Limnological Review (2012) 12, 1: 11-17
DOI 10.2478/v10194-011-0040-2

External water exchange of lakes as the integral indicator of water body types

Arkady M. Doganovsky

Russian State Hydrometeorological University, Malookhtinsky prospect 98, 195196, Saint-Petersburg, Russia, e-mail: dekanat_gf@rshu.ru

Abstract: External water exchange of overflow lakes is presented as the integral indicator, defining the type of lake basin. Intensity of water replacement in the lake (K_w) determines many processes taking place in the lake and its drainage area. Simultaneously this process influences the runoff of the outflowing river. Among the processes in the lake, depending on K_w, transitory-accumulative possibilities, predominance of allochton and limnic processes, and the participation of K_w in forming trophic status are considered. Some examples of the dependence of the parameters of lake level distribution curves upon the K_w values are given. The problem of calculation of K_w for unexplored objects is also regarded. The text contains specific examples of the results of calculations and analysis.

Key words: lake system, water exchange, water balance, level, morphology, transit, accumulation, trophic status, autocorrelation

Introduction

There are more than 8 million lakes on the Earth. They are everywhere on the continents, occupying approximately 1.5-2% of their area. However, there are regions where due to the natural conditions their share is more than 10-15%. The northwestern territory of Russia is such a lacustrine region (Fig. 1). The origin of the lake basins here is the result of the last Quaternary glaciation, the extent of which is delimited by the main moraine belt. Depressions situated to the south of the area of the last Quaternary glaciation were formed mainly during the retreat of the more ancient Moscow glaciation.

There are many lakes in the northwestern part of Russia, including the biggest European lakes: Ladozhskoe (18), Onezhskoe (17), Chudsko-Pskovskoe (19), Ilmen (20), and others. Lakes with their drainage areas create lake systems which are part of a special lacustrine landscape. The considered territory is a zone of excess and sufficient humidity. All the lakes are with outflow, and the river flow is regulated by these overflow lakes. The length of time for which river water stays in the lakes affects its physical and chemical properties. Also, lakes can be considered as accumulators, where all different natural and anthropogenic compounds which find their way into the lake are partially detained.

Many lakes are widely exploited for water supply and irrigation, fishery, and sapropel output, and also lakes are used for recreation. The diversity of lake types predetermines their reaction to climate and weather variations, hence we have various regime characteristics (hydrologic, hydrodynamic, hydrobiologic and others). Such distinctions can be estimated with the integral indicator of intensity of external water exchange of lakes, specified as the coefficient of external water exchange (K_w). Its physical meaning is the intensity or frequency of water mixing in the lake.

So, the main objective of this research is the application of this coefficient for the estimation of a large number of regime characteristics of the lakes. For this purpose it is necessary to determine the coefficient K_w, also for unexplored objects. Lakes with a water surface of more than 5 km^2 and longstanding evolution are considered.

