Acta Hydrobiol., 37 (1995), suppl. 1, 47–54. Kraków, March 1996

Heat content as a basis for lake classification

Nina P. SMIRNOVA[1] and Andrei L. SMIRNOV[2]

[1]Institute of Limnology, 9 Sevast'yanova St., 196199, St. Petersburg, Russia

[2]St. Petersburg State University, 7/9 Universitetskaya Nab., 199034,
St. Petersburg, Russia

(Received 27 April 1995, Accepted 28 December 1995)

Abstract – The heat budget, which is an integral factor characterizing the thermal state of a lake is proposed as a basis for lake classification in the paper. Calculation of the heat budget according to the morphometric characteristics of more than 4000 lakes allowed lake classification to be made. The relationship between water temperature and total radiation was chosen as a secondary classification factor.

Key words: heat budget, lake morphometry, lake classification, water temperature.

Pojemność cieplna jako podstawa klasyfikacji jezior. Jako podstawę klasyfikacji jezior zaproponowano bilans cieplny, który jest istotnym czynnikiem charakteryzującym stan termiczny jeziora. Klasyfikację jezior oparto na bilansie cieplnym obliczonym z uwzględnieniem charakterystyki morfometrycznej ponad 4000 jezior. Zależność pomiędzy temperaturą wody i całkowitym promieniowaniem uznano za dodatkowy czynnik klasyfikacji.

1. Introduction

In the life of both a water body and all life on Earth the solar radiation incom and its spatial distribution play a leading role. Solar radiation determines th intensity of the hydrological (evaporation, freezing, water temperature), dynami (mixing), biological (primary production, life cycles of hydrobionts), and hydr chemical (mineralization, gas regime) processes. Qualitative and quantitativ characteristics of the heat input and its transformation are most significant. Th heat balance method may be used for lake classification and regionalization.

When analysing the well-known lake classifications (Smirnova 1993) one ma draw the conclusion that the structure of the heat balance may be a reliable bas for lake thermal classification. It is known that the best means of classification that based on the pivotal process, which determines the development of th classified object.

The radiation input is a zonal phenomenon and therefore brings about th specific physico-geographical features of lakes and their basins.

2. Heat budget as a main classification factor

The lack of long-term data on the components of heat balance demands a search for another integral factor, which could characterize the thermal state of the lake and take into account its peculiarities, such as origin of the lake and characteristics of the lake basin (average depth, water area, and volume). This factor must also be dependent on the local climatic conditions etc. For choosing between various classification factors preference must be given to those which would correlate with a greater number of heat balance components and other elements of the lake complex (morphometry, catchment area, specific physico-geographical and climatic features, trophic level). These factors should be simple and reliable as well as easily determined in the study and they would permit comparison of the lakes on the given territory of an entire country.

The heat budget was chosen as suitable basic classification factor. The heat budget is determined as the difference between the maximum (for the temperate latitudes this is late July to early August) and the minimum (late February to early March) values of heat storage in the lake. The annual heat cycle in lakes is controlled by the geographical location of the lake, its altitude (the effect of great altitude is similar to that of high latitude) and degree of continentality.

It is not difficult to determine the heat budget if thermal observations are carried out in lakes throughout the year. However, it is known that the available thermal data are insufficient and incomplete. For example, in the territory of the European part of Russia thermal data are available for only 83 lakes, in the Intermediate region for 54, and on the remaining territory for 39 lakes. Such a database is obviously insufficient, since it only covers about 0.001% of all lakes in the country.

Attempts to establish a relationship between the heat budget and the morphometric characteristics were made by Forsh (1968). Forsh and Varentsov (1978) generalized the data for the Polar Ural region (8 lakes), Kola peninsula (10), North-Western Russia (25), and Byelorussia (21) and plotted graphs of relationships between the heat budget and the average lake depth. As a result four following zones were singled out: Tundra lakes, Forest Tundra and Northern Taiga lakes, Middle and Southern Taiga lakes, and Mixed Forest lakes.

This classification was based on the heat budget as a function of lake average depth, geographical location (the coordinates and altitude), and latitudinal zone. The heat budget value reflects the rate of water and heat exchange in the lake. Forsh was the first to prove by means of field data that: (1) heat budget depends on the average lake depth and the latitudinal zone and (2) the rate of increase in the heat budget rises southward as the average depth increases.

