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Classification of the ecological status of volcanic lakes in Central Italy

Fiorenza G. MARGARITORA*, Marcello BAZZANTI, Ornella FERRARA, Luciana MASTRANTUONO, Marco SEMINARA and Daria VAGAGGINI

Dip. di Biologia Animale e dell'Uomo, Università degli Studi di Roma La Sapienza, V.le dell'Università 32, 00185 Rome, Italy
*e-mail corresponding author: fiorenza.margaritora@uniroma1.it

ABSTRACT

A synthesis is made of biological data collected in the last three decades on five volcanic lakes in Central Italy with the aim of evaluating their environmental status by means of biological parameters related to zooplankton, littoral and profundal zoobenthos frequently used to detect water quality changes in lakes. A number of bioindicators and bioindices were selected for this purpose, as far as possible following an integrated approach using information drawn from physical and chemical variables. Our results allowed the lakes to be classified according to their biological quality level, which proved to be in good agreement with physical and chemical diagnoses. Lake Bracciano exhibited the best environmental quality, due to the presence of a ring waste water collecting system, to its large size and depth, and to its strong hydrodynamism. Lake Martignano followed, with some symptoms of stress in the hypolimnion due to a marked summer deoxygenation. Oxygen depletion in the profundal characterized also Lake Vico, which showed a mesotrophic condition in the sixties, and 20 years later now shows clear signs of increased trophy (meso-eutrophy). Lake Albano seemed meso-eutrophic with total absence of fauna below a depth of 120 m due to a meromictic status. Finally Lake Nemi, exposed to domestic wastes in the 70s, suffered a heavy eutrophication with dramatic algal blooms and fish kills. Following the diversion of discharges that occurred in the early 90s, today this lake is characterized by the partial improvement of many ecological features. The need for integration between physical and chemical analyses and biological data in order to obtain a reliable evaluation of lake environmental quality is stressed, especially as far as routine implementation in managing and recovery procedures is concerned.

Key words: volcanic lakes, zooplankton, littoral zoobenthos, profundal macrobenthos, biological indicators, ecological diagnosis

1. INTRODUCTION

Volcanic lakes constitute the majority of natural lakes in Central Italy. They are generally characterized by reduced watershed size, great depth and hypolimnetic zone wider than the epilimnetic one (for detailed information see Margaritora 1992). They also generally show long water renewal times (Tab. 1) which make them very sensitive to deterioration, with a clear tendency to summer-autumn hypolimnetic anoxia and sometimes to meromixis. In the last century these lakes were progressively exposed to various phenomena of water quality deterioration due to a whole range of factors involving the urbanization of their watershed area, water captation for agricultural purposes and increasing recreational use of the lakes.

In the last three decades, the limnological group of "La Sapienza" University of Rome carried out several studies on the physical and chemical aspects and on littoral and eulimnetic zooplankton, littoral zoobenthos associated with both sand and submerged macrophytes, and sublittoral and profundal zoobenthos in the volcanic lakes of the Latium Region. A large amount of biological information has been collected on the composition and structure of invertebrates to constitute a reference base for a comparison aimed to allow an integrated evaluation of the trophic state of lake ecosystems, to identify trends towards conditions of deterioration or recovery, and to suggest some monitoring guidelines to enhance policies for the conservation and management of the lakes. A synthesis of these data is provided with the aim of evaluating the environmental status of the lakes studied by means of an integrated approach using biological parameters referring to zooplankton, littoral zoobenthos and profundal macrobenthos, which are frequently used to detect water quality changes in lakes.

2. USE OF PLANKTONIC AND BENTHIC COMMUNITIES IN LAKE MONITORING

It is widely accepted that the investigation of biological communities plays a basic role in a correct evaluation of environmental quality in lake ecosystems (cf. Rosenberg & Resh 1993; Ravera 1996), because they allow the combined effects in time and space of various stresses influencing water and sediments to be detected. So, if traditional physical and chemical analyses constitute the fundamental reference for an exact identification and quantification of pollutants, the parallel use of biological and abiotic approaches represents the most suitable way to the correct environmental diagnosis, and provide a complete picture of lacustrine health.

As regards the zooplankton, perturbations changing the physical and chemical environment (i.e., increased nutrient load, conductivity fluctuation, dissolved oxygen depletion, etc.) because of human activities and/or natural stress may cause zooplankton population changes. The relative abundance and dominance of some species within the community can be a sensitive indicator in

Tab. 1. Main morphometric characteristics of the Latium volcanic lakes (revised from Gaggino *et al*. 1985; * Calenda *et al*. 1992; ** Ciccacci *et al*. 1987).

	altitude (m a.s.l.)	area (km^2)	volume (m^3 10^6)	mean depth (m)	max. depth (m)	t_w (years)
Albano	293	6.0	464	77	175	47.6*
Bracciano	164	57.0	5050	88.6	165	137
Bolsena	305	113.6	9200	81	151	121
Martignano	207	2.4	72.3	29.64	60	29.6
Monterosi	239	0.3	1.3	4.3	6.2	3.9
Nemi	316	1.6	26.5	16.5	27.5	15**
Vico	510	12.1	260.6	21.6	48.5	17

