ISSN 1995-0829, Inland Water Biology, 2008, Vol. 1, No. 1, pp. 1–6. © Pleiades Publishing, Ltd., 2008.
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GENERAL HYDROBIOLOGIA

Relations Between Biological Diversity in Continental Waterbodies and Their Morphometry and Water Mineralization

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Received April 25, 2007

Abstract—The number of phytoplankton, zooplankton, and macrobenthos species was studied in continental lakes of diverse origin, geographical position, and hydrochemical (water mineralization) and morphological (area and capacity) characteristics. It is shown that the diversity of benthos communities depends on mineralization, area, and capacity of the waterbody, the dependence on area and mineralization being stronger than the dependence on capacity. Zooplankton community diversity depends on water mineralization and, to a very small extent, on waterbody area. The number of phytoplankton species in a lake is not strictly determined by morphometric characteristics and water mineralization. This number is to a greater extent dependent on other factors (e.g., light, nutrients, etc.). The largest number of benthos and plankton species was observed in waterbodies with water mineralization around 0.4 g/l. Increase in mineralization leads not only to decrease in species number, but also to simplification of community structure in plankton and bottom organisms, which is reflected by the Shannon index of diversity decreasing accordingly. The studied relations show wide dispersal in the number of species that can result, beside other factors unaccounted for, from the uneven reliability of the identifications and recordings of plankton and benthos species due to the different proficiency level of experts in taxonomy and systematics.

DOI: 10.1134/S199508290801001X

INTRODUCTION

The complexity of ecosystem organization is determined by the number of species and the number of interrelations between them, i.e., by diversity. The number of species may be viewed as an index of structural complexity of ecosystems; it is largely dependent on the influence and dynamics of environmental factors, including the abiotic factors. It is possible to estimate the complexity of structure in animal communities by a diversity index, the Shannon index, that accounts for the number of species and the degree of their predominance. The higher the index, the more complex is the system organization. There is no statistically significant difference between diversity index values in communities of plankton and benthos under the same environmental conditions [1]. It has been shown earlier [2, 3] that the number of plankton and bottom animal species is power dependent on the lake area and capacity (E). The latter parameter is the ratio of average and maximum lake depth, thus also representing the share of the littoral in total lake area. It has been indicated that the influence of these morphometric parameters on the number of animal species strongly varies, which means that the relationship is ambiguous. General mineralization and active reaction of waters also, along with waterbody area, influence the formation of animal diversity [6, 7]. The subject of this study is the influence of morphometric parameters of waterbodies and of water mineralization (the most important ecological characteristics of waterbodies) on the diversity of species in phytoplankton, zooplankton, and benthos in different lakes. The number of plankton and bottom species usually referred to in publications comprises crustacean and rotifer zooplankton and macrozoobenthic animals. This is also the case in this study.

MATERIALS AND METHODS

Data on hypersaline lakes of the Crimea [15] and unpublished data on the same lakes, by courtesy of colleagues from the Laboratory of Freshwater Biology, Zoological Institute of RAS, are used in this study. Data on diverse lakes of Europe, Canada, Siberia, Africa, Bolivia, and Australia with different level of mineralization [4, 5, 8–14, 16–25] are also used. The studied lakes differ in geographic position (arctic, boreal, tropical, and of the northern and southern hemisphere), area (from 0.05 to 18000 km^2), and water mineralization (from 0.05 to 340 g/l). Data on the greater lakes were not used, with the exception of the Ladoga Lake area, which was included for enlarging the range of lake areas. Data on the Great Lakes should be considered separately.

Regressions, including multiple, were analyzed with polynomials of higher power and with the pro-