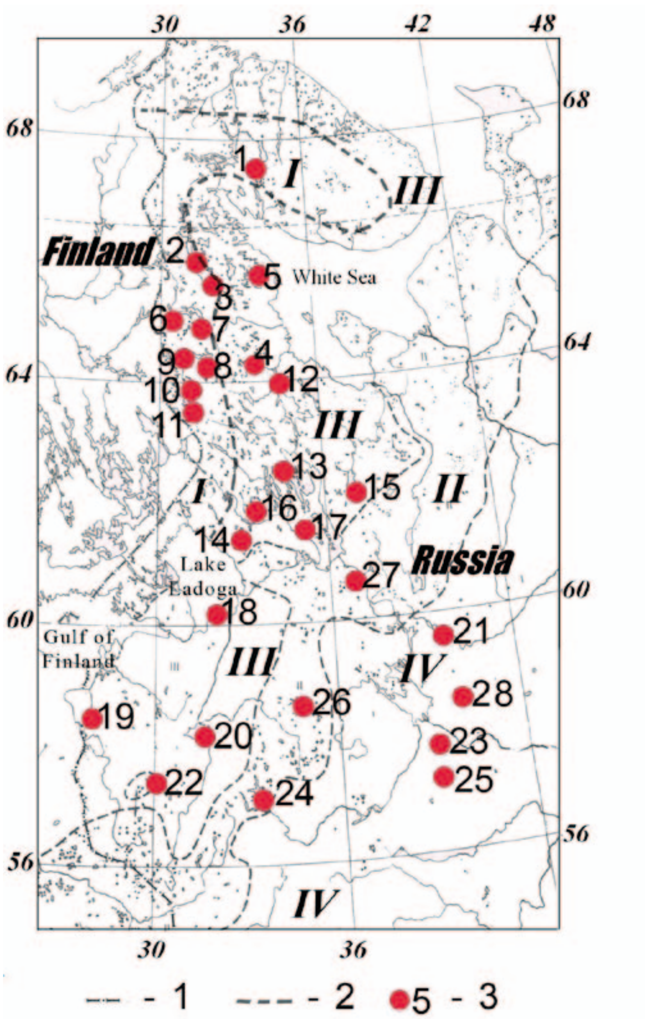

Fig. 1. Map of the northwestern part of Russia: 1 – state border, 2 – boundaries of lake regions with numbers, 3 – positions of the lakes with their numbers. Names of the lakes are in the text

Materials and methods

Coefficient of external water exchange K_w can be determined in volume units (km^3) from the equation of water balance:

$$V_{infl} + V_{atm} - V_{evap} - V_{runoff} = \pm \Delta V_{acc}, \quad (1)$$

where: V_{infl} is inflow of water from drainage areas, V_{atm} are atmospheric precipitations to the lake water surface, V_{evap} is evaporation from the lake surface, V_{runoff} is runoff of lake water, and V_{acc} is retention of water in the lake. When $\Delta V_{acc} = 0$, the balance becomes equilibrated.

Coefficient K_w is determined as the ratio of the sum of yearly inflow or evaporation components to the volume of water in the lake (V_0). However usually, for internal water body processes the water exchange coefficients are calculated as yearly inflow or runoff quantities divided by volume of water V_0 in the lake (Sorokin, 1988):

$$K'_w = V_{inflow}/V_0 \text{ and } K''_w = V_{runoff}/V_0. \quad (2)$$

There are more than 100 thousand lakes in the investigated area; however, 98% of them have an area less than 5 square kilometres.

Many lakes have not been investigated. There are neither hydrometric data nor determinations of volumes of their water masses. Therefore, we obtain data on volumes of water by using the relationship $V_0 = f(A_0)$, where A_0 is the lake surface area. Parameters V_{inflow} and V_{runoff} are calculated by methods well-known in hydrology. Known methods for estimation of water volumes and their analysis in unexplored water bodies are presented by Salo et al. (2010).

In our case it is supposed that basins of the same origin and similar periods of evolution should have comparative dimensions. For example, basins with the same A_0, but tectonic origin are deeper than glacial ones (Doganovsky, 1994). In total, in the considered territory more than 70 explored objects with areas more than 5 km^2 were studied and the dependences were plotted (Fig. 2).

Analysis of all obtained data permitted us to determine four regions. Each of them is characterized with its own close dependence $V_0 = f(A_0)$, presented by the equation:

$$Y = ax^m e^{x-1}, \quad (3)$$

where: $Y = lg(V_0 + 1)$, $x = lg(A_0 + 1)$, a and m are empirical parameters depending on the geomorphologic and geologic peculiarities of the regions. They are given in Table 1 for the four determined regions. These four regions, mainly, correspond to areas with basins of similar origin (Chebotariova et al. 1969; Doganovsky 1996).