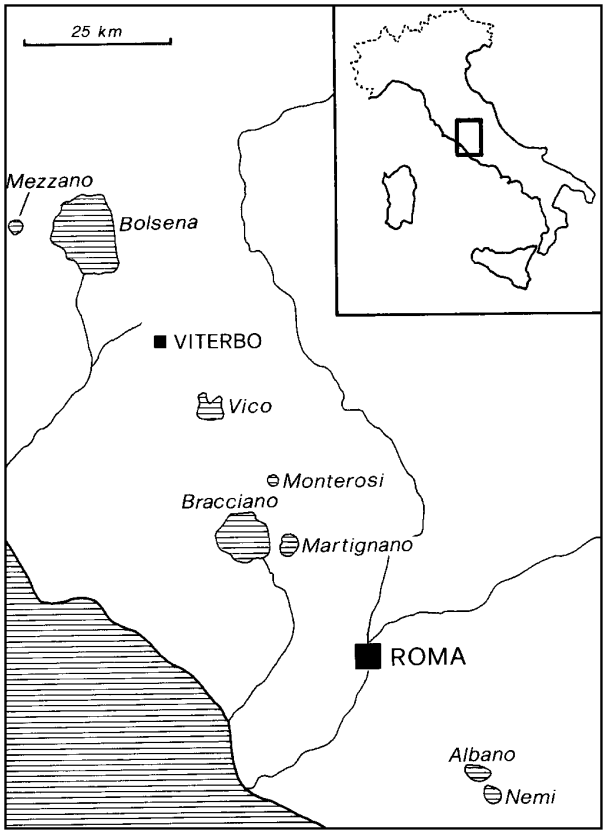

Fig. 1. Map of Central Italy volcanic lakes.

waters displaying different trophic conditions. Changes in the relative proportions of the major groups of zooplankton as well (Cladocera, Copepoda, Rotatoria) appear to be useful indication of trophic status. Calanoid copepods are relatively more abundant in oligomesotrophic waters than rotifers and cyclopoid copepods, which are generally better adapted to waters having higher trophic levels (Andronikova & Smel'skaia 1994; Karjalainen *et al*. 1999). Therefore, zooplankton community characteristics can have a high information potential in monitoring studies as a bioindicator tool.

Over time the littoral zone has increased in importance for the purpose of water quality evaluation in lakes especially because it represents an area subject to extensive morphological modifications deriving from human activities, mainly of the recreational type. Several recent investigations (Irvine *et al*. 1989; Hansson *et al*. 1998; Hough *et al*. 1989; James *et al*. 2000) have extensively demonstrated that the presence of a well developed system of zoobenthos-aquatic vegetation plays a basic role in the maintenance of good water quality due to its influence on the food chain and on the recycling of nutrients, partly stored in the macrophyte tissues and continuously recycled by the grazing activity on the periphyton of some benthic invertebrates (mainly microcrustaceans, gastropods and some others). Moreover, the littoral community, owing to its high species richness, represents a fundamental resource of biodiversity, which gives the lakes a degree of resilience increasing their recovery capability.

Tab. 2. Annual mean of total P values (as range in the water column) and minimum hypolimnetic dissolved oxygen (D.O.) in the studied lakes.

Lakes	Bracciano	Martignano	Vico	Albano	Nemi
Total P (μg l^{-1})	5-22	9-25	14-35	69-263	27-1137
D.O. (mg l^{-1})	3.1	0.7	0.2	0	0
Trophic evaluation	oligo-mesotrophy	oligo-mesotrophy	mesotrophy	meso-eutrophy	eutro-hypereutrophy

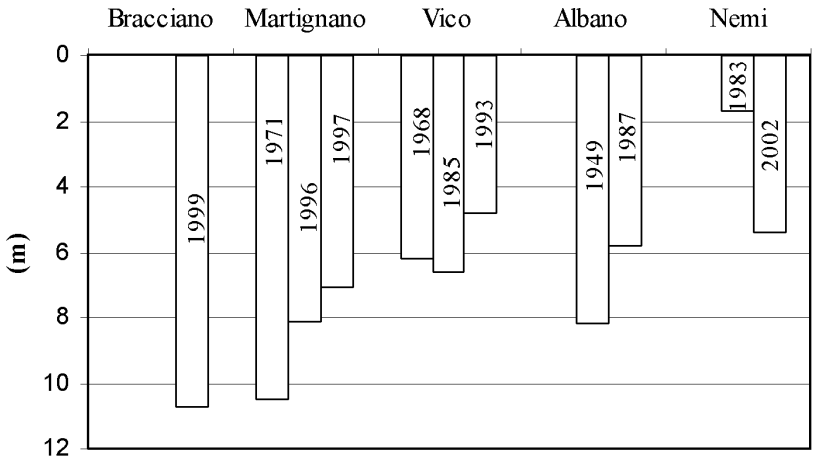

Fig. 2. Mean annual transparency in the five studied lakes, referred to all the available study periods.