Studies conducted by Forsh (1968, 1974) and Tikhomirov (1982) showed that the mean water temperatures for a time period of 5–7 years are sufficient to characterize the mean multi-year variables, which agrees with results reported by Pivovarova (1977) that showed the validity of the 10-year reference period for characterization of the mean multi-year value of the total radiation.

To evaluate the heat budget through morphometric characteristics for a large number of lakes (51) of the North-Western Russia, the following formula was proposed (Khubbatullin and Lubyanoi 1988, Khubbatullin 1989):

$$W = 1.56\, h_a - 0.14\, h_{max} + 4.51\, V - 0.02\, S - 0.49\, \alpha + 3.38 \qquad (1)$$

where W is the mean multi-year heat budget of the lake (kcal cm^{-2}), h_a and h_{max} are the average and maximum lake depths (m) correspondingly, S and V are the lake water area (km^2) and the lake volume (km^3) correspondingly, a is the lake depth coefficient equal to $h_s/S^{1/3}$.

Coefficients of the regression equation (1) are statistically significant with a probability greater than 95%. The proposed formula has been tested against independent data and revealed that its error does not exceed 10%. However, we should be sure that the coefficients in formula (1) are relatively invariant for different geographical regions. A comparison made for 40 lakes showed that the difference between the experimental and theoretical results is less than 10–12%. It is quite difficult to make such a comparison since formula (1) is valid for the multi-year values and the experimental data for the heat budget are usually obtained for a 1–2 year period. Such data have been obtained for 23 lakes in the Transural region (Forsh and Varentsov 1978). The average difference between the theoretical and experimental results is 10.5%, and for the Kola peninsula and Karelian lakes it is about 10–12.5% (Freindling 1962, 1965).

The heat budget analysis was made for 3877 lakes by means of formula (1). The mean heat budget values are given as a function of the average lake depth for various regions (Table 1, fig. 1). It may be noted that increase in the lake area leads to increase in the heat budget. Therefore, there is the problem of scaling the lakes, for which formula (1) could be used. An analysis of the data shows that for lakes with water areas exceeding 200 km^2 and for the shallow lakes, with depths down to a few cm, which are characteristic of the arid zone, evaluation of the heat budget by means of formula (1) is not valid.

