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Physical limnology of Italian lakes. 2. Relationships between morphometric parameters, stability and Birgean work

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ABSTRACT

The relations of morphometric parameters with maximum stability (S) and maximum Birgean work (B) are analysed for 31 Italian lakes. Results show that in deep lakes the depths are more correlated with S, while fetch is more correlated with B. In contrast, in shallow lakes the depths are correlated both with S and B, while the correlation with fetch is insignificant. Power regressions are used to define the relation between maximum depth, S and B, and an analysis is made of lakes showing a marked deviation from the curves, whether on account of their environmental features or their internal hydrodynamic state. In meromictic lakes total stability is subdivided into chemical and thermal stability; major inferences are made as to the depth of their winter mixing. The relationship between B and maximum depth is less significant than that between z_{max} and S, as lakes with depth >100 metres and therefore with a very thick hypolimnion do not fully satisfy the regression function. Lastly, heating efficiency (E) is evaluated and related to depth and surface area of the lakes; the conclusion is that shallow lakes are more efficiently heated than deep ones.

Key words: Italian lakes, morphometry, stability, Birgean work, efficiency

1. INTRODUCTION

Bowling (1990) and Bowling & Salonen (1990) suggested using standard energy parameters (thermal stability and Birgean work) to quantify lake energetics and to compare the physical characteristics of lacustrine environments. Viner (1984) in New Zealand, Loranger & Brakke (1988) in the western USA, Kling (1988) in Cameroon, Ferris & Burton (1988) in Antarctica, Henry & Barbosa (1989) in Brazil, Bowling & Salonen (1990) in Finland, Geller (1992) in Chile, Kjensmo (1994) in Norway, Ambrosetti & Barbanti (2001) in Italy, among others, also demonstrated the importance of these parameters in describing the internal processes of the waters of both shallow and deep lakes, with the additional aim of describing them in chemical and biological terms.

These parameters can be evaluated all together on the whole water column, allowing a comparative analysis to be made with other lakes, or they can be analysed in their vertical distribution along the water column, so as to permit quantitative verification of the hydrodynamic mechanisms occurring within the water mass of an individual lake, as well as the trend of stability and Birgean work at the different levels during summer stratification and winter mixing.

The aim of this study is to evaluate and analyse the energy content in 31 Italian lakes of different morphometric characteristics, both in terms of stability and of wind work. Relations existing with the size of the lakes will be established, and the values of the lakes showing a marked deviation from the correlation curves on the basis of their morphometric, hydrological, climatic and internal hydrodynamic characteristics will be analysed.

To verify the energetic behaviour of 31 selected Italian lakes, we looked at the following physical characteristics: volume (V); area (A); maximum depth (z_{max}); mean depth (z_{mean}); fetch area (F_{area} = Area$^{1/2}$); effective fetch [F_{eff} = (maximum effective length + maximum effective width)/2]; depth of epilimnion (z_{epi}); depth of thermocline (z_{term}); maximum stability (S); total (S_T), chemical (S_{ch}) and thermal (S_t) stability; maximum Birgean work (B); parameter G = (B+S); efficiency (E) and depths of 50 and 90% annual heat exchange in the lakes, indicated by z_{50} and z_{90} respectively.

2. METHODS

In evaluating the thermal stability (S) and the Birgean work (B) in the 31 Italian lakes, we used the same temperature data as those used in Part 1 of this study to determine the values of heat content and thermal budget.

The LIMNOX programme devised by Bob Banens (University of New England, Armidale NSW, Australia) was used to calculate the work required to produce thermal stratification in a lake (Birge 1916) taking as the starting point for each lake the minimum winter bottom temperature. The same programme was used to calculate the stabilities of both Schmidt (1928) and Walker (1974). These values are identical if evaluated on the entire water column, but their vertical distribution is different. In fact, Schmidt's formulation, developed by Idso (1973), determines the stability of each layer referring to a fixed depth which corresponds to the

Tab. 1. Morphometric parameters and mean annual values of maximum stability (S) and Birgean work (B), G = (B+S) in 31 Italian lakes.