The profundal benthic zone acts as a fundamental source of environmental information because the sediments constitute the main level of both accumulation of several contaminants and exchanges of them between bottom and overlying waters. Consequently the organisms living in the profundal zone can provide an integrated synthesis of these disturbance factors and, therefore, a complete picture of quality conditions of both sediments and overlying waters in a lake (Brinkhurst 1974; Rosenberg & Resh 1993). Environmental stress produce severe changes in the natural parameters of a lake, and often these effects can be well synthesized by the seasonal dynamics and the depth distribution of benthic organisms (Bazzanti & Seminara 1987a; Bazzanti *et al*. 1993, 2001). Moreover, biological monitoring studies on profundal benthic macroinvertebrates can reveal short and long-term changes in ecological quality of lakes involving both worsening or recovery action towards the original conditions (Bazzanti & Seminara 1987b; Schloesser *et al*. 1995; Lang & Lods-Crozet 1997).

At present, several bioindices and bioindicators belonging to all three communities are widely utilized and have proved to have a good reliability in many situations, as demonstrated by their global diffusion. In our opinion, the community parameters contributing most to the evaluation of environmental quality are: species richness, the presence and abundance of bioindicators, the Shannon diversity index and some other indices based on the numerical ratio between taxa.

3. STUDY AREA AND METHODS

The lakes studied (Bracciano, Martignano, Vico, Albano, Nemi) are located close to Rome (Fig. 1), and their main features are shown in table 1. For each community and field study the samples were collected over a period of at least one year on a monthly or bimonthly basis, in several stations chosen according to the morphological characteristics of each lake and possible anthropogenic impact.

Some physical and chemical parameters commonly adopted in the evaluation of the lake trophic level (OECD 1982) are reported in table 2. Among these, mean values of transparency were plotted in figure 2 for enhanced comparison, as they were available for each lake for more than one study period. Conversely, chlorophyll-*a* concentrations were not available for all the lakes and/or for all seasons, so this parameter was not considered in this paper.

From these data there emerged a first trophic classification in which Lake Bracciano showed the best environmental conditions whereas, at the opposite end, Lake Nemi presented a strongly altered situation clearly exceeding all limits of trophic classification. Lake Martignano, Vico and Albano trophy levels were situated among these extremes, gradually shifting from the former to the latter.

For analytical information on study sites, materials, methods and detailed descriptions of the indices adopted

Tab. 3. Zooplankton community parameters utilized in the quality evaluation of the studied lakes. ^{P} = pelagic zone; ^{L} = littoral zone; --- = not calculated. Ro/Cla/Cop = Rotatoria/Cladocera/Copepoda ratio.

Lakes	Bracciano	Martignano	Vico	Albano	Nemi
Number of species	24 ^{P} – 48 ^{L}	26 ^{P} – 24 ^{L}	16 ^{P}	17 ^{P} – 18 ^{L}	19 ^{P}
Shannon's index (range)	0.93-3.13 ^{P}	0.94-2.73 ^{P}	1.3-2.6 ^{P}	1.75-2.34 ^{P}	1.15-1.79 ^{P}
% groups: Ro/Cla/Cop	29/9/62 ^{P}	28/16/56 ^{P}	20/22/58 ^{P}	36/4/60 ^{P}	51/15/34 ^{P}
	17/17/66 ^{L}	38/19/43 ^{L}	---	---	---
% Calanoids	46.5 P-56.4 ^{L}	37.2 P-14.6 ^{L}	Absent	26.8 ^{P}	Absent
Trophic evaluation	oligo-mesotrophy	oligo-mesotrophy	mesotrophy	mesotrophy	eutrophy

for water quality assessment, see the original articles (Bazzanti 1981, 1983; Ferrara 1984; Margaritora 1992; Mastrantuono 1986a, 1990, 1991, 1993; Bazzanti & Loret 1982; Bazzanti & Seminara 1985, 1987a, b, 1995; Mastrantuono & Mancinelli 1999; Bazzanti *et al*. 1993, 1994a, b, 2001; Ferrara *et al*. 2002; Margaritora *et al*. 1999, 2001; Mastrantuono *et al*. 2000; Seminara *et al*. 1990).

4. RESULTS AND DISCUSSION

4.1. Zooplankton

The results of thirty years of investigations on plankton communities were used for the evaluation of the ecological status of the volcanic Latium lakes, revealing a progressive deterioration for some of them (Ferrara 1984; Margaritora 1992; Bazzanti *et al*. 1994b; Ferrara *et al*. 2002; Margaritora *et al*. 1999, 2001).

The present description considers the five lakes in succession of increasing trophic level beginning from Lake Bracciano, which proved to be the environment with the best conditions. At the beginning of the 80s, urban waste was channelled into a sewage collecting system to reduce the nutrient loads and thus protect the basin from increasing anthropic impact. Our data revealed (investigation 1998-99; Tab. 3) a good diversification in the zooplankton community, dominated by *Eudiaptomus padanus etruscosexetosus*, the only species of Calanoida, which reached the maximum density in winter. Cladocerans and rotifers were present in small numbers throughout the year but increased moderately in spring and summer both in pelagic and littoral zones. Some species typical of low trophic level environments were found (i.e. *Kellicottia longispina*) and the species richness and Shannon index showed high values for most of the year. This research confirms the oligo-mesotrophic condition of the lake as it emerged without any substantial differences also from previous studies (Ferrari 1972; Ferrara 1984).