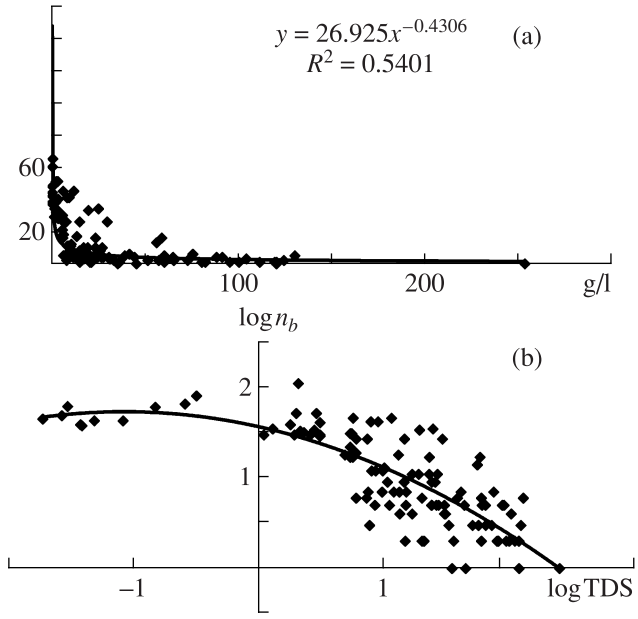

Fig. 1. Relation between number of zoobenthos species (ordinate) and degree of water mineralization (g/l) (a) and between logarithm of species number (ordinate) and logarithm of mineralization (abscissa) (b) in different lakes.

gram STATISTICA. Extremums of functions were determined with their derivatives equated with zero.

RESULTS

The relation between the number of animal species in macrozoobenthos and the mineralization of water is rather conclusively ($R^2 = 0.54$) described by an exponential equation (Fig. 1). On the other hand, double logarithm of such an equation is a linear equation ($y = ax^b$, $\log y = \log a + b \log x$). But in the studied case, as we can see from Fig. 1, the relation between logarithm of species number and logarithm of water mineralization should be described with an equation more complex than the exponential equation.

Based on these results, the relation between number of animal macrobenthos species (n_b) in 108 different lakes and logarithm of water mineralization ($\log \mathrm{TDS}$) in these lakes is analyzed. Fig. 2a shows that this relation is rather safely described by the cubic equation

$$n_b = (4.38 \pm 1.01)\log \mathrm{TDS}^3 - (7.43 \pm 1.56)\log \mathrm{TDS}^2 - (22.34 \pm 2.5)\log \mathrm{TDS} + 42.4 \pm 2.578; \quad (1)$$

$$R^2 = 0.68.$$

Equation (1) and Fig. 2 show that the number of species in communities first increases and then decreases acceleratingly as water mineralization increases.

Equating derivative of equation (1) to zero and solving the resulting quadratic equation, we find the function's maximum, or the value of TDS providing for maximum number of animal benthos species: $\log \mathrm{TDS} = -0.354$, exponentiating, we obtain TDS = 0.443 g/l. Substituting values of $\log \mathrm{TDS}$ into equation (1), we can easily calculate the number of species, 51, at the function's maximum.

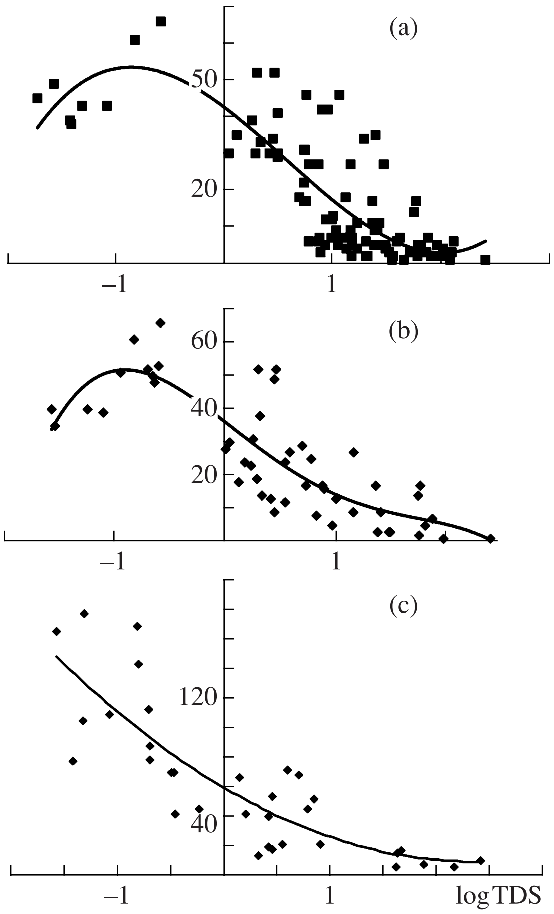

Fig. 2. Relation between number of species in zoobenthos (a), zooplankton (b), and phytoplankton (c) (ordinate) and logarithm of mineralization (abscissa).

Thus, among the studied waterbodies, a maximum number of bottom animal species is observed at mineralization around 0.443 g/l.

The influence of water mineralization on number of zooplankton species was similarly analyzed in 58 lakes. Fig. 2b shows that the number of plankton species (n_z), like the number of bottom species, first increases and then decreases as water mineralization ($\log \mathrm{TDS}$) increases, and the relation can be described by a quartic equation:

$$n_z = (-1.97 \pm 1.09)\log \mathrm{TDS}^4 + (7.15 \pm 2.13)\log \mathrm{TDS}^3 - (1.25 \pm 3.24)\log \mathrm{TDS}^2 - (25.75 \pm 3.95)\log \mathrm{TDS} + 36.17 \pm 2.37; \quad R^2 = 0.7. \quad (2)$$

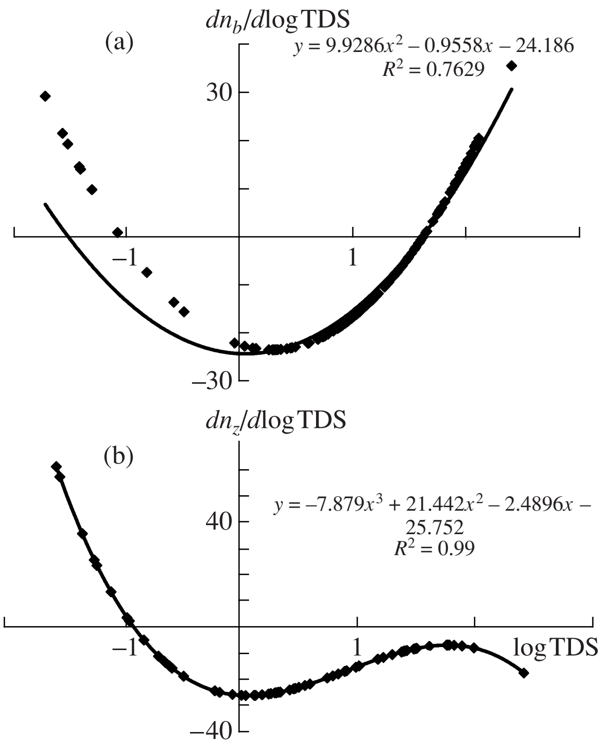

Fig. 3. Relation between derivative of number of species in benthos (a) and zooplankton (b) (ordinate) and logarithm of mineralization (abscissa).

The maximum of function (2) is at logTDS = –0.4 or at TDS = 0.398 g/l, with maximum number of species 50.

Data on the number of phytoplankton (n_f) species were obtained for 34 lakes with different water mineralization (logTDS). The relation between these parameters (Fig. 2c) could be described, unlike the cases of zooplankton and benthos, by the quadratic equation:

$$n_f = (8.99 \pm 3.85)\log TDS^2 - (42.49 \pm 5.05)\log TDS + 59.76 \pm 6.19; \quad R^2 = 0.66. \tag{3}$$

Analysis of equation (3) shows that, among the studied lakes, a minimum number of phytoplankton species (6) is observed in waterbodies with TDS = 231 g/l, and maximum number (178) is observed at TDS = 0.03 g/l. Thus, within the studied range, the number of plankton algae species decreases as mineralization increases.

Data represented in Fig. 2 show that the number of animal plankton and benthos species first increases and then decreases as water mineralization increases. It is useful to determine the approximate mineralization at which the direction of this dynamics is changed. We can do this with the help of the rate of species number change depending on mineralization level, using a derivative ($dn/d\log TDS$) of the function describing the relation between species number and logarithm of mineralization (logTDS).

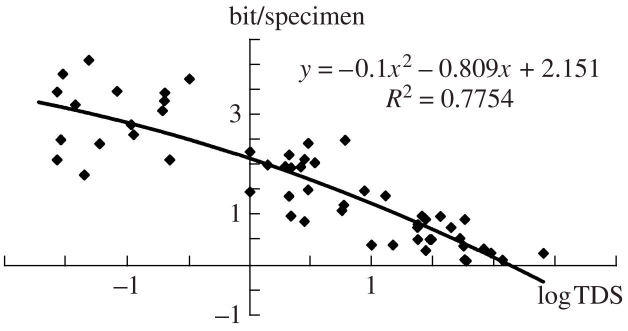

Fig. 4. Relation between Shannon index in communities of zooplankton and zoobenthos (ordinate) and logarithm of mineralization (abscissa).

Derivative of bottom animal species number as a function of mineralization (equation (1)) has the following form:

$$dn_b/d\log TDS = 13.15\log TDS^2 - 14.85\log TDS - 22.34. \tag{4}$$

Fig. 3a shows this derivative, which is the rate of change for macrozoobenthic species number as a function of mineralization. Solving the equation given in Fig. 3a, we have its roots and determine the extremums of the function, and then by exponentiating we find that species number decrease strongly accelerates as mineralization increases at mineralization greater than 1.12 g/l (logTDS = 0.048).

Similar calculations are made for zooplankton (Fig. 3b):

$$dn_z/d\log TDS = -7.88\log TDS^3 + 21.44\log TDS^2 - 2.49\log TDS - 25.75. \tag{5}$$

It is easily found from equation (5) that the rate of species number change decreases and, reaching its minimum at TDS = 0.398 g/l (logTDS = –0.399), slightly increases. Thus, in zooplankton communities the most abrupt decrease in the rate of species number change takes place in waterbodies with mineralization greater than 0.4 g/l, which is around 1/3 of the same parameter for benthic animal communities.

The Shannon diversity index for plankton and benthos ($H_{z,b}$), a measure of species diversity and of the degree of community structure complexity, can be estimated, based on 54 lakes, as a function of water mineralization (logTDS). Species diversity and degree of community structure complexity decrease as mineralization increases (Fig. 4):

$$H_{z,b} = (-0.1 \pm 0.06)\log TDS^2 - (0.81 \pm 0.07)\log TDS - 2.15 \pm 0.15; \quad R^2 = 0.78. \tag{6}$$

Table 1. Parameters (a, b, c) from equations of influence of area ($\log S$) and mineralization ($\log \mathrm{TDS}$) on number of species in communities of phytoplankton, zooplankton, and zoobenthos in different lakes

Parameter	Phytoplankton	Zooplankton	Zoobenthos
N	42	65	51
a	–0.30 ± 0.15	–0.18 ± 0.05	0.017 ± 0.002
b	–0.06 ± 0.07	–0.02 ± 0.02	–0.29 ± 0.14
c	60.37 ± 8.66	25.86 ± 2.47	36.60 ± 2.05
R^2	0.13	0.44	0.56
Beta S	–0.12	0.09	0.7
Beta TDS	–0.32	–0.42	–0.2

Note: N, number of studied lakes; Beta, correlation coefficient of multiple regression.

Table 2. Parameters (a_1, b_1, c_1, d) from equations of influence of area ($\log S$), capacity (E), mineralization ($\log \mathrm{TDS}$) of species in communities of zooplankton and zoobenthos in different lakes

Parameter	Zooplankton	Zoobenthos
N	33	27
a_1	–11.41 ± 2.215	28.79 ± 7.65
b_1	–0.472 ± 1.315	–30.73 ± 11.36
c_1	–24.24 ± 8.76	–114.2 ± 53.23
d	40.3 ± 5.4	120.3 ± 25.5
R^2	0.69	0.7
Beta S	0.04	0.45
Beta $\log \mathrm{TDS}$	–0.6	–0.4
Beta E	–0.34	–0.31

It follows from equation (6) and Fig. 3 that maximum species diversity (H = 4.1 bit/specimen) and structure complexity are observed at minimum (among the studied waterbodies) mineralization 0.027 g/l ($\log \mathrm{TDS} = -1.569$).

The mutual influence of mineralization and area of some lakes on plankton and benthos diversity was estimated using mineralization and area data. Results of two-factor analysis are shown in Table 1. The relation between species number (n) and area (S, km^2) plus mineralization (TDS g/l) can be represented as the following equation:

$$n = aS + b\mathrm{TDS} + c.$$

Neither water mineralization nor lake area influence the number of phytoplankton species (Table 1). Species diversity of phytoplankton is determined by other factors. The number of zooplankton species depends on water mineralization and is almost independent of lake area. Both lake area and water mineralization influence the number of benthic animal species. Lake area in this case influences species number to a greater extent. At the same time, some other factors may play an important part here, because their share of dispersion is around 30%.

Another morphometric parameter of lakes was considered for zooplankton and zoobenthos, namely, lake capacity ($E = h_{\mathrm{av}}/h_{\max}$, where h_{av}—average depth, $h_{\max}$—maximum) which reflects the shape of bottom relief and the share of littoral in total lake area. The results of three-factor analysis (area, capacity, water mineralization) are shown in Table 2.

Inverse relation is observed between number of zooplankton species and water mineralization and lake capacity and, to a relatively very small extent, lake area (Table 2). The number of bottom animal species is determined by both morphometric parameters and level of water mineralization, whereas species diversity mostly depends on lake area and water mineralization.

DISCUSSION

The number of plankton and benthos species in lakes depends on such environmental factors as lake morphometry and water mineralization. In the studied lakes, the number of phytoplankton species generally decreases as mineralization increases, from 178 at mineralization 0.027 g/l to 6 at mineralization 230 g/l. In plankton and bottom animal communities, the number of species first increases and then, after reaching its maximum, decreases as mineralization increases. Maximum number of zooplankton and zoobenthos species was observed at mineralization around 0.4 g/l. According to M.B. Ivanova and T.I. Kazantseva [7], maximum zooplankton species number, with widely dispersed data, is observed in lakes with mineralization smaller than 1–3 g/l. My data and the results of that study [7] may differ because maximum mineralization in the latter is no greater than 17 g/l, whereas in this study maximum mineralization is 230 g/l. Change from increase to decrease in zooplankton species number is observed in lakes with water mineralization around 1/3 (0.4 g/l) of the same parameter in zoobenthos (1.12 g/l). Thus, zoobenthos is probably less sensitive to mineralization changes than zooplankton.

Analysis of the influence of morphometric characteristics and water mineralization on species diversity of lake communities has shown that both these factors are not crucial for phytoplankton. Phytoplankton species number is more dependent on other factors (probably, e.g., light, nutrients, etc.). Zooplankton species number is strongly dependent on water mineralization and lake capacity and quite weakly dependent on lake area. Zoobenthos species number depends on all of the three studied factors, but the influence of lake capacity is weaker than the influence of the other two.

Comparison of waterbodies with different water mineralization has shown that mineralization increase leads to a decreasing number of species and to simplification of structure in plankton and bottom communities. This effect is reflected in the decreasing diversity index. Maximum value of this index (4.1 bit/specimen) was observed at the lowest mineralization of all of the lakes studied. This value is close to the theoretically estimated (around 5 bit/specimen) for aquatic communities. Importantly, the share of the production of each species in the aquatic community increases as community structure becomes simpler. Aquatic communities and ecosystems react to increased mineralization by structural simplification; a similar effect is observed in the course of eutrophication or pollution of waterbodies.

Ecosystems of many saline lakes are structurally simple. For instance, the structure of a hyperhaline lake ecosystem often consists of the producer link and a single consumer species (the crustacean *Artemia salina*). For this reason, saline lake ecosystems are useful as model objects for the study of processes and mechanisms of aquatic ecosystem functioning and their changes under the influence of environmental factors, including the anthropogenic ones.

The wide range of species numbers (see equations and figures) can be explained, beside the influence of other factors unaccounted for, by the varying degree of preciseness in identifications and records of plankton and benthos species. This is probably due to the unequal proficiency of experts in taxonomy and systematics.

ACKNOWLEDGMENTS

The author is grateful to E.V. Balushkina, S.M. Golubkov, M.S. Golubkov, and Yu.I. Gubelit for the chance to use their data on lakes of the Crimea and to T.I. Kazantseva for advice on and help with statistical and mathematical methods. This study was supported by the Ministry of Science and Education of the Russian Federation, NSh-1634.2002.4 (“School of Production Hydrobiology”); by the Russian Foundation for Basic Research, project no. 05-04-49703 (“Study of the Patterns of Structure Formation and the Interrelations of Biotic Matter and Energy Flow in Lake Ecosystems”); and by the Program of the Presidium of the Russian Academy of Sciences, “Scientific Basis for the Conservation of the Biodiversity of Russia.”

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