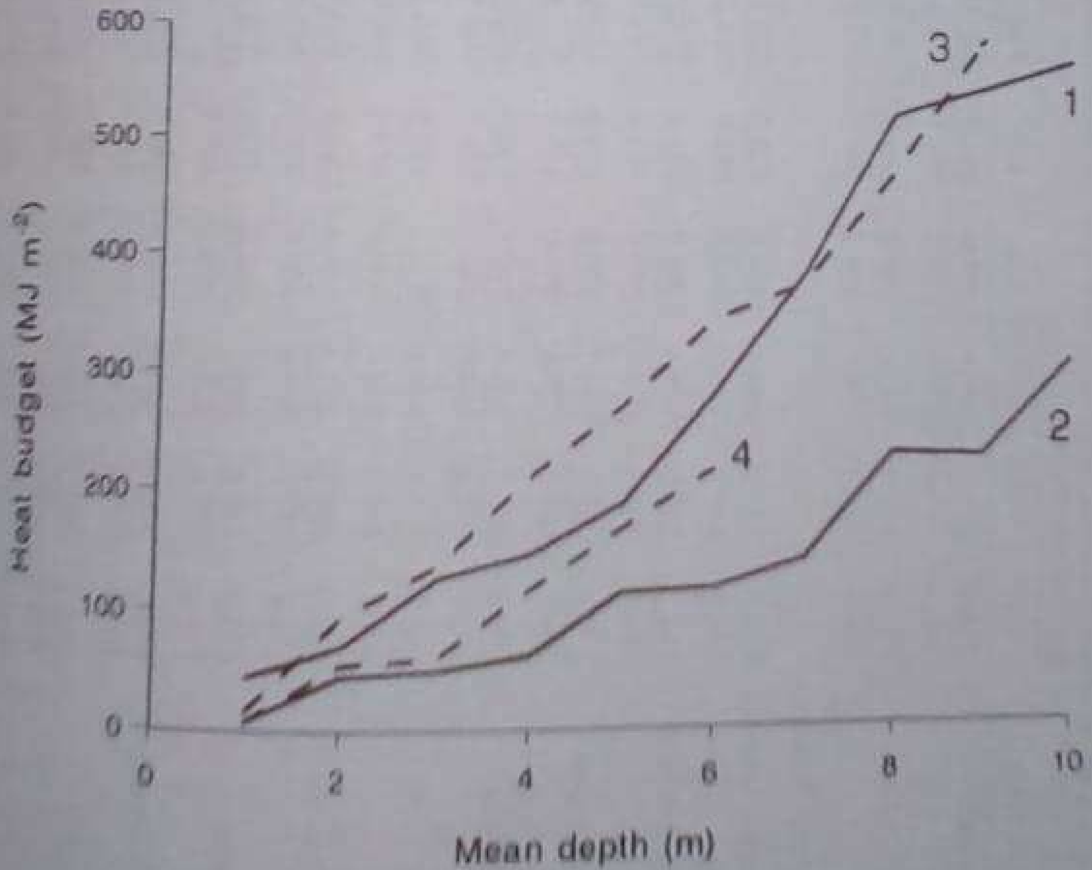

Fig. 1. The effect of average depth of the lake on the heat budget: 1 – Karelia lakes with areas 1–200 km^2, 2 – Karelia lakes with areas 1 < km^2, 3 – Kazakhstan lakes with areas 1–200 km^2, 4 – Kazakhstan lakes with areas 1 < km^2

Table 1. The heat budget (MJ m^{-2}) of lakes with different average depth (numerator for lakes with areas 1–200 km^2, denominator for lakes with areas 0.1–200 km^2)

Region	Average depth (m)										Number of lakes	Share of lakes with area < 1 km^2 (%)
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10		
Kola peninsula	$\frac{176.0}{169.7}$	$\frac{201.1}{194.4}$	$\frac{230.0}{217.0}$	$\frac{267.0}{257.3}$	$\frac{297.9}{294.1}$	$\frac{320.1}{328.5}$	$\frac{357.8}{350.3}$	$\frac{451.7}{368.7}$	$\frac{455.0}{455.0}$	$\frac{463.4}{454.2}$	150	24.7
Karelia	$\frac{179.8}{166.8}$	$\frac{201.1}{189.4}$	$\frac{242.6}{206.0}$	$\frac{258.9}{216.2}$	$\frac{289.5}{264.8}$	$\frac{360.3}{295.0}$	$\frac{438.3}{352.4}$	$\frac{541.3}{442.5}$	$\frac{565.4}{}$	$\frac{582.9}{533.0}$	365	57.3
North-western Russia												
Leningrad region	$\frac{175.1}{171.8}$	$\frac{213.3}{188.6}$	$\frac{245.1}{221.0}$	$\frac{284.5}{248.5}$	$\frac{333.5}{261.0}$	$\frac{375.4}{304.2}$	$\frac{399.7}{360.3}$	$\frac{468.0}{}$	$\frac{495.7}{406.0}$	$\frac{505.3}{505.3}$	248	54.8
Novgorod region	$\frac{177.2}{166.8}$	$\frac{212.0}{182.3}$	$\frac{254.1}{204.9}$	$\frac{283.7}{246.0}$	$\frac{331.4}{271.6}$	$\frac{353.2}{284.5}$	$\frac{429.0}{297.5}$	$\frac{466.3}{332.7}$	$\frac{507.4}{396.0}$		594	81.2
Vologda region	$\frac{179.3}{160.9}$	$\frac{207.8}{196.5}$	$\frac{244.7}{225.8}$	$\frac{269.8}{261.9}$	$\frac{293.3}{278.2}$	$\frac{357.4}{357.4}$	$\frac{410.6}{397.2}$			$\frac{437.4}{}$	229	55.9
Pskov region	$\frac{180.2}{169.7}$	$\frac{232.1}{203.2}$	$\frac{255.2}{234.6}$	$\frac{308.4}{267.7}$	$\frac{339.0}{304.6}$	$\frac{375.8}{346.5}$	$\frac{403.9}{364.5}$	$\frac{477.7}{429.5}$	$\frac{500.7}{438.3}$	$\frac{}{476.4}$	643	66.3
Byelorussia	$\frac{166.3}{167.6}$	$\frac{205.3}{196.5}$	$\frac{248.5}{221.2}$	$\frac{274.4}{246.0}$	$\frac{315.5}{274.4}$	$\frac{338.1}{282.2}$	$\frac{399.7}{331.4}$	$\frac{415.6}{352.8}$	$\frac{427.0}{383.8}$	$\frac{479.8}{412.3}$	492	68.9
Ural and Transural	$\frac{179.3}{178.9}$	$\frac{196.1}{197.3}$	$\frac{251.4}{251.4}$	$\frac{308.0}{308.0}$	$\frac{360.8}{360.8}$	$\frac{398.5}{400.6}$		$\frac{460.9}{460.9}$			82	6.1
Tyumen region	$\frac{178.5}{174.3}$	$\frac{210.8}{202.8}$	$\frac{249.7}{238.0}$	$\frac{286.6}{279.0}$	$\frac{313.4}{305.9}$	$\frac{371.2}{371.2}$					373	43.7
Novosibirsk region	$\frac{184.4}{184.4}$	$\frac{209.9}{222.9}$	$\frac{222.5}{222.5}$	$\frac{305.9}{305.9}$	$\frac{356.2}{356.2}$	$\frac{406.8}{406.8}$					29	3.5
Kazakhstan	$\frac{164.7}{162.6}$	$\frac{221.2}{208.7}$	$\frac{251.8}{244.7}$	$\frac{308.4}{295.4}$	$\frac{350.7}{350.7}$	$\frac{408.9}{393.4}$	$\frac{433.2}{433.2}$	$\frac{504.5}{504.5}$	$\frac{592.5}{592.5}$		550	38.0
Altai	$\frac{158.8}{158.0}$	$\frac{178.1}{176.4}$	$\frac{213.3}{213.3}$	$\frac{278.2}{278.2}$	$\frac{308.8}{308.8}$	$\frac{380.9}{380.9}$				$\frac{440.8}{440.8}$	122	23.0