The zooplankton community of Lake Martignano (1995-98 survey; Tab. 3) revealed a high diversity in the pelagic zone, while a decrease in species richness was observed in the littoral because of the disappearance of some rotifer species sporadically found in a previous study (Stella *et al*. 1972). The limnetic community was characterized by a winter copepod dominance (Cyclopoida, but also *Eudiaptomus padanus etruscosexetosus*) and an increase in rotifers and cladocerans in summer, due to *Daphnia hyalina*, *Diaphanosoma lacustris* and *Keratella cochlearis*. Conversely, in the littoral zone *Eudiaptomus* showed low density in all seasons and the summer peak of cladocerans was due to the occurrence of the microfilterer *Bosmina longirostris*, characteristic of eutrophic basins. The numbers of rotifers showed a considerable variability, the highest values being reached in spring when this group dominated the littoral biocoenosis. This marked predominance influenced the Shannon index trend, which showed values considerably lower than the comparatively high values of the other seasons. The reason for negative signals coming from the shores is to be sought in human activities and especially in the expanding agricultural practices of recent years, which have changed nutrient input into the lake. The picture that consequently emerged from our data was that of an oligo-mesotrophy for the pelagic zone, which confirmed previous evidence, while the condition of the littoral zone seemed to have worsened with respect to the past.

In comparison with a previous investigation of the pelagic zooplankton in Lake Vico (Ferrari 1972) a reduction in the taxa number and an increase in rotifer and copepod density were observed in the latter study (1985-86 survey, Tab. 3). Copepoda, represented only by cyclopoids, were the dominant group in the winter community, and *Cyclops abyssorum* was the major contributor to the total density. The spring community of rotifers consisted of eurythermic, mainly phytophagous species, and was dominated by *Kellicottia longispina*, *Keratella cochlearis* and *K. quadrata*. The temporal evolution of cladocerans was characterized by the presence of seasonal species, with higher densities during summer (*Diaphanosoma brachyurum*) and autumn (*Daphnia hyalina*) months. The species diversity (Shannon index) was characterized by a relatively small seasonal variability and by medium/high values. The diversity data and the good differentiation and stability of the zooplankton community, which was affected slightly by anthropic activities, confirmed a mesotrophic status for the lake.

The trophic status of Lake Albano (investigation 1986-87, Tab. 3) seems to show a trend similar to Lake Vico. However, the increase in the number of rotifer taxa compared with the sporadic results observed between 1950 and 1960, both in the littoral and pelagic zones, may be indicative of a shift in the lake's trophic condition (Cannicci 1953; Stella 1951, 1954; Stella &

Tab. 4. Parameters of the littoral vegetation substrate community used for a trophic evaluation. * Diversity values are reported as mean of sampling occasions and stations.

Lakes	Bracciano	Martignano	Vico	Albano	Nemi
Belt colonized by vegetation (m)	0-20	0-20	0-12	0-8	0-3
Taxa of plants	9	9	13	7	5
Species richness	125	117	108	78	61
Shannon diversity (H)*	4.1	3.3	3.6	3.2	2.2
N. of cladoceran species	13	16	12	8	3
Chydorus sphaericus (%)	4.2	4.0	6.6	18.4	57.7
Trophic evaluation	oligotrophy	oligotrophy	oligo-mesotrophy	mesotrophy	eutrophy

Socciarelli 1949). As a result of stronger human impact, a decrease was observed in the number of species of the other two groups in the littoral. Conversely, in limnetic areas no modification was recorded. Copepods (represented in particular by *Eudiaptomus padanus etruscosexsetosus*) quantitatively dominated the community, whereas Cladocera were scarcely represented throughout the study period. *Conochilus unicornis* was the dominant rotifer species, its density peaking in autumn and spring, when substantial numbers of high trophic level indicators (*Keratella cochlearis* and *K. quadrata*) were observed. The Shannon index varied little and its maximum values corresponded to the rotifer spring increase. These results point to a mesotrophic condition of the lake.

In Lake Nemi (1982-83 survey, Tab. 3) the process of eutrophication was more evident when compared to the other lakes. The considerable changes in the planktonic populations recorded around the 80s in comparison with previous results (Stella *et al*. 1978) were especially evident as regards species richness and vertical distribution. The zooplankton, represented by 19 species, was actually limited in its distribution to the epilimnetic zone. Rotifers qualitatively and quantitatively dominated the spring and summer communities. Even if cladocerans were relatively low in abundance during the year, they increased in late summer and autumn due to a *Diaphanosoma lacustris* peak. Copepods were exclusively represented by cyclopoids, and were the major contributors to zooplankton density in winter months. The generally high abundance of species indicators of high trophic level, such as *Keratella quadrata*, *K. cochlearis* and *K. cochlearis* f. *tecta*, and the presence of species association with *Keratella-Polyarthra-Asplanchna-Trichocerca-Pompholix*, clearly indicated the stress affecting the lake as a result of human activities. Diversity values fluctuated irregularly and tended to be lower than in other volcanic lakes. Some signs of improvement were observed during the last study period (2001-02). It will thus be important to observe whether the recovery in lake water quality will lead to further ecological improvement over the next few years.