		Mean alt. m (a.s.l.)	A (km^2)	V (km^3)	z_{max} (m)	S ($J\ m^{-2}$)	B ($J\ m^{-2}$)	G ($J\ m^{-2}$)
1	Como	198	145.91	22.5	410.0	38706	6276	44862
2	Maggiore	194	212.51	37.5	370.0	37259	4648	41561
3	Garda	65	367.94	49.031	350.0	43177	9308	51140
4	Lugano NB	271	27.5	4.69	288.0	26700	1766	26514
5	Iseo	186	60.94	7.57	258.0	17093	1891	18718
6	Bracciano	164	57.02	5.053	165.0	20227	4447	24440
7	Bolsena	305	113.55	9.2	151.0	15345	3632	18599
8	Orta	290	18.02	1.25	143.0	10694	1593	12239
9	Idro	368	11.5	0.684	120.5	7012	1631	6822
10	Lugano FG	271	20.3	1.14	95.0	5567	1121	6622
11	Mergozzo	194	1.825	0.083	73.0	5720	1336	7037
12	Lugano PT	271	1.1	0.03	50.0	3145	2042	5141
13	Vico	510	12.08	0.26	48.5	2708	1716	4423
14	Caldonazzo	448	5.63	0.149	49.0	2302	1292	3539
15	Monate	266	2.51	0.0453	34.5	1182	858	2040
16	Nemi	320	1.792	0.0305	32.4	1272	971	1903
17	Varese	238	14.95	0.162	26.0	739	586	1300
18	Pusiano	259	4.93	0.069	24.3	638	590	1228
19	Oggiono	224	3.81	0.024	11.3	122	449	530
20	Endine	334	2.34	0.012	9.4	65	318	362
21	Segrino	374	0.38	0.0012	8.6	18	147	165
22	Alserio	260	1.23	0.007	8.1	70	189	245
23	Candia	226	1.52	0.0072	7.7	35	220	211
24	Comabbio	243	3.58	0.0164	7.7	70	283	334
25	Montorfano	397	0.46	0.002	6.8	19	222	241
26	Canzolino	540	0.072	0.0007	15.0	254	185	412
27	Frassino	74	0.31	0.0024	15.0	331	398	659
28	Annone West	224	1.7	0.007	10.1	30	286	289
29	Campagna	237	0.126	0.00035	5.0	11	110	60
30	Michele	241	0.069	0.00061	18.5	345	395	629
31	Nero	305	0.126	0.00162	27.0	669	439	932

centre of density, which is simply the point where the mean temperature of the column is found. In contrast, the modification of Walker (1974) evaluates stability by reference to the density of each successive layer. For meromictic lakes we also evaluated total stability (S_T), corresponding to the sum of the thermal (S_t) and chemical (S_{ch}) stability, the latter evaluated taking account of the vertical distribution of conductivity within the water column.

Note that these values, calculated on the whole column, do not take account of hydrostatic pressure which, in the opinion of Imboden & Wuest (1995), can lead to an increase in stability corresponding to a decrease in the water temperature of 0.2 °C every 100 metres.

3. RESULTS

3.1. Relationship between S and B

For deep lakes, the annual values of maximum S markedly exceed those of B, while for the shallow lakes Birgean work is generally higher than S. This different behaviour of deep and shallow lakes may be attributed to the percentage of water volume, compared with the total volume, involved in the process; the difference is also due to the two different methods of evaluating S and B. In shallow lakes (Ambrosetti & Barbanti 2002), the heat stored involves almost all of the water mass, so that the work required to bring it back to isothermy (i.e. S) is less than the work required to stabilise the stratification B, which starts from water temperatures usually close to 4 °C.

In contrast, in deep lakes, the high z_{max} contributes to the increase of work required for mixing (S) compared to that required to produce the stratification (B); in fact, 90% of the heat in these lakes is trapped in the upper layers, so that there is an increase in the energy gap between these layers and the deep hypolimnion, which forms 60-80% of the whole volume. The deep hypolimnion is partly isolated and participates to a lesser extent in the seasonal thermal events, with its water temperature remaining at values typical of early spring. The consequence is that to make ineffective a certain S, i.e. for a uniform temperature to be produced on the whole column, as well as to break down the stratification, the temperature of the hypolimnion must be increased considerably, involving a very large amount of work. In the lakes with z_{max} >25 m (Tab. 1), the maximum stability (S) values are reached in August, when the heat content is greatest; that is, at the moment when the thermocline displays its maximum vertical heat gradient. On the other hand the maximum wind work (B) is found in September, with some time lag compared to S, i.e. when the thermocline is still fairly pronounced and tends to move downwards, with distribution of heat to the deeper layers.

In the shallow lakes, however, the moments of maximum stability and wind work coincide and generally occur between July and September, depending on the meteorological conditions of the year.

3.1.1. Temporal variability

Table 2 highlights the fact that in deep lakes the interannual variations (CV) in wind work (B) are always higher than the corresponding values determined following Schmidt, while in the shallow lakes the opposite is true. This is probably because in large lakes the stratification process, which begins almost immediately after the end of the limnological winter and involves the superficial part of the water mass, undergoes all the meteorological anomalies which occur until the moment of maximum stratification, and therefore this active component has a more important role than the passive component (morphometry). For S the latter component is probably more important, as the heat exchange takes place in adiabatic conditions within the lake, with consequently smaller interannual variations.

Tab. 2. Interannual coefficients of variation (CV) calculated for the maximum thermal stability (S) and Birgean work (B) of Italian lakes.

