearson's correlations between the set of variables and a principal component analysis (PCA) run with the CANOCO 4.5 software. RDA analysis was also run between hydrophyte and lake morphometry data in order to distinguish spatial patterns of aquatic macrophytes among the lakes and relationships between aquatic macrophytes and lake morphometry. The number of the morphometry parameters included in the analysis was reduced after a forward selection and the statistical significance of each variable was judged by a Monte-Carlo permutation test.

3 RESULTS

3.1. Relationships between parameters

Regarding the results of correlation analysis, total phosphorus was found to present significant positive correlations with catchment area (Figure 2), lake surface area, development of volume and MEI as well (Table 3). Chlorophyll-a concentration was correlated negatively with mean, maximum and secchi depth and positively with Schindler's ratio and the value of Morphoedaphic index (Figure 2). These results indicate that higher concentration of chlorophyll-*a* is expected to be found in lakes that are more susceptible to the influences of the catchment and in lakes with higher capacity of productivity according to the MEI. Other notable correlations include a positive correlation between the concentration of DIN and Schindler's ratio and between chlorophyll-a concentration and conductivity as well.

3.2. Ordination analysis

The three components of the PCA explain the 88.7% of the data variance. According to the PCA, lake volume and altitude seem to be the most influential parameters on the lake discrimination. Although PCA is not a p-value driven technique and it doesn't require any assumptions about normality distribution, the PCA plot reveals a gradient of increasing lake volume along the first component from the left towards the right and a gradient of increasing altitude along the second component from the top towards the bottom part (Figure 3). Therefore the largest "lowland" water bodies are distinguished on the top right quadrant of the plot while the smallest "highland" water bodies, with the exception of the lake Koronia, are sited on the bottom left quadrant. Also a grouping of the lakes Kalodiki, Zazari, Petron, Koronia and Chimaditida is apparent on the bottom left part which seems to be associated with the vectors of MEI and Schindler's ratio (Figure 3).

3.3. Relationships between aquatic macrophytes, lake morphology and water quality

The results of the RDA between the lake morphology and hydrophytes showed that the first 3 axes explain the 32.3% of variance of species data and the 64.4% of species-environment relation. Altitude presents a strong correlation with axis 1 and catchment area with axis 2. According to the results large catchments at high altitude are characterized by a larger number of hydrophytes (Figure 4).

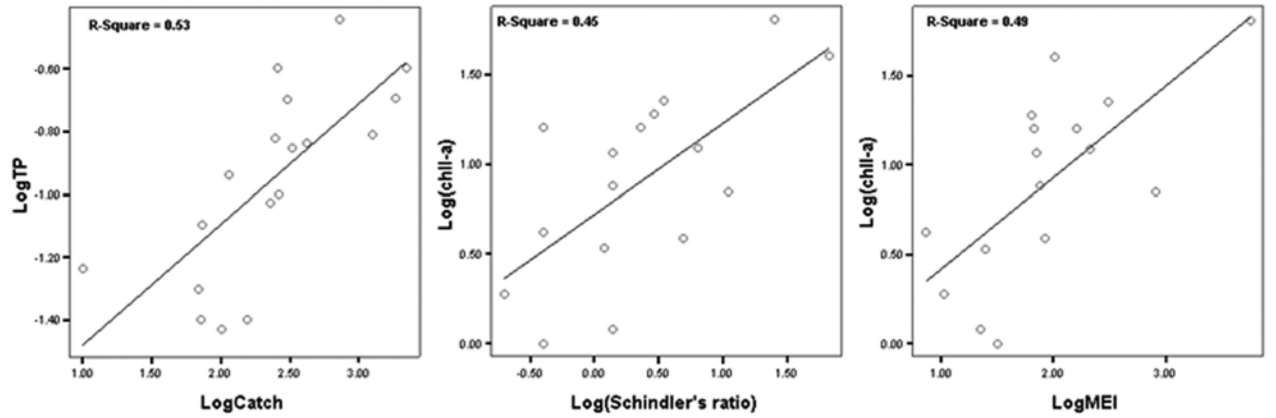

FIGURE 2 - Scatter plot between Log of TP and Log of Catchment area, Log of Chl-a and Log of Schindler's ratio and Log of Chl-a and Log of MEI.