It was noted that the heat budget increases with the lake water area, and reaches its climatic maximum for a lake area of about 20 km^2 (Birge 1915, Hutchinson 1957). Gorham (1964) was of the same opinion, but he believed that the relationship between the water area and the average depth is also important, since even small volume lakes with steeply sloped banks have slightly higher heat budget values than lakes with gentle slopes. The lakes of Karelia belong to the first group and those of Kazakhstan to the second. The effect of the form of basin for small lakes has been found to be stronger.

The effect of the water area on the heat budget of the shallow lakes in the Kazakhstan arid zone and of the small lakes (up to 1 km^2) in the Karelia humid zone is the following. On account of greater wind velocities, openness of reservoirs in the arid zone and significant water mixing in lakes of equal depth the heat budget is slightly greater than in the humid zone. For depths greater than 5 m and lake water areas larger than 5 km^2 the heat budget increases significantly (fig. 1). We derived regression equations with correlation coefficients of about 0.97–0.99. These equations are of the same type as Gur'yanova's (1988) equation derived for lakes in Byelorussia.

What is the typical size of lakes (area and depth) in different regions, for which the heat budget has been calculated by formula (1)? The most common size of lakes for which the heat budget has been calculated by formula (1) is about of 1–5 km^2 for the lakes of the Kola peninsula, Leningrad, Vologda, and Tyumen regions, Kazakhstan and Altai, and about 0.1–0.5 km^2 for those of Karelia, Novgorod, and Pskov regions and Byelorussia. The series of lakes in the Novosibirsk area, Ural, and Transural regions are not representative. In all the considered regions most common are lakes with depths of about 1–2 m. However, in the Pskov region there are lakes with depths of about 2–3 m, while in Karelia and Leningrad regions they are about 3–4 m. The shallowest lakes (down to 1 m) are characteristic of Kazakhstan. A histogram of the heat budget of the lakes indicates that in the humid zone lakes are deeper and smaller.

3. The annual heat cycle as a secondary classification factor

Since the thermal regime of the lake is determined by total income of radiation, the annual water temperature cycle in the lake expressed in the form of dependence of the water temperature on the total radiation Q ($t = f(Q)$). This cycle, which has the form of an ellipse (fig. 2) may characterize the thermal features of the lake and the effect of morphology, morphometry, local climate, and hydrological peculiarities such as mixing etc. (Szumiec 1978).