Lake	z_{max} (m)	years	CV	
			S	B
Como	410	10	9	23
Maggiore	370	40	13	20
Garda	350	10	7.5	31
Orta	143	20	15	26
Mergozzo	73	5	9.4	11.8
Varese	26	5	12	16
Endine	9.4	12	19	16
Candia	6.5	8	18.9	6.26
Lugano FG	95	3-4		
Vico	48.4	3-4	11.9	27.7
Lugano PT	50	3-4		
Oggiono	11.3	3-4		
Idro	120	3-4		
Annone West	10.1	3-4	32.3	24.7
S. Parmense	22	3-4		

In the shallow lakes (for example Endine, Candia and Annone West) the opposite situation occurs, with S presenting an interannual CV higher than that of B: the explanation here may be sought in the shallow depth, which determines a high hydrodynamic instability in the whole water mass (see below for a more detailed account of this).

3.1.2. Correlation of investigated parameters

Both S and B in the 31 Italian lakes revealed a good correlation with all morphometric parameters; r varies from 0.72 to 0.98, with significance at the level of p >0.001 (Tab. 3). In the deep lakes all the depths except that of the thermocline maintain with S an r >0.90, while with B it is the wind run which is dominant (z_{max} and z_{mean} are not significant). In contrast, in the shallow lakes the depths are correlated with S and B, while fetch is actually insignificant. In both sets of lakes the r value remains high with the depths of 50 and 90% heat exchange.

In shallow lakes, the higher correlation of B with the three very similar depths (z_{max}, z_{ter} e z_{90}) might be explained by what Schindler (1971) found for ELA lakes. The work attributed to the wind in Birgean calculations may actually be done at least partly by inverse density currents induced by a warming of the water in contact with the lake bottom in the littoral zones. This happens because the proportion of littoral zone is larger in shallow lakes. It should also be remembered that in shallow lakes the wind is not able to lower the thermocline to any great extent during the warm season; in fact, as has been recorded (Ambrosetti *et al*. 1996), in round, shallow lakes the depth of the thermocline is established early at the beginning of the summer, and moves downward with a less steep gradient than in deep lakes.

In deep lakes, on the other hand, wind run on the surface plays a decisive part; the highest correlation is with fetch (both with area and effective), and with the depths of 50 and 90% heat exchange, followed by the depth of the thermocline. As discussed previously, this is clearly due to the fact that the stratification process in deep lakes involves only a superficial portion of the water, small compared with their z_{max}, and the fact that their orientation (North-South) greatly facilitates wind action on the surface. In fact, the thermocline moves downward as the season advances with a steeper gradient than in shallow lakes, and also with the increasing morphometric dimensions of the lakes.

3.2. Stability

As we have seen, thermal stability is the estimate of the quantity of work required to mix a thermally stratified lake to a new condition of isothermy, without adding or subtracting heat (adiabatic conditions).

The relationship between maximum stability and z_{max} in our 31 lakes is illustrated in figure 1, and is expressed in a power equation which fits the experimental data very well ($r^2 = 0.98$). As discussed in previous papers (Viner 1984; Geller 1992), small variations in z_{max}, in its lower values, correspond to very large increases in S. The shape of the curve alters abruptly between 30 and 80 metres maximum depth, determining an almost horizontal, asymptotic trend with increasing z_{max}: the influence of morphometry at this point does not make any difference to the S.

In agreement with Wetzel (1983) and Allot (1986), we found that the relationship between stability and morphometric parameters cannot be a simple linear ra-

Tab. 3. Correlation matrix of morphometric variables, stability, and Birgean work.

	V	z_{max}	F_{area}	F_{eff}	z_{mean}	A	z_{epi}	z_{term}	z_{90}	z_{50}
Lakes (31)										
S	0.89	0.98	0.77	0.75	0.98	0.77	0.72	0.87	0.97	0.96
B	0.92	0.93	0.84	0.83	0.92	0.84	0.83	0.94	0.96	0.98
Eff.	0.91	0.88	0.87	0.86	0.85	0.87	0.86	0.94	0.92	0.94
Deep lakes										
S	0.93	0.94	0.85	0.75	0.91	0.85	0.63	0.68	0.76	0.77
B	0.90	0.69	0.94	0.91	0.58	0.94	0.80	0.88	0.93	0.95
Eff.	0.88	0.69	0.92	0.89	0.56	0.92	0.78	0.87	0.93	0.96
Shallow lakes										
S	0.48	0.96	0.19	0.16	0.96	0.19	0.29	0.71	0.91	0.92
B	0.79	0.87	0.48	0.45	0.84	0.48	0.50	0.86	0.87	0.92
Eff.	0.78	0.62	0.66	0.64	0.56	0.66	0.66	0.85	0.74	0.75