TABLE 3 - Pearson correlations between morphological and water quality parameters (* =significant at p<0.05, **= significant at p<0.01, ns=non significant)

	Surface	Volume	Catchment	Zmax	Zmean	Zrel	Zmean/ Zmax	Schindler's ratio	MEI	Dv	TP	DIN	Chl-a	Secchi	Cond.	pH
Surface	-	0.948**	0.79**	ns	0.567*	ns	ns	ns	ns	ns	0.471*	ns	ns	ns	ns	ns
Volume		-	0.773**	0.565*	0.712**	ns	ns	ns	ns	ns	ns	ns	ns	0.562*	ns	ns
Catchment			-	0.483*	0.586*	ns	ns	ns	ns	ns	0.568*	ns	ns	ns	ns	ns
Zmax				-	0.917**	0.686**	ns	ns	ns	ns	ns	ns	-0.564*	0.976**	ns	ns
Zmean					-	ns	ns	ns	ns	ns	ns	ns	-0.545*	0.894**	ns	ns
Zrel						-	0.973**	ns	ns	ns	ns	ns	ns	0.693**	ns	ns
Zmean /Zmax							-	ns	0.68**	1**	0.559*	ns	0.579*	ns	0.719**	ns
Schindler's ratio								-	ns	ns	ns	0.467*	0.662**	ns	ns	ns
MEI									-	0.684**	0.545*	ns	0.794**	ns	0.977**	0.466*
Dv										-	0.56*	ns	0.579*	ns	0.724**	ns
TP											-	ns	ns	ns	0.524*	0.469*
DIN												-	ns	ns	ns	ns
Chl-a													-	-0.556*	0.742**	ns
Secchi														-	ns	ns
Conductivity															-	ns
pH																-