Table 1. Values of empirical parameters in equation (3)

Region	I	II	III	IV
a	0.07	0.03	0.02	0.01
m	0.90	1.10	1.02	1.13

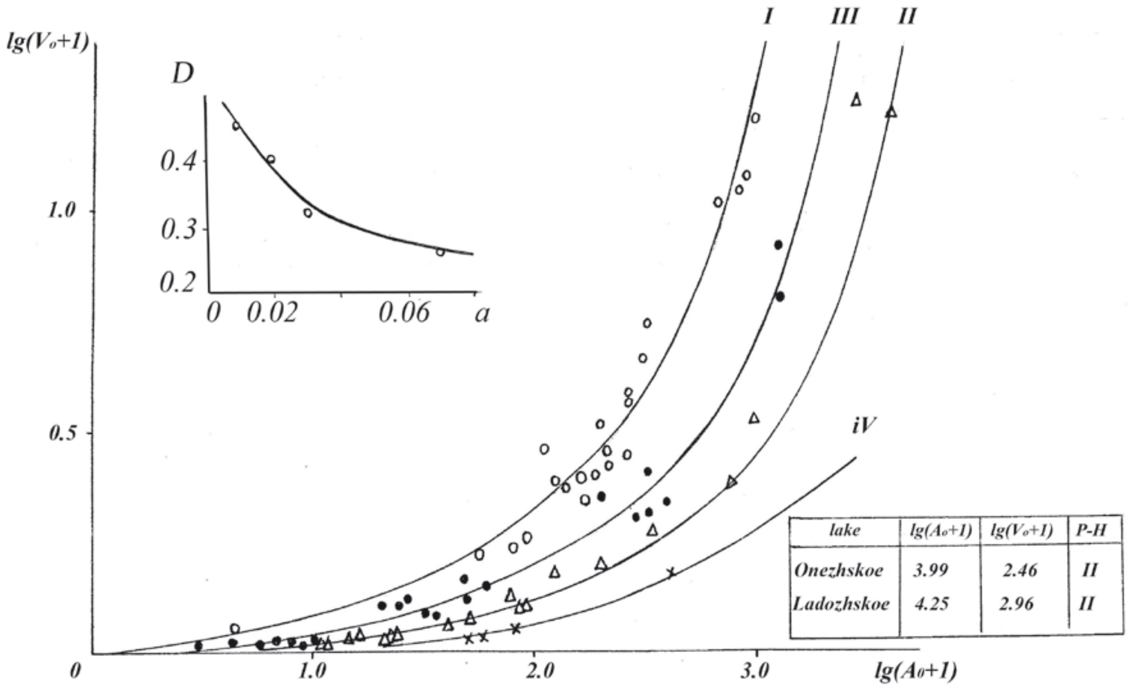

Fig. 2. The dependences of the volume of water in the lake on its area

Additionally, the dependence between the average values of parameters *a* for the investigated region and mean characteristics of the shapes of basins ($D=\overline{H}/H_{max}$, where $\overline{H}$ and H_{max} are average and maximum values of the depths) is presented in Fig. 2.

The lakes from west Karelia and from the greater part of the Kola Peninsula with their location at a height of 100 m and more are referred to as the first region (I). Basins of this region are mainly of tectonic and glacial origin. Lakes here are relatively large-sized with considerable depths and oriented in the direction of tectonic dislocations (Lake Topozero (3), Lake Niuk (8), Lake Rovkulskoe (10), Lake Leksozero (11), Lake Umbozero (1) and others).

The second region (II) stretches along a narrow strip along the main moraine belt, which is a zone of maximum glacial retention. It is a hill-morain territory with Andomskaya, Vepsovskaya and Valdaiskaya uplands and Tikhvinskaya and Baltiiskaya ridges. Lake Kovzhskoe (27) and Lake Valdaiskoe (26) are located here. Having levels of water at the edge usually more than 100 m the lakes of this region are deeper than lakes of region III and shallower than lakes of region I.

The lakes from east Karelia and the Kola Peninsula located at heights of less than 100 m (Lake Vedlozero (15), Lake Sumozero (12), Lake Lizhmozero (13) and others) are referred to as the third region (III). Ladozhskoe, and Onezhskoe, the largest lakes of northwestern Russia, with the altitude of their location less than 100 m can also be classified in the third region. The south and south-east boundary of this region is the boundary of late valdai glacial relief. It is a region of lake-glacial plains. In comparison with the first region lakes here with the same A_0 are shallower.