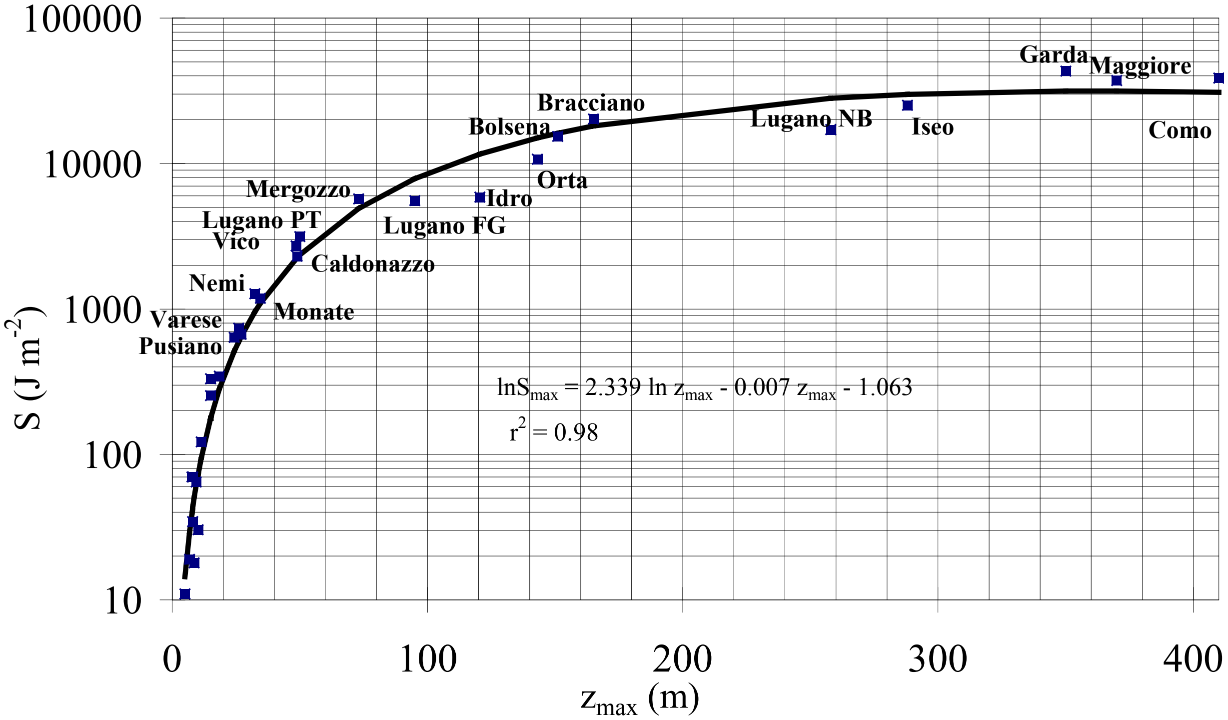

Fig. 1. Relationship between maximum stability and maximum depth in 31 Italian lakes.

tio, and that small lakes are less stable per unit area than large ones. For instance, comparing lakes Mergozzo, Nemi and Lugano PT with lakes Alserio, Candia and Annone West, which all have similar areas, we found the first group much more stable (between 1200 and 5000 J m^{-2}) than the second one (50-70 J m^{-2}), exactly because the first is 5 to 10 times deeper (Tab. 1). The conclusion is the same if we compare lakes Idro and Vico with Lake Varese; they also have very similar areas.

A parameter such as stability, if evaluated as total on the whole water column, can be used in a comparative analysis with other lakes, but if it is analysed in its vertical distribution, it can also explain the mechanisms occurring within the water mass and justify the slightly anomalous position of the lakes in figure 1. This is the case of lakes Lugano NB, Idro, Orta, Iseo and Garda, which are the deep lakes that show the greatest deviation from the curve. In particular, the position of lakes Lugano NB and Idro below the line of regression can be explained by the fact that they are in a condition of meromixis, which means that thermal stability does not coincide with total stability, but is conditioned by chemical stability. In Lugano NB there is a deep anoxic

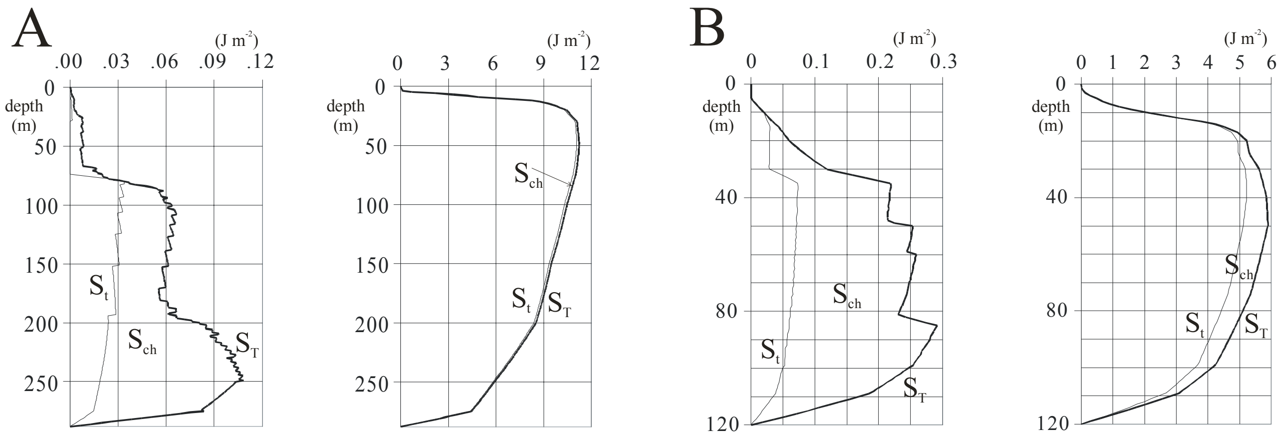

Fig. 2. Vertical profiles of total (S_T), chemical (S_{ch}) and thermal (S_t) stability in winter and summer *sensu* Walker in lakes Lugano NB 1987 (A) and Idro 1970 (B).

layer containing reducing substances like ammonium, sulphides, methane, iron and manganese, resulting in a conductivity of 246 µS cm^{-1} at 20 °C (Barbieri & Simona 1997). In Lake Idro the meromictic layer is caused largely by bicarbonate and calcium entering the lake from the watershed: these two ions, together with magnesium and sulphates, produce conductivity values in the deep water of around 350-400 µS cm^{-1} (Garibaldi *et al*. 1997).

In Lake Lugano NB, total stability of the whole water column presents a winter value 3-4 times greater than that determined on the basis of temperature alone, while the summer value shows an increase of only 2%. Lake Idro shows the same increase as Lugano in winter, with summer values reaching +14%. The influence of the solutes on stability in both lakes decreases during the warm season, i.e. with increasing temperature in the lakes and consequently increasing thermal stability. This is clearly seen in figure 2, which illustrates the vertical distribution of stability *sensu* Walker in its three components at the time of winter minimum and the summer maximum. In both lakes chemical stability plays a major role in winter. It increases sharply below 70 m in Lake Lugano NB (1987) and below 30 m in Lake Idro (1970), impeding the vertical mixing of the water. In contrast, in summer the chemical stability contributes very little to the total, due to the general heating of the water. A similar situation is found in Lake Iseo: a lack of oxygen in the deep layers and a high solute content determine conductivity of between 250 and 300 µS cm^{-1} (Garibaldi *et al*. 1997).

In the cases of lakes Orta and Garda, the deviations of stability from the curve, respectively negative and positive, are attributable to the different depths of mixing layer in the two lakes in summer. In Lake Orta a stable stratification is already present in April, so that the accumulation of heat remains in a restricted surface layer; whereas in Lake Garda the heat is driven by the action of the strong winds down to deeper layers. In fact, in Lake Garda 90% of the heat exchange occurs in the top 46 metres, while in Orta the same quantity is exchanged in 23 metres.

3.3. Birgean work

We follow the definition of Birgean work (B) as the quantity of external energy required to produce a certain distribution of density, not taking into account how the energy enters the lake (Kjensmo 1994). The values of B are therefore due to a series of factors affecting the distribution of heat energy within the lakes, rather than to wind action alone (Bowling & Salonen 1990)

Thus, infiltrations of groundwater, ascending currents in small lakes or high volumes of water from tributaries in large ones may cause considerable changes in their thermal structure and consequently in the structure of B (Barbanti *et al*. 1995; Ambrosetti & Barbanti 2000).

On the other hand Johnson *et al*. (1978), Barbanti & Ambrosetti (1986), Mackey (1991) and Ambrosetti & Barbanti (2001) use the curves of the so-called direct work (ΔB), the difference in B calculated on two successive dates, to show the distribution of the work ascribed to the wind or to other actions within the water column during the considered interval of time.

The relationship between B and z_{max} of the 31 Italian lakes expressed by means of the exponential function in figure 3 is less significant than that calculated for S. This is because the lakes deeper than 50 m are characterised by a very thick hypolimnion where external action is practically irrelevant during the stratification period, and decreases exponentially with depth (Allot 1986; Smith 1979). Other kinds of mechanism (Welander 1968) determine the movements of the water in this portion of a lake, and act in different ways and at depths which vary from lake to lake, in conformity with their morphometry and the bathymetric characteristics of the basin (Ambrosetti & Barbanti 1999; Michalsky & Lemmin 1995).

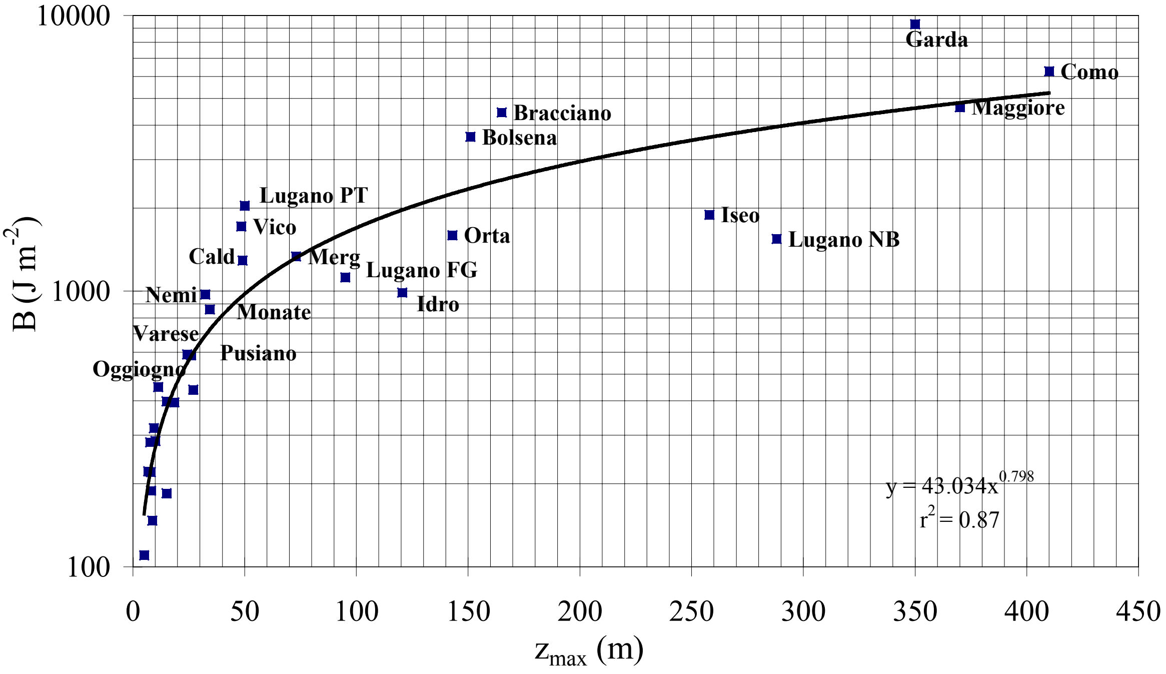

Fig. 3. Relationship between maximum Birgean work and maximum depth in 31 Italian lakes.

If we compare the deep lakes Garda, Como and Maggiore, it is Lake Garda that shows the greatest deviation from the exponential curve. Due to its surface area, which exceeds that of Como and Maggiore by factors of 2.5 and 1.7 (Tab. 1), Garda is very exposed to the wind, resulting in a greater surface thickness of warm water. Its thermocline is in fact on average 3 metres deeper than in the other two lakes; moreover the effect of the wind, as emerges through the correlation between the logarithms of vertical turbulent mixing coefficients (K_z) and Brunt-Väisälä frequency $(N)^2$, reaches a depth of 180 metres (Ambrosetti & Barbanti 1999, 2000) compared with 150 m in the other two lakes, though they are deeper.

The Birgean values of Lakes Lugano NB and Idro are strongly affected by the presence of stable monimolimnetic water, which means that the z_{max} of these lakes should be regarded as considerably less than their actual depth. Besides, Lake Lugano NB is in a very sheltered position, so that wind action is very weak, and the heat exchange becomes exhausted at a shallower depth than might be expected (Fig. 4).

The B values of the lakes in Latium are also affected by their geographical situation: besides being at a lower latitude, they are located in a very windy area and are exposed to more solar radiation, so that the depths of percentage heat exchange are much greater, comparable to those of the largest lakes in Northern Italy (Ambrosetti & Barbanti 2001).

The situation of Lake Orta is unique among our 31 lakes. Its values are below the correlation curve, and in an anomalous position compared to other lakes with similar morphometric characteristics. The lake is partly sheltered from the action of the wind, which in any case is of moderate strength; the heat is trapped in an epilimnion of limited thickness, but which reaches very high temperatures and determines thermoclines with gradients of 4-5 °C per metre, so that the heat is stored almost entirely in the upper layers.

In discussing the influence of passive (morphometry) or active (weather conditions) components in determining the maximum values of S and B, we can say that neither is more important than the other, but rather that they are complementary.

If the Birgean work is related to the different depths of heat exchange in the stratification period, the r^2 coefficients of each curve are all significant (Fig. 4). However, B presents its greatest correlation with the depth of the 50% exchange of heat, which is more or less the depth of the thermocline. The other values of r^2 referring to other depths are equally significant, and show that the portion of lake affected by Birgean work is very extensive, and much deeper than the depth of the thermocline.

3.4. *Efficiency*

Hutchinson (1957) defined the ratio between Birgean wind work and summer heat income as an "efficiency" term, by which he meant the work required to account for the heat stored by the lake. Hutchinson states that heating is relatively inefficient in small lakes, and that low values of the above ratio are essentially the result of loss by evaporation, or of long wave back- radiation due to high surface temperatures, values which

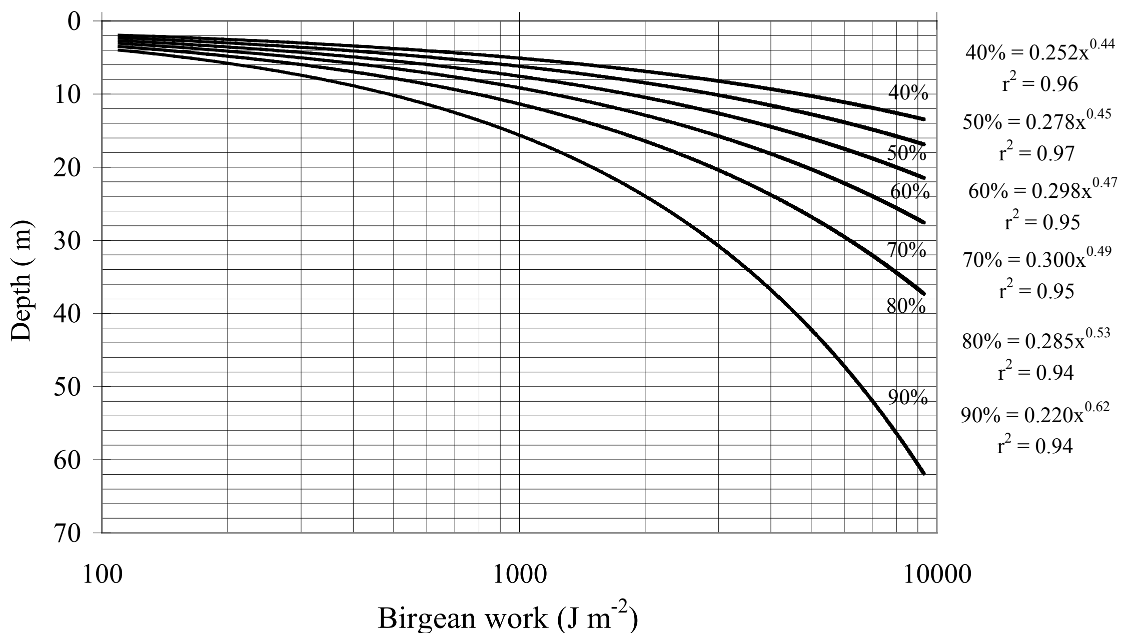

Fig. 4. Relationship between Birgean work and depths of percentage (40 to 90%) heat exchange in 31 Italian lakes.

are in proportion higher, if the heat absorbed is equal, than those occurring in an ordinary "first order" lake, *sensu* Hutchinson (1957).

Schindler (1971) investigated ELA lakes believing that Hutchinson's affirmation regarding the inefficiency of heating in shallow lakes would be confirmed, but the result he obtained was the opposite, i.e. that small lakes are more efficiently heated than large ones. Schindler offers several reasons in support of his affirmation that heat distribution to the deep layers is not caused by wind alone, so that a calculation of heating efficiency in terms of wind work, i.e. starting from the parameters B and the summer heat income (Q_t) , must be regarded with great suspicion.

Recent studies performed on thirty Italian lakes of different depths subdivided into elongated and round, shallow and deep, by Pompilio *et al*. (1996), Barbanti *et al*. (1996) and Ambrosetti *et al*. (1996), revealed different behaviours in the downward movement of the thermocline which confirm Schindler's affirmations. Moreover, studies by Blanton & Winklhofer (1972), Ivey & Boyce (1982), Ivey & Patterson (1984) and Gorham & Boyce (1989) suggest that currents may be triggered in the hypolimnion of shallow lakes as a response to those caused by wind stress on the water surface. These currents limit the downward movement of the thermocline and alter the thermal structure present, which may be partially eroded from the bottom, when the depth of the epilimnion is more than 60% of the maximum depth of the lake. Therefore, without excluding any of the mechanisms indicated in the distribution of heat within the water mass, the use of the parameter of heating efficiency (E) in terms of "wind work" is of undoubted utility in classifying the lakes.

In this paper, also for convenience of graphic representation, we have used the ratio E=B/Qt in agreement with Ferris & Burton (1988) and Geller (1992), with the low values indicating efficient heating, and high values the contrary.

The efficiency values of 31 Italian lakes are reported in table 4, while figure 5 presents their trend in relation to the surface areas and maximum depths of each lake. The deeper lakes have ratios (E) over 0.05, while the shallower lakes have lower values, with consequently low heating efficiency for deep lakes and high efficiency for shallow ones. This trend merely confirms what has been asserted so far, with regard to all Italian lakes in relation to their depth and surface area.

Tab. 4. Efficiency values of 31 Italian lakes.

lake	B/Q_t	lake	B/Q_t
Como	0.205	Varese	0.037
Maggiore	0.151	Pusiano	0.042
Garda	0.263	Oggiono	0.037
Lugano NB	0.072	Endine	0.032
Iseo	0.093	Segrino	0.025
Bracciano	0.145	Alserio	0.022
Bolsena	0.134	Candia	0.028
Orta	0.071	Comabbio	0.033
Idro	0.082	Montorfano	0.026
Lugano FG	0.050	Canzolino	0.020
Mergozzo	0.056	Frassino	0.035
Lugano PT	0.074	Annone West	0.032
Vico	0.078	Campagna	0.017
Caldonazzo	0.059	Michele	0.035
Monate	0.048	Nero	0.036
Nemi	0.065		

Lastly, we must consider the parameter G, which is simply the sum of B + S, and which represents the hy-

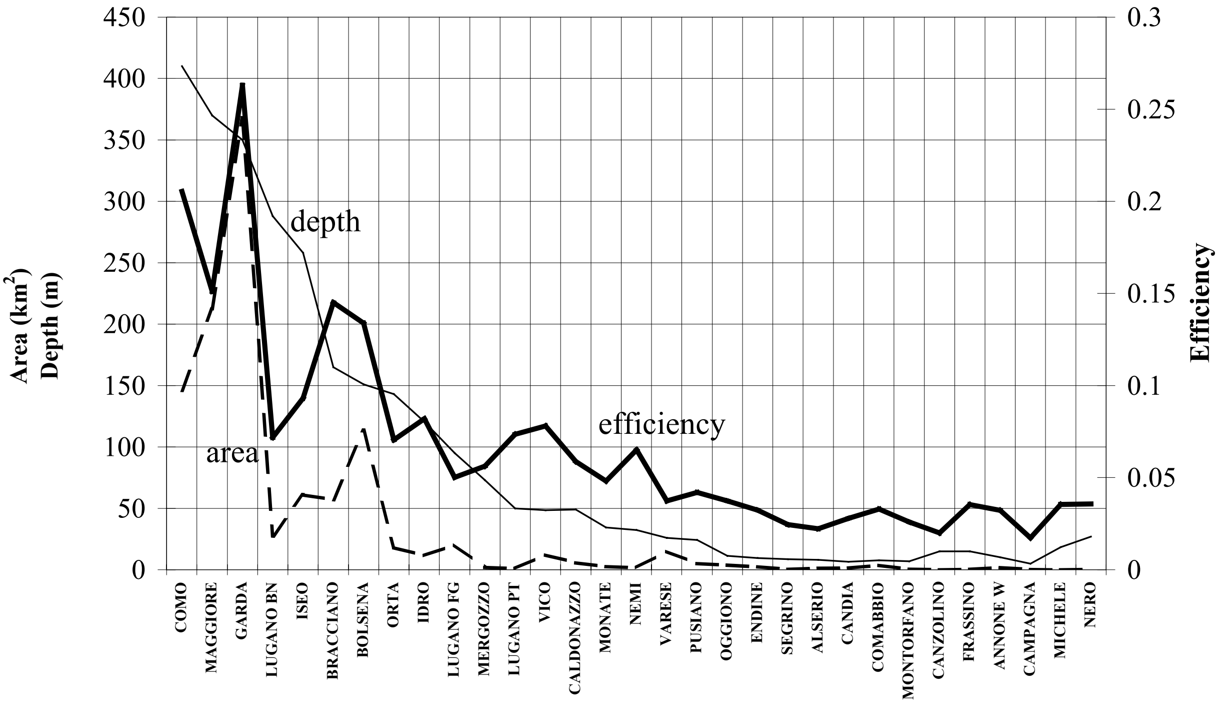

Fig. 5. The relation of efficiency, surface area and depth in 31 Italian lakes.

pothetical work which would be necessary to maintain homothermy at the current mean lake temperature throughout the heating season (Geller 1992). The G/B ratio expresses the ratio between the amount of energy required to maintain homoiothermal conditions in a lake during the summer heating and the actual energy supplied to build up the real stratification found (Kjensmo 1994). This ratio is important because it provides a good picture of the degree of stagnancy of the deep waters in a lake, and of the importance of the morphology of the basin in determining the amount of internal energy stored through the work of external agents.

4. CONCLUSIONS

The starting data for evaluating thermal stability and Birgean work in the 31 Italian lakes are the same thermal data used to calculate the heat contents and thermal budget in Ambrosetti & Barbanti (2002). For the whole set of the 31 lakes, we found significant correlation between energy parameters and the corresponding morphometric parameters, whereas if we consider the shallow lakes separately from the deep ones, there is greater significance in the latter between B values and fetch, which is conditioned by the morphometric characteristics and to some extent by the hydro-climatic situation of the lake.

For each lake we evaluated the maximum stability during stratification, which allowed us to make a comparative analysis of the 31 lakes; by analysing its distribution along the vertical column we arrived at an interpretation of the mechanisms occurring within the water mass and the deviation of some of the lakes from the correlation curve, especially in the deepest lakes, which may be explained by an ongoing situation of meromixis.

The Birgean work reveals how the morphometry, the hydrological and meromictic characteristics, and the geographical situation of the deep lakes in particular have a considerable influence on the energy required to reach a certain stratification. In fact, the exponential regression function between B and z_{max} is less significant than that between S and maximum depth. The heating efficiency of each lake was evaluated from the quantities of Birgean work and caloric content; it was observed that the shallower lakes are heated more efficiently than the deep ones, which have higher stagnancy values.

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