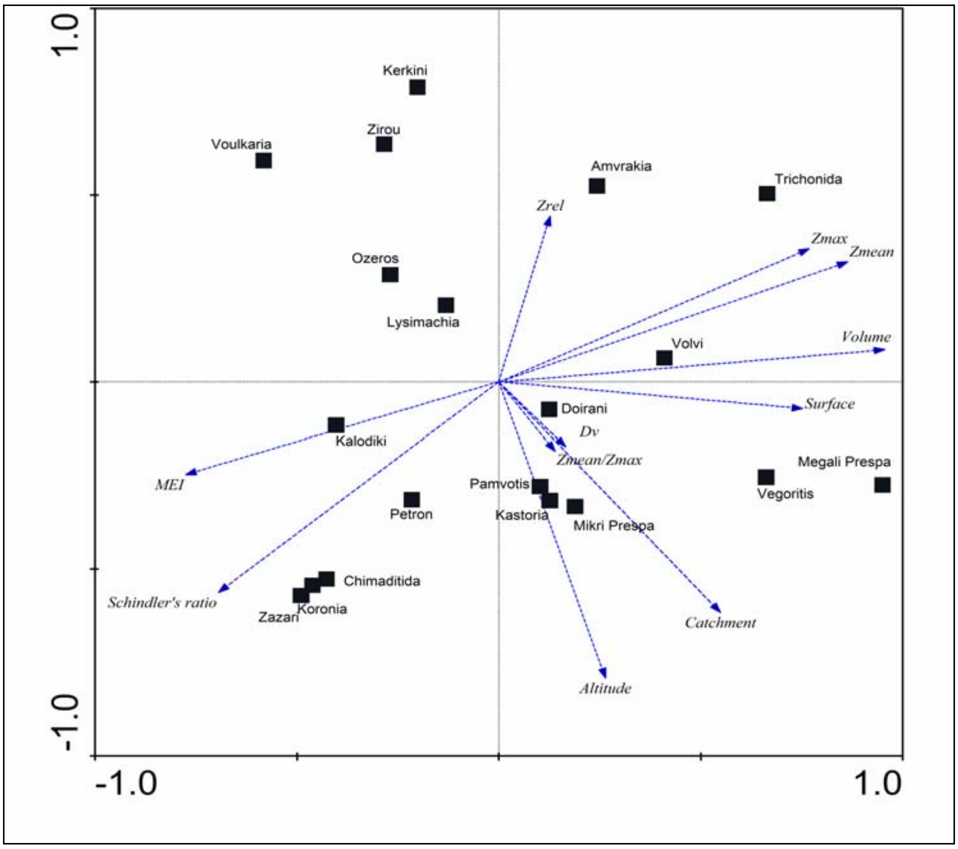

FIGURE 3 - PCA ordination plot showing the positioning of lakes (squares) along environmental and morphological parameters (vectors).

These lakes are also characterized by low relative depth which could be interpreted as a preference of hydrophytes to large and shallow lakes which happen to occur in higher altitude. The plot graph reveals an association between the average depth and the hydrophytes *Potamogeton perfoliatus* and *Vallisneria spiralis*, which suggest that these two species actually occur in deeper lakes in contrast with other hydrophytes.

According to the results of the RDA between water quality data and hydrophyte data, the first 3 axes explain the 29.4% of variance of species data and the 80.7% of species-environment relation. Total phosphorus, Secchi depth, and Chl-a shows the strongest correlations with axes 1 and 2. However, there doesn't seem any apparent pattern of hydrophyte distribution along the key water quality parameters (Figure 5).

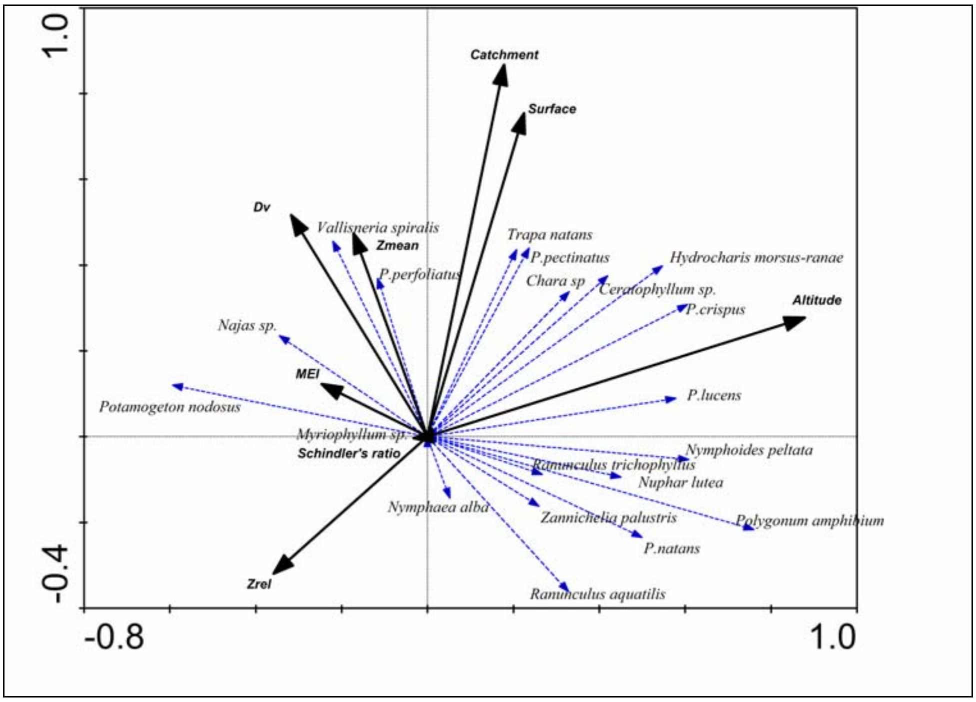

FIGURE 4 - RDA ordination bi-plot revealing the relationships between morphological parameters (bold vectors) and aquatic macrophytes (dashed vectors).