The fourth region (IV) is situated to the South-East and is limited by the boundary line of the Moscow glaciation, i.e. before Smolensk-Moscow upland. There are lakes Nero (23), Pleshcheevo (25), Chukhlomskoe (28) and others here. The lakes of this region are shallower than lakes of other regions. For area A_0 = 100 square km, for example, approximate average depths for regions I, II, III, and IV are 10-11 m, 3-4 m, 5-6 m, and 2-3 m respectively.

These regions are characterized by their own shapes of river channel that were typified according to the dependence of their average yearly water discharge in riverheads (Q) on the levels of lakes (H). Data from 20 sites were analysed for this task.

Determinations of K_w' and K_w" were made on the basis of observations. In the event where there were no observations, the determinations were obtained by indirect methods using the equations of water balance:

$$K'_w = V_{inflow}/V_0 = h_{runoff} A_{drarea}/A_0 \overline{H} = h_{runoff} K/\overline{H} 10^2, (4)$$

$$K'_w = V_{runoff} / V_0 = 1/\overline{H} \, ((h_{runoff} K / A_0 10^2) + P - E), (5)$$

where: h_{runoff} is the runoff from the lake drainage area (mm); A_{drarea} is the drainage area (km^2); K is special drainage ($K = A_{drarea} / A_0$); $\overline{H}$ is an average depth of the lake (m); P and E are precipitations and evaporation from the lake surface respectively (mm).

From the above equations (4) and (5) it follows that values of water exchange coefficients are determined by climatic parameters (h_{runoff}, P, E) and the structural peculiarities of the lake systems ($\overline{H}$, K, A_0).

Values V_0 ($V_0 = A_0 \overline{H}$) and K are determined on the basis of corresponding maps and equation (3), h_{runoff} on the basis of river runoff (mm) maps or with the help of the method of analogy.

In the considered territory, K_w' and K_w" were calculated for many explored and unexplored lakes. The results of calculation for lakes with an area of more than 5 km^2 showed that water exchange coefficients by inflow vary in wide limits, from $K_w' = 0.08$ (Ladozhskoe lake) and more. However, usually, $K_w" > K_w'$.

Transit and retention possibilities of the lakes

External water exchange together with the morphology of basins determine the development of interior processes and, first of all, the ability to retain diverse compounds incoming from drainage areas including eutrophic (for example, phosphorus) and erosion products. These substances affect the evolutionary changes of the water body (during sedimentation) and also the formation of physical and chemical properties of water.

From these positions the lake basins can be divided into two specific groups: transitory ($K_w" > 100$) and retention ($K_w" < 1$).

For the first group it is typical for there to be a predominance of transitory waters and a dependence of hydrologic regimes upon drainage, the area of which can be tens or hundreds of times as large as the areas of the lakes themselves. The processes in the basin of this group are allochtonic (terrigenous, external).

The processes of accumulation of water and incoming matter prevail in the second group of lake basins. Interior lake processes (limnic, autochtonic) determine the regime of these lakes. This classification of lake basins proposed by Bogoslovsky (1975) is given, with minor revision, in Table 2.

For endorheic lake basins, where $K_w" = 0$, the main water exchange takes place through evaporation, and all incoming substances accumulate. There are no such lakes in our territory. Calculations of K_w' and K_w" allow regions to be marked out with types of lakes shown in Table 2.

The majority of lakes of the considered territory are of the transit-retention class and they are middle drainage lakes (Upper Kuito, Cheremnetskoe (22), Vodlozero, Kubenskoe, Leksozero, Niuk, Kimasozero and others). One should consider Chudsko-Pskovskoe, Seliger, Nizhnee Kuito, Vedlozero, Rugozero, Engozero, Syamozero, Pleshcheevo as weakly transitory lakes. Ladozhskoe, Onezhskoe, Topozero, and Pyaozero are lakes with insignificant water exchange.