The ellipse parameters such as the ratio of the large and small semi-axes (λ) and the slope angle between the large axis and the abscissa (α) are considered as the second factor in the thermal classification of the lake. The difficulties of such an approach are in the development of the method of calculating the ellipse parameters. Szumiec (1978) suggested considering the canonical equation for an ellipse and obtaining its parameters by the least mean squares method. In this case even in the absence of observations of the annual water temperature one can find parameters λ and α, and coordinates of the ellipse centre x_c and y_c, which approximately account for the mean annual values of water temperature and total radiation. In view of the lack of a comprehensive database, the collection of initial information is difficult. One must find the time interval of computation in order to prove that it reflects the mean multi-year values of the total radiation and the surface water temperature.

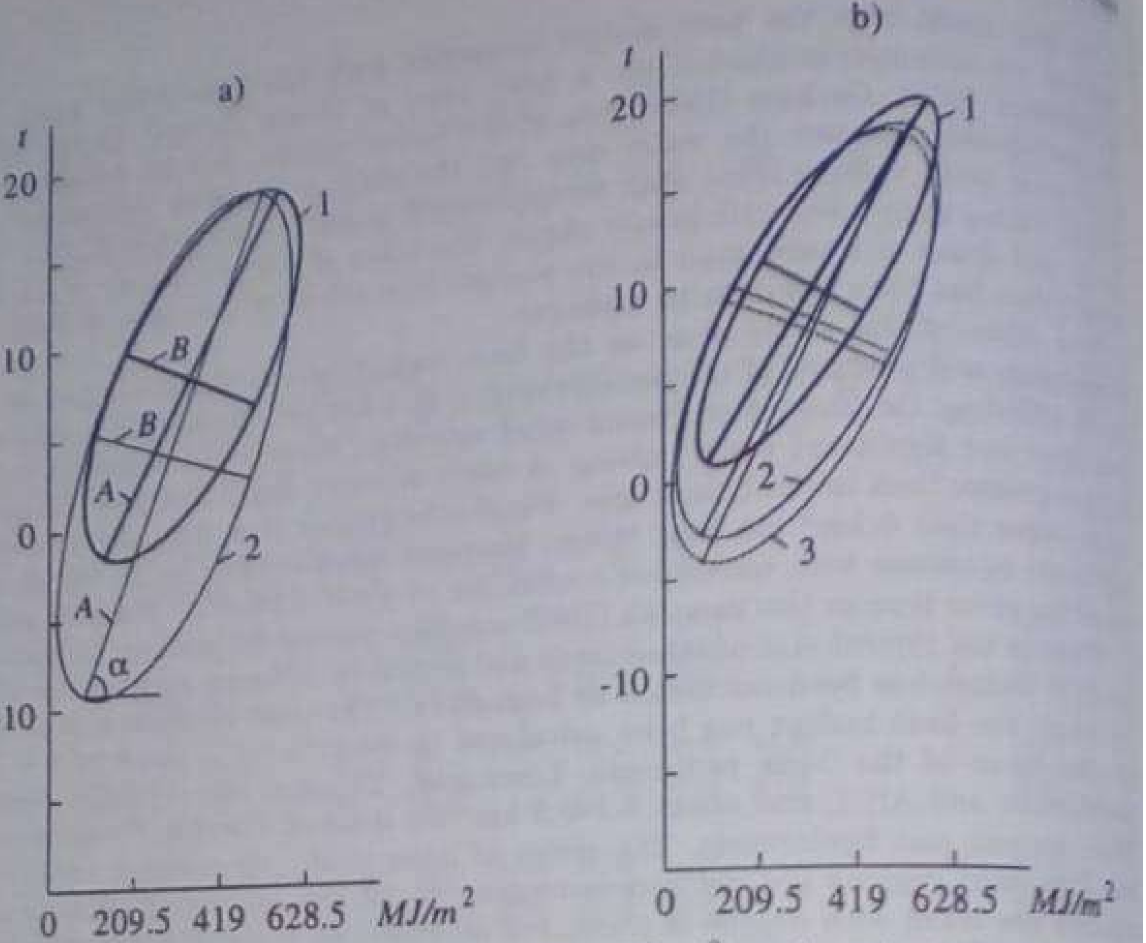

Fig. 2. The effect of the total radiation flux density (MJ m^{-2}) on the water temperature (t, °(in two groups of lakes, a (1 — Suoyarvi, 2 — Syamozero) and b (1 — Kavgolovskoe, 2 — Kr 3 — Cheremenetskoe): A — large ellipse axis, B — small ellipse axis, α — slope angle betwe the large ellipse axis and the abscissa.