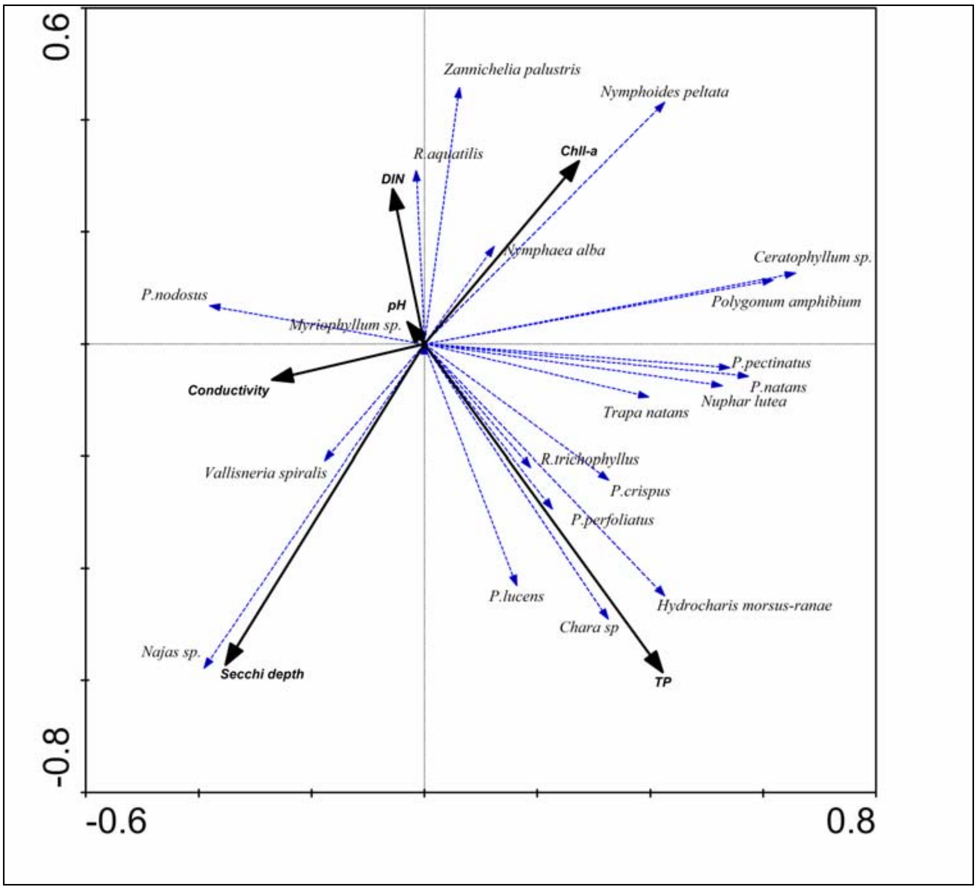

FIGURE 5 - RDA ordination bi-plot revealing the relationships between water quality parameters (bold vectors) and aquatic macrophytes (dashed vectors).

4 DISCUSSION

According to our results, lake area and lake volume are correlated with catchment area which comes as a result of larger and deeper lakes being contained in larger catchments. Total phosphorus concentration presented a strong positive correlation with catchment area which could be interpreted as strong influence of catchment area on the phosphorus inputs in the lake. Although watershed size does not affect nutrient transport directly [5] it may alter the extent of land use impacts by modifying the spatial scale at which land use contributes to water quality. Therefore, in smaller catchments the land use near the shore is more important than in larger catchments where the whole catchment affects the nutrient loading [23]. Chlorophyll-a concentration was negatively correlated with mean, maximum and Secchi depth which clearly reflect the fact that deeper lakes are characterized by lower chlorophyll-a concentration. Obviously, deeper lakes exhibit greater resistance in nutrient mixing that could benefit phytoplankton growth and it seems to be a solid explanation of the above results. Moreover, relative depth is a parameter that can indicate the resistance to mixing and our results showed a weak negative correlation with chlorophyll-a concentration ($p=0.056$).

Schindler's ratio was correlated positively with chlorophyll-a and negatively with Secchi depth reflecting the influence and importance of catchment area on the lakes. It was also correlated positively with the MEI, probably indicating the influence of catchment area on capacity of productivity of lakes. MEI exhibited several correlations with other parameters as well like chlorophyll-a, pH, dissolved oxygen, Secchi depth, catchment area, relative depth and Schindler's ratio. Correlations between phytoplankton and MEI have been noted by former studies [24] and it seems that in our case can be used to describe effectively the trophic state. It is also notable the fact that it showed a strong negative correlation with relative depth acknowledging the influence of a great mixing resistance on the productivity of the lake. MEI has been used widely as a descriptor of trophic state since it has been significantly correlated with fish biomass [21, 25] and total phosphorus concentration [22, 26].

More or less the above conclusions can be interpreted according to the results of PCA as well. Most lakes showed a preference towards to the Schindler's ratio, MEI and chlorophyll-a vectors while the deepest lakes only were positioned along the maximum depth, surface area and lake volume vectors. Only two lakes were associated positively with relative depth emphasizing the fact most lakes are characterized by small relative depth which represents a greater susceptibility to mixing effects.

Overall, we can postulate that catchment influence and relative depth are quite important factors regarding their effects on lakes' water chemistry and quality. Most probably the nutrient inputs which are associated with the size of the catchment area and the mixing procedures that are determined by the shape of the lake seem to affect the trophic state. Therefore, solely the maximum depth of the lake or the surface area of the lake cannot be efficient descriptors for Greek lakes, as many Greek lakes are characterized by large lake surface and a quite large average and maximum depth but with rather small relative depth which enhance the effect of mixing nutrients. On the other hand the largest Greek lakes are characterized by larger relative depth which makes them resistant to mixing effects. These results seem to come in line with the recent results of Nõges [17] who investigated the effect of lake's morphometry on water chemistry assessing a large dataset of 1337 European lakes. Those results revealed that larger catchment area with respect to the depth of the lake has stronger influence on water quality and specifically on transparency, concentration of chlorophyll-a and nutrients. Moreover was found that the morphometry of larger and shallower lakes has a stronger influence on their water quality.

Regarding the possible relationships between morphology and aquatic macrophytes, it can be postulated according to our results that lake area and catchment size did not seem to have some kind of effect. The Schindler's ratio, MEI, volume development and the altitude of the lakes were the parameters which presented strong relations with the two axes of RDA and seemed to associate with most macrophyte species. Development of volume is a morphometric parameter that basically measures to what degree the volume of a lake deviates from the volume of a cone [18, 19]. Development of volume presents higher values in shallow lakes with flat bottoms. Therefore association of many aquatic macrophyte species with the development of volume parameter could be interpreted as a preference of macrophytes for shallow lakes with gently sloped littoral. On the other hand the larger and deeper lakes (Megali Prespa, Trichonis, Vegoritis and Zirou) presented associations with few only macrophytes. Specifically lake Zirou, which exhibited the largest relative depth, seemed to relate with *Najas marina, Najas minor* and *Myriophyllum alterniflorum*. Most of the macrophyte species that seem to be related with shallower lakes (M*yriophyllum spicatum, Ceratophyllum demersum. Potamogeton pectinatus* etc.), are widely common and abundant in Greek eutrophic lakes [27] implying that these lakes apart from common morphological features share also similar trophic status. On the contrary, as far as the relationships between hydrophytes and water quality parameters are concerned, the results of the current study did not reveal any specific pattern. Most lakes in Greece exhibit high total phosphorus and high chlorophyll-a concentration due to eutrophic conditions. Moreover, in warmer climates, the high temperature combined with large water level decrease, enhance the eutrophication effects due to increased internal loading of phosphorus and cyanobacteria dominance [28, 29]. Phytoplankton becomes dominant in warm lakes even in low nutrient concentrations [29]. Under these conditions, it is postulated that in warmer lakes the effect of aquatic macrophytes on water quality is considered to be very low.

5 CONCLUSIONS

Our analysis suggests that MEI and Schindler's ratio can be used in order to provide an efficient description of water quality. Schindler's ratio is a measure of estimation of the susceptibility to the influences of catchment area but it was also demonstrated that was correlated with water quality parameters such as secchi depth and chlorophyll-a. MEI was also correlated with secchi depth and chlorophyll-a as well, and therefore further research regarding possible relations of MEI and other limnological parameters could reveal an effective use as a predictor of water quality and trophic state.

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