Each class of lakes retains the compounds incoming from the drainage area in its own way, which forms its unique composition of the water. During the lake water exchange process waters entering from different zones of the drainage area, so with their own physical, chemical, and biological properties, interact and mix, forming the composition of lake water and also of waters of rivers outflowing from the lake. The slower the water exchange, the longer water stays in the lake basin and experiences more impact of limnic factors. This promotes an increase in biomass, for example zooplankton, the quantity of which is determined not only by its allochtonic content, but also by its formation in the lake. Therefore at the present time inverse dependences between zooplankton biomass and intensity of external water exchange are determined (Drabkova and Sorokin 1979).

Being the main characteristic of the intensity of transit through the lake of all waters and compounds

Table 2. Classification of lake basins by their external water exchange.

Class	Transit	Transit–Retention	Retention–Transit		
	strongly drainage lakes		middle drainage lakes	weakly drainage lakes	large lakes
Water exchange K_w"	< 100	10-100	1-10	0.1-10	< 0.1
Period of water exchange	hours, days	weeks, months	months, seasons, years	years, tens of years	tens and hundreds of years

incoming from the drainage area, the value of the coefficient of water exchange under definite conditions can be the indicator of the trophic level of lake. It is known that general phosphorus (P_{gen}) is one of the most important eutrophic substances. Its intensity in the eutrophication of lakes depends on the quantity incoming. The ratio of the accumulating part (P_{acc}) to the incoming one (P_{inc}) characterizes the ability of lake to retain the phosphorus. The magnitude of this ratio depends on the indicator of conditional water exchange, P_{gen} content in water coming from the drainage area, and the degree of overgrowing of the lake with superior water vegetation, which promotes the retention of P_{gen} (Prytkova 2002).

The ratio of the incoming part of phosphorus matter (P_{inc}) to the area of the lake characterizes the external biogenic load (L), which determines the trophic status of the lake, or the present state of the lake.

At present, the dependences between the lakes' ability to retain phosphorus, average concentration of phosphorus entering from the drainage area and conditional magnitude of water exchange were established. A clear connection between these characteristics was determined for the lakes of the Karelian isthmus (Prytkova 1987).

For estimation of the average phosphorus concentration in the lake water usually the equation of Dillon (Prytkova 2002) is used:

$$P = L(1-R)/\ \overline{H}\, K_w, \qquad (6)$$

where: L is phosphorus load per year, g m $^{-2}$ yr $^{-1}$, R is a lake's ability to retain phosphorus (in fractions), and $\overline{H}$ is the average depth of the lake basin, m.

As follows from the equation, the more intensive the water exchange, the lower the lake's ability to retain phosphorus in the lake.

Every lake basin has a definite critical load, including phosphorus. An excess of the acceptable load induces a change in trophic level (L_c), i.e. the lake basin attains another trophic status. The magnitude of this acceptable load can be determined by the Vollenvaider formula (Prytkova 2002):

$$L_c = 10\,\overline{H}\,(1+\sqrt{\tau}\,)/\tau, \qquad (7)$$

where: τ is the time for full water exchange, in years ($\tau = 1/K_w$" or V_0/V_{runoff}).

The equation (7) presents the approximation of the dependence $L = f(\overline{H})$, which is shown in Fig. 3.

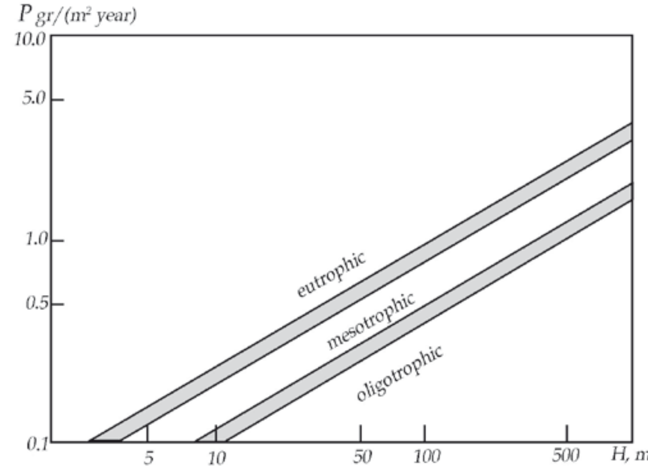

Fig. 3. Trophic state of the lake in dependence on its average depth (H) and quantity of entering phosphorus (P)