All data were obtained for a 8–9 year period (from 1978 to 1985 or 1986). was pointed out above that for the total radiation and the water temperature su a period of observation is sufficient to characterize the multi-year period. For t lakes considered, with the water temperature measured over the mentioned peri 18 actinometric stations were chosen in North-Western Russia and in t Intermediate region, situated as close as possible to the lakes. The mean wa surface temperatures for 62 lakes in the European part of Russia and for 90 la of the Intermediate region were calculated for each month during the same peri The form of the plotted ellipse shows the intensive increase in the solar radiat in the first part of the year. In this period the heat loss in a lake is greater th the absorbed radiation. In spring the rate of increase rises both in the case of t radiation and water temperature (May–June). At latitudes 50–60° the t radiation income decreases from mid August but the water body still accumul heat. Only in November do the lakes start significantly to lose heat, but different rates, depending on the lake depth (fig. 2). Naturally, all of the ell parameters depend on the water body morphometry and morphology, local clim and continentality.

Analysing the results (Table II) it was found that the small degre continentality correlates with the small value of the mean monthly total radi and the water temperature. The length of the large ellipse axis increases wit annual total radiation amplitude, and the length of the small axis increases the volume of the water body. Table II also gives information about the eff

Table II. The factors in thermal classification of lakes: α — the slope angle between the large ellipse axis and the abscissa, and λ — the ratio of the large and small semi-axes of ellipse of the annual water temperature cycle as a function of the total radiation.

Region	λ	α		Degree of continentality	Latitude (°N)	Longitude (°E)
		mean	range			
Kola peninsula	1.1–2.4	29	18–30	24	67–69	30–35
Karelia	1.2–3.2	52	40–64	24–30	66–64	31–33
North-west Russia[1]	1.7–3.6	54	44–69	25–31	56–62	28–38
Byelorussia	1.7–3.7	44	33–53	31–34	55–56	24–31
Poland	2.4–5.8		57–58	30–40	50–55	17–23
Great Britain	2.3–3.1		55–57	10	55	3
Ural and Transural	3.2–4.7	61	41–83	61–65	54–57	60–64
Western Siberia[2]	3.4–6.3	61	44–69	55–67	52–56	76–78
Kazakhstan	2.6–8.5	64	44–88	58–65	50–56	69–78
Altai	3.5–4.1	63	56–70	60–62	52–56	81–90

[1] Leningrad, Novgorod, Vologda and Pskov regions

[2] southern part

the geographical latitude, the lake depth, and continentality on λ and α factors both for the European part of Russia and the Intermediate region. The larger slope angle corresponds to the larger temperature amplitude in comparison with the total radiation amplitude. This effect characterizes the lakes and lake groups of the Intermediate region, the continentality of which is about 65–67 (Smirnova 1993).

The comparison of different ellipse elements allows determination of the water temperature in lakes as a function of:

- lake morphology, for lakes situated in similar climatic, orographic, and hydrological conditions;
- local climatic factors, for lakes with similar morphometric, orographic, and hydrological conditions;
- meteorological conditions of a given year, which may be revealed by comparison of the ellipse parameters for a given year and those for mean multi-year total radiation and water temperatures.

Moreover it allows the determination of the deviation of the annual cycle $t=f(Q)$ for a given year from the mean multi-year data, which testifies to fluctuations in the total radiation income.

4. Conclusions

The classification of lakes by means of factors λ and α shows that lakes must be classified not over the entire region but over sub-regions, where they may be divided into groups with similar values of the mentioned factors. The thermal state of a lake may be classified by heat budget W and by factors λ and α. These factors are sufficiently reliable and available and do not require special observations, except main morphometric characteristics and 6–7 month observations of the water surface temperature and total radiation.

The factors chosen for lake classification reflect the natural, geophysical peculiarities of regions and take into account their morphology, morphometry, lake hydrology, and local climate. Thus they are integral and informative. Within these regions a more detailed division of the lakes may need to be done

Acknowledgements - The authors would like to express their gratitude to S. Leontiev (Institute of Limnology, Russian Academy of Sciences) for developing the computer programs and to Prof. D. Pozdnyakov (Institute of Limnology, Russian Academy of Sciences) and to Prof P. Frise (Carleton University, Canada) for their kind advices.