4.2. Littoral zoobenthos

All the studies carried out in the last twenty years on lake littorals in Central Italy have attained two objectives: first, the definition of the fauna composition in terms of species richness and biodiversity of the ecosystems; second, the identification of the most useful community parameters (bioindices and bioindicators) for quality assessment. Two littoral communities were analysed in these studies: a) the community associated with submerged vegetation; b) the community associated with sandy bottoms.

4.2.1. Vegetation substrate

The lakes were ordered according to the increase in environmental quality in the littoral area (Tab. 4), as defined by means of community parameters which were identified as the more significant ones (Mastrantuono 1986a, 1990, 1991, 1993, 2000; Mastrantuono & Mancinelli 1999). In the 1980s Lake Nemi clearly displayed a strong eutrophication (Tab. 4), as indicated by the extreme reduction of aquatic vegetation, which colonized the bottom only down to a depth of three meters and comprised only a few taxa (five), but also evidenced by the values of the faunal parameters: low Shannon diversity, low number of cladoceran species, high percentages of a species considered as a bioindicator of meso-eutrophic conditions (*Chydorus sphaericus*) (Bērzinš & Bertilsson 1989). If we observe the trend of these parameters in the other lakes studied (Tab. 4) we note a progressive increase in the belt colonized by aquatic vegetation as we go from Lake Albano to Lake Bracciano; also species richness increases in a similar way and all these elements indicate increasing water quality. Moreover, in lakes Vico, Martignano and Bracciano an increase in diversity (H) and a greater presence of bioindicators of good environmental conditions (number of cladoceran species) may also be observed. The decrease in the percentage presence of the microfilterer cladoceran *Chydorus sphaericus* is considerable both between Lake Nemi and Lake Albano and between Lake Albano and the other lakes. All these results reveal the differences in the trophic status of the lakes studied. The good environmental condition of lakes Bracciano and Martignano is particularly outstanding, and they have a very similar faunal composition both qualitatively and quantitatively.

4.2.2. Sandy substrate

The synthesis of the faunal parameters referring to the community associated with sandy shores, as inferred

Tab. 5. Parameters of the littoral sandy substrate community used for a trophic evaluation. * Diversity values are reported as mean of sampling occasions and stations. ** Ratio between number of Naididae species and number of Tubificidae species. *** Tub. ind. eutr. = tubificidae indicators of eutrophy belonging to one or more of the following species: *Limnodrilus hoffmeisteri*, *L. claparedeianus*, *L. udekemianus*, *Potamothrix heuscheri*, *P. hammoniensis*, *Tubifex tubifex*.

Lakes	Bracciano	Martignano	Vico	Albano	Nemi
Species richness	100	59	115	76	65
Shannon diversity (H) *	3.2	3.4	3.6	3.2	2.7
N/T ratio **	3.6	5.0	2.4	2.6	2.0
N. of nematode species	18	19	20	13	9
T Tub. ind. eutr./total fauna(%) ***	0.06-19.1	0.1-10.8	3.0-57.0	3.0-27.0	1.7-71.9
Trophic evaluation	oligo-mesotrophy	oligotrophy	mesotrophy	mesotrophy	eutrophy

from the investigations carried out by Mastrantuono (1986b, 1995a, b), Mastrantuono & Baldetti (1998), Mastrantuono & La Rocca (1988), Mastrantuono *et al*. (2001), shows that the lakes can be ordered in the same sequence of quality increase as that observed for the community associated with submerged vegetation, although a higher trophic degree was evidenced for the littoral sediments of two lakes (Lake Vico and Lake Bracciano) (Tab. 5). The eutrophic condition of Lake Nemi clearly emerged both from the values of the bioindices (very low diversity, low N/T ratio: number of naidid taxa/ number of tubificid taxa) and from the high percentages (mainly the maximum values) reached by tubificids considered as indicators of eutrophy (Lang & Reymond 1993, 1995). As observed for the community associated with submerged vegetation, data referring to the remaining lakes evidenced a difference between Lake Nemi and Lake Albano. The latter was characterized by a mesotrophic condition indicated both by the measure of the bioindices (species richness, diversity, N/T ratio), all showing good values, and by the moderate quantity of indicator tubificids (Tab. 5). As regards Lake Vico, which was studied in two different periods (1985 and 1993), the community revealed some clearly positive characteristics (high species richness, good diversity value, large number of nematode species) and some other less positive ones (low N/T ratio, substantial densities of tubificid high trophy indicators). The reason for this situation lies in the substantial difference between the stations located in the northern part of the lake, which are characterized by higher trophy due to a lower shore slope and the presence of hazelnut cultivations in the environs, and the stations in the southern part of the lake, which have a steeper bottom slope, are partly embanked, and also characterized by scanty input of fine organic sediments. Also Lake Bracciano revealed an unhomogeneous situation due to the difference among stations, which are rather distant from each other. Some positive parameters have thus been observed in this lake (species richness, N/T ratio and number of nematode species), associated with a relatively low diversity value. Only Lake Martignano showed an oligotrophic condition, although a portion of its shoreline was exposed to washing away by run-off from the surrounding land. The invertebrate fauna was poor in number of taxa (only 59), but the other parameters indicated a very positive environmental status (good diversity value, high N/T ratio, high number of nematode species and moderate percentages of tubificid indicators of eutrophy).