The magnitude of L is determined according to the level of intensity of external exchange of the water body. The position of the point in one of three zones reflects the trophic level of the lake.

Examinations by the Institute of Limnology on the lakes of Latgalia including lakes in the considered territory showed that lakes of eutrophic types are already found, especially as regards small lake basins.

External water exchange and lakes' level regime

Intensity of external water exchange through the change in the parameters of statistical distribution curves determines the forming of lakes' level regime.

Lakes, unlike rivers, can retain water, which leads to the internal connection of the time series and an increase in their autocorrelation expressed through the first autocorrelation coefficient (r(1)) (Doganovsky 2007). The connection of K_w' and r(1) is given by the equation:

$$r(1) = 1 - (K_w'/\varphi)\ , \qquad (8)$$

where: φ is the empirical parameter depending on the lake system structure, first of all of the form of the basin and outflowing river channel in the variation level zone and on dimensions of specific drainages (K).

For a 60-year period of the yearly levels of lakes Ladozhskoe, Lache, and Umbozero the magnitudes of φ are equal to 0.3, 3.26, and 6.5 and of K_w' to 0.08, 3.6, and 4 respectively.

The magnitude of external water exchange determines the amplitude of level variations, expressed through the dispersion of series ($\sigma_{\Delta H}^2$). It follows from the known formula of precipitation runoff (σ_1^2) and evaporation (σ_2^2) dispersions that are components of water balance:

$$\sigma_{\Delta H}^2 = \sigma_1^2 + \sigma_2^2 - 2r\sqrt{\sigma_1^2\sigma_2^2}\ , \qquad (9)$$

where: r is the correlation coefficient between precipitation runoff (σ_1^2) and evaporation (σ_2^2) components of water balance.

Values of r and r(1) are connected with the relationship:

$$r = \sqrt{1-r(1)^2}\ . \qquad (10)$$

Therefore the equation (9) can be presented as:

$$\sigma_{\Delta H}^2 = \sigma_1^2 + \sigma_2^2 - 2\sigma_1\sigma_2\sqrt{1-r(1)^2}\ . \qquad (11)$$

For the lakes of the considered territory the values of r(1) are always within the limits from 0 to 1. So, for r(1) = 0, $\sigma_{\Delta H}^2 = (\sigma_1 - \sigma_2)^2$ and r(1) = 1 results in $\sigma_{\Delta H}^2 = (\sigma_1^2 + \sigma_2^2)$. As the result, $(\sigma_1^2 + \sigma_2^2) > (\sigma_1 - \sigma_2)^2$, which is obvious.

Thus, the amplitude of level variations increases with the diminution of K_w' for equal σ_1^2 and σ_2^2, i.e. peculiarities of the lake system structure are an essential factor.

The amplitudes of many years of level variations are shown in Table 3.

Table 3. The amplitudes of many years of level variations

Lake	$\overline{H}$ (cm)	$\sigma_{\Delta H}$	K_w'
Umbozero	70	60	0.26
Rugozero	44	13	0.73
Onezhskoe	61	28	0.08
Sumozero	12	4	0.87
Ilmen	400	120	4.50

Analysis of the structure of time series of lake levels permitted the presence to be established of strongly marked approximately 20-year periods of variations in lake levels.. These periods are especially noticeable on large lakes. By the diminution of external water exchange intensity the amplitudes of variations increase and simultaneously low-frequency fluctuations appear.