References

Birge E.A. 1915. The heat budgets of American and European lakes. Trans. Wis. Acad. Sci Arts Lett., 18, 166–213.

Forsh L.F. 1968. (Forš L.F.) Termičeskij režim, teplovoj balans ozer i rol' ilovoj tolši v teplovom büdžete [The thermal regime, heat balance of the lakes and the role of the silt sediments in lake heat budgets]. In: Ozera različnyh landšaftov Severo-Zapada SSSR [Lakes of different landscapes of the North-Western USSR]. Vol. 1. Leningrad, Nauka, 166–208 [in Russian].

Forsh L.F. 1974. (Forš L.F.) Termičeskij i teplovoj režim ozer Kol'skogo poluostrova [The thermal regime and heat balance of Kola peninsula lakes]. In: Ozera različnyh landšaftov Kol'skogo poluostrova. Gidrologiâ ozer i harakteristika ih vodosborov [Lakes of different landscapes of Kola peninsula. Hydrology of lakes and characteristics of their catchment areas]. Vol. 1. Leningrad, Nauka, 156–194 [in Russian].

Forsh L.F. and Varentsov L.N. 1978. (Forš L.F. and Varencov L.N.) Termičeskij režim i teplovoj balans [The thermal regime and heat balance]. In: Landšaftnij faktor v formirovanii gidrologii ozer Ùžnogo Urala [The landscape factor in formation of hydrology of the lakes in Southern Ural]. Leningrad, Nauka, 154–180 [in Russian].

Freidling V.A. 1962. (Frejndling V.A.) Temperaturnyj režim i oborot tepla v nekotoryh ozerah Karelii [The thermal regime and the heat cycle in lakes of Karelia]. PhD Thesis, Leningrad, 19 pp. [in Russian].

Freidling V.A. 1965. (Frejndling V.A.) Termika i èlementy gidrofiziki ozer Zaonež'â [The thermics and the elements of hydrophysics in lakes of Transonega]. Trudy Sev. NIIGM, Petrozavodsk, 79–92 pp. [in Russian].

Gorham E. 1964. Morphometric control of annual heat budgets in temperate lakes. Limnol. Oceanogr., 9, 525–529.

Gur'yanova L.V. 1988. (Gur'ânova L.V.) Morfometriâ malyh ozer i ih termika [The morphometry of small lakes and their thermics]. Vestnik Belorusskogo Universiteta, Ser. 2 2, 42–46 [in Russian].

Hutchinson G.E. 1957. A treatise on limnology. Geography, physics and chemistry. Vol. 1. New York, J. Wiley and Sons, 1015 pp.

Khubbatullin V.L. 1989. (Hubbatullin V.L.) Osobennosti temperaturnogo režima malyh oze (na primere Zapada i Severo-Zapada EČS) [The peculiarities of the thermal regime of smal lakes (for the West and the North-Western region)]. PhD Thesis, Leningrad, 20 pp. [i Russian].

Khubbatullin V.L. and Lubyanoi A.V. 1988. (Hubbatullin V.L. and Lubânoj A.V.) Vliâni morfometričeskih faktorov ozer na ih termičeskij režim [The effect of morphometric factor of lakes on their thermal regimes]. Deposited in IC VNIIGMI-MCD 10.08.88, N 801-g Leningrad, 11 pp. [in Russian].

Pivovarova Z.I. 1977. Radiacionnye harakteristiki klimata SSSR [The radiation characteristi of climate in the USSR]. Leningrad, Gidrometeoizdat, 336 pp. [in Russian].

Szumiec A.M. 1978. Relationship between the surface water temperature of temperate lak and solar radiation. Verh. Int. Ver. theoret. angew. Limnol., 20, 1013–1016.

Smirnova N.P. (ed.) 1993. Teoretičeskie voprosy klassifikacii ozer [The theoretical problems lake classification]. St. Petersburg, Nauka, 192 pp. [in Russian].

Tikhomirov A.I. 1982. (Tihomirov A.I.) Termika krupnyh ozer [The thermics of large lake Leningrad, Nauka, 232 pp. [in Russian].