4.3. Sublittoral and profundal macrobenthos

Data from more than twenty years study of the sublittoral and profundal benthic communities in Central Italy ensured satisfactory biological water quality assessment of five volcanic lakes, with particular emphasis on hypolimnetic conditions (Bazzanti 1981, 1983; Bazzanti & Loret 1982; Bazzanti & Seminara 1985, 1987a, b, 1995; Bazzanti *et al*. 1993, 1994a, b, 2001; Seminara *et al*. 1990).

Lake Bracciano (year of study: 1998-99, Bazzanti *et al*. in preparation) showed (Tab. 6) a high number of taxa (genera and/or species). Most of the taxa sensitive to environmental stress and typical of oligo-mesotrophic waters were recorded also in the deep part of the lake. Among these, especially the presence of the malacostracans *Echinogammarus veneris*, *Niphargus* sp. and *Proasellus coxalis* and the Gastropoda *Valvata piscinalis*, *Bithynia leachi* and *Belgrandia latina* confirmed the good quality of Lake Bracciano. At the end of the summer thermochemical stratification (October-November) we detected the absence of some taxa only at the maximum depth (165 m), probably because of a slight reduction in oxygen concentration near the bottom (minimum value: 3.1 mg l^{-1}); however, these taxa reappeared during the winter overturn, when the hypolimnetic water again became well-oxygenated (8.7-10.4 mg l^{-1}). The biological diagnosis based on sublittoral and profundal benthos therefore indicated a good condition of the lake, which can also be considered biologically oligotrophic with a few faint signs of mesotrophy. The benthic community seemed to be very similar to that described in a previous study (Bonomi & Ruggiu 1971), indicating that the profundal zone of the lake maintained good environmental characteristics over a long period of time.

The sublittoral and profundal benthos of Lake Martignano (years of study: 1997-98) showed a high number of taxa (Tab. 6), but the community distribution depicted a clear environmental trend according to the

Tab. 6. Indicator taxa and selected parameters of biological evaluation belonging to sublittoral and profundal macrobenthos in the studied lakes. * occurring only at one 10 m station. **Sensitive taxa: *Psammoryctides barbatus*, *Peloscolex velutinus*, Lumbriculidae, *Echinogammarus veneris*, *Niphargus* sp., *Proasellus coxalis*, *Micropsectra*, *Microtendipes*, *Paratendipes*, *Pisidium* spp., Gastropoda (Saether 1979; Wiederholm 1980; Milbrink 1983; Mouthon 1993). ***Tolerant taxa: *Potamothrix heuscheri*, *P. hammoniensis*, *Tubifex tubifex*, *Chaoborus flavicans*, *Procladius choreus*, *Chironomus* gr. *plumosus*, *Limnodrilus hoffmeisteri* (Sikorowa 1968; Saether 1979; Wiederholm 1980; Milbrink 1983).

Lakes	Bracciano	Martignano	Vico	Albano	Nemi
N. taxa	48	36	49	27	16*
N. sensitive taxa**	9	5	6	4	0
N. tolerant taxa***	4	5	4	5	6
Diversity (range)	not calculated	0.93 – 3.08	0.34 – 3.42	0.00 – 2.80	0.00 – 3.1*
Trophic evaluation	oligo-mesotrophy	oligo-mesotrophy	mesotrophy	meso-eutrophy	eutro-hypereutrophy

depth gradient. The upper zone (20-40 m) was characterized by the highest abundances of oligo-mesotrophic taxa and high diversity values, whereas in the deeper zone, between 45 to 60 m (the maximum depth), a clear reduction of densities, diversity and number of untolerant taxa occurred. These results indicate a good condition of epilimnetic and early profundal zones and an appreciable worsening of the environmental conditions in the deepest part of the lake, due to the strong summer-autumnal hypolimnetic deoxygenation (near total anoxia). A noticeable difference in both physical and chemical and biological conditions is observed between the two main depth zones of the lake.

Also in Lake Vico (years of study: 1985-86) the number of taxa and the diversity values were high at 10 and 20 m (Tab. 6), but decreased with increasing depth. The density of sensitive taxa typically found in oligo-mesotrophic waters decreased with the depth and some groups (such as Bivalvia) disappeared at 30 and 40 m. These trends are compatible with a stressed condition of the lake, which is subjected to a dramatic hypolimnetic deoxygenation (near total anoxia) during the summer-autumn stratification. The profundal zone was also colonized by the dipteran *Chaoborus flavicans*, a species widely known to be tolerant to organic pollution and anoxia. The distribution of the species and the variation of community parameters with depth confirmed the worsening conditions in the profundal zone. Also for this lake a clear discrepancy of abiotic and biological parameters was found between the epilimnetic and hypolimnetic zones. Compared with a previous study (Bonomi & Ruggiu 1971), the general conditions of the hypolimnetic zone seemed to show a more marked deoxygenation of the water, which limited the diversity of the benthic fauna in the deeper part of the lake.