In accordance with the growth of K_w' the input of 30-year fluctuations to the general dispersion of lake level variations decreases. For lakes Ladozhskoe and Ilmen, where values of K_w' are 0.08 and 0.4, we receive $\sigma^2/\sigma_{\Delta H}^2$ are equal to 0.4 and 0.2 respectively (Doganovsky, 2006). Simultaneously with the growth of K_w' the proportion of the random component increases. And the variations in lake levels come nearer to variations in river runoff. Evidently, that magnitude of K_w' exerts influence on other characteristics of distribution curves of water.

Conclusion

Evidence of the important role of the intensity of external lake water exchange in the formation of some peculiarities of hydrologic, hydrochemic, and hydrobiologic regimes is presented. In real situation this indicator can be used more widely. It becomes one of the important indicators of the process of mineralization of lake waters, their regime, the presence of biogenic elements, and summer biomass of zooplankton and zoobenthos.

The development of new more reliable methods for the calculation of regime characteristics with K_w' as the argument is a problem of the first order. Also it is necessary to have more perfect procedures for the calculation of this parameter for unexplored objects and estimation of its behaviour over time.

References

Bogoslovsky B.B., 1975, Nekotorye osobennosti vodoobmena i vodnykh mass kontinentalnykh vodoemov (Some features of water and water masses exchange of continental water bodies), [in:] Krugovorot veshchestva i energii v ozernykh vodoemakh (Circulation of substance and energy in lake reservoirs), Izd. Nauka, Novosibirsk: 270-275 (in Russian).

Chebotariova N.S., Kvasov D.D., Kirillova V.A., 1969, Orogidrograficheskie osobennosti (Orohydrographic characteristics), [in:] Gerasimov I.P., Posledniy lednikovyi pokrov na severo-zapade Evropeiskoi chasti SSSR (The last ice sheet in the northwestern part of the USSR), Izd. Nauka, Moscow, 7-11 (in Russian).

Doganovsky A.M., 1994, Amplitudy kolebaniy urovney vody v vodoyomakh ozernogo rayona ETR i ikh raschet (Amplitudes of water level fluctuations in water bodies of lacustrine region ETR and their calculation), Voprosy Ekologii i Gidrologicheskie Raschety: Sbornik Nauchnykh Trudov 116: 115-125 (in Russian, English summary).

Doganovsky A.M., 2006, Mnogoletnie kolebania urovnia Ladozhskogo ozera. Sovremennye problemy gidrometeorologii (Long-term fluctuations of Ladozhskoe lake levels. Modern problems of hydrometeorology), Izd. Asterion, St. Petersburg: 175-183 (in Russian).

Doganovsky A.M., 2007, Urovennyi rezhim ozer – integralnyi pokazatel klimaticheskikh i ekologicheskikh izmenenii (Lake water level regime as an integral indicator of climatic and ecological changes), Obshchestvo. Sreda. Razvite (Terra Humana) 2(1):103-110 (in Russian, English summary).

Drabkova V.G., Sorokin I.N., 1979, Ozero i ego vodosbor – edinaya prirodnaya sistema (Lake and its watershed as a single natural system), Izd. Nauka, Leningrad, p.196 (in Russian).

Sorokin I.N., 1988, Vneshnii vodoobmen ozer SSSR (External water exchange of the lakes of USSR), Izd. Nauka, Leningrad, p. 141 (in Russian).

Prytkova M.Ya., 2002, Nauchnye osnovy i metody vosstanovleniya ozernyh ekosistem pri raznyh vidah antropogennyh vozdejstvij (Scientific principles and methods for recovery of lake ecosystems under different types of anthropogenic impacts), Izd. Nauka, Sankt Petersburg, p.148 (in Russian).

Prytkova M.Ya., 1987, Zakonomernosti razmeshcheniya i vodoobmena malykh ozer i malykh vodokhranilishch (Principles of the location and water exchange of small lakes and small reservoirs), Geografiya i Prirod. Resursy 3: 96-101 (in Russian).

Salo Yu.A., Potakhin M.S., Tolstikov A.V