The discrepancy between the two main zones of the lakes was highly evident in Lake Albano (years of study: 1986-87), in which the great depth and the small surface area significantly influence the profundal macrobenthic structure and composition (Tab. 6). Densities and biomasses of Oligochaeta and Chironomidae decreased significantly with depth and only in the upper zone (20-50 m) were some sensitive species abundant. From 65 m to 95 m their abundances decreased until they disappeared and were replaced by tolerant taxa. Also the number of taxa and Shannon diversity dramatically decreased with depth and from 100 m until the maximum depth (175 m) no macrobenthic taxon was found in the sediments. In synthesis, Lake Albano showed three depth zones of different biological quality: from 20 to 35 m, in which the community parameters still showed values compatible with the adequate oxygenation of the sediments, from 50 to 95 m in which the macrobenthos showed clear signs of worsening caused by a marked summer deoxygenation (minimum values: 0 mg l^{-1}), and from 100 to 175 m where the community was lacking. This marked zonation in Lake Albano was attributable to a well-defined meromictic condition of the lake, which was also indicated by a palaeolimnological study (Lami *et al*. 1994).

The sublittoral and profundal benthic communities of Lake Nemi have been studied for a longer time than the other lakes (years of study: 1975-78, 1979-80, 1982-84 and 2000-01). A comparison made between the first three periods of study provided a clear picture of the eutrophication process which leads to total anoxia in the hypolimnion for more than six months a year. The effects of heavy stress on the benthic communities (Tab. 6) were evidenced by a strong reduction in benthic densities with depth, low number of recorded taxa, and a substantial taxonomic simplification of the community which, at 20 and 30 m, was composed only of Oligochaeta, with *Potamothrix heuscheri* as the dominant species. The fauna, therefore, in the first period of study (1975-78) showed the consequences of an acute organic pollution (algal blooms and severe fish kills occurred in the lake), and in the next period (1979-80) a further worsening of these conditions. Finally, (1982-84) a steady state typical of hypereutrophic waters undergoing chronic pollution was observed. For the years 2000-01 (Bazzanti *et al*., unpublished data), a recent study indicated a partial improvement of the environmental conditions of the profundal bottom of the lake due to sewage diversion, and some benthic groups attempted to recolonize the deeper zone (i.e. bivalves at a depth of 10 m and chironomids at 20 m), slightly increasing the diversity and species richness of the profundal fauna.

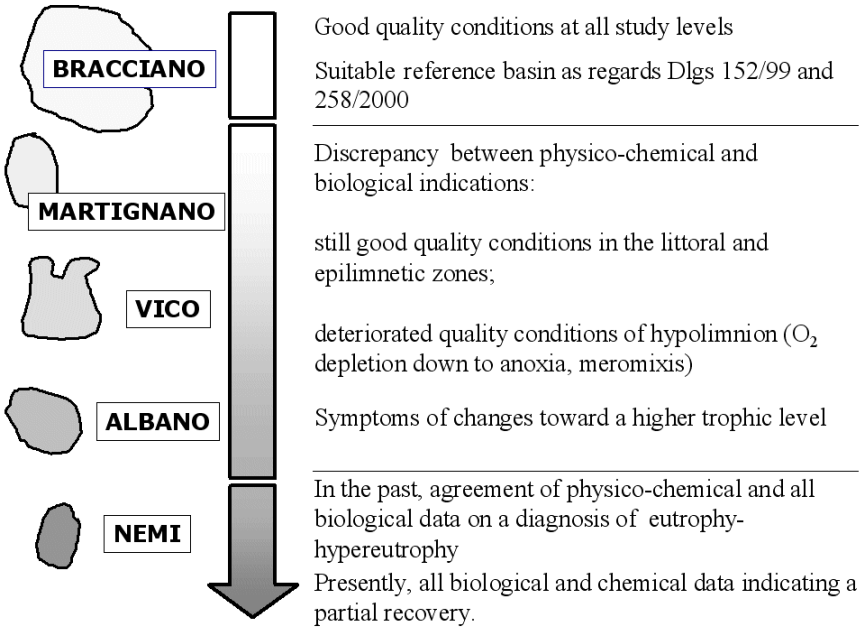

Fig. 3. Sketch representation of environmental quality rank of the studied lakes.

5. CONCLUDING REMARKS

The results of our work provides a strong indication of the need for a biological approach to a correct environmental diagnosis of lakes. Many different modifications of the water quality are to be borne by the various lacustrine communities, which then become themselves peculiar and informative responses to the environment alterations. A synthetic diagram of the trophic evaluations derived from the studies reported in the present work is plotted in figure 3, as a function of decreasing environmental quality. In general, all the biological communities and the physical and chemical parameters showed the same classification rank in all the lakes studied. Slight differences in the quality level are attributable to the specific spatial allocation of each biological assemblage forming a subjective response to pollution.

Of the environments considered herein, Lake Bracciano doubtless exhibits the best environmental characteristics, as is reflected in the agreement of all the indications emerging from the communities investigated. It could therefore constitute a valid quality reference environment, to which other lake ecosystems of the same origin or in the same geographical region could be referred when assessing whether the desired standard level of biological integrity has been reached. As underlined above, in the cases of Lakes Martignano, Vico and Albano the communities provided different diagnoses of lake trophy levels. In this respect, the littoral and/or the epilimnion of these lakes was found to be still in a good condition, while the hypolimnion showed a deterioration gradient that increased with depth. This discrepancy highlights the high-resolution diagnosis obtained by means of the biological approach, which is able to detect a similar worsening trend also in lakes at different trophic levels. The different duration of anoxia recorded in the deeper part of these lakes must be considered as a serious warning of increasing eutrophication, in the view of more effective release of phosphorus by anoxic sediments (Burden *et al*. 1987; Straskraba 1996). The severe biological consequences of this phenomenon have been already observed in Lake Vico, in which a clear worsening of trophic conditions occurred in 1993-94 (Franzoi *et al*. 1997) with respect to the previous works (Bonomi & Ruggiu 1971; Bazzanti *et al*. 1994a, b).

For Lake Nemi, the data provided by all the biological communities investigated in the period 1975-84 agree with the water chemical assessment of a eutrophic-hypereutrophic status, a condition that developed and was reinforced until it ultimately gave rise to impressive biological phenomena (massive algal blooms, extinction of coregonid fishes in the late seventies). Yet, our recent study of the lake (2000-03) evidenced clear signs of recovery in all the biological communities investigated, as a consequence of domestic sewage diversion since early 1990.

Differences between the trophic indications from epilimnetic and hypolimnetic waters and/or between waters and sediments are well documented (i. e. Laville 1971; Lafont 1982; Wasson 1984). In particular it has been stressed (Gliwicz & Kowalczewski 1981) that the commonly used indices for trophic assessment in lakes may provide good results for epilimnetic waters, but that are not necessarily suitable for estimating the water quality of a lake as a whole. Nevertheless, even the dif-

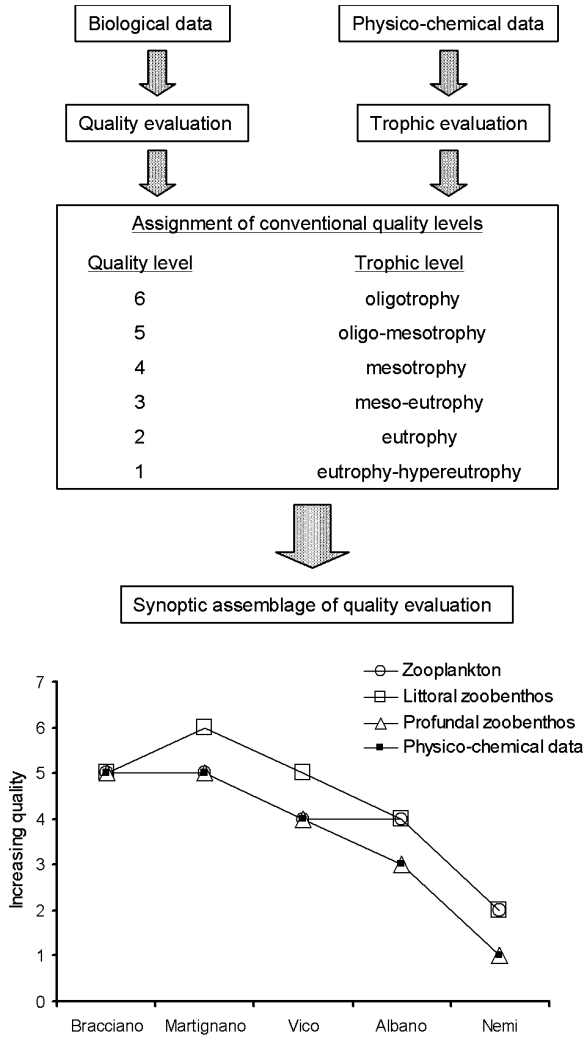

Fig. 4. Schematic representation of procedures leading to quality evaluation based on both biological and physico-chemical data.

ferent responses regarding lake environmental quality provided by both the biological and/or the abiotic approaches, rather than introduce conflicting evaluations, seem to acquire predictive strength when considered synoptically (see Fig. 4 for a simple graphic representation of these responses).

In synthesis, our results suggest the basic need for an integration between biological data and physical and chemical analyses of the water in order to obtain high-profile evaluations of both present lake environmental quality and the possible future evolution of trophic status. In our opinion, such procedures are to be considered as routine operating tools in managing and monitoring programmes aimed at the protection of lake ecological integrity and to the conservation of high water quality levels, as well as in recovery intervention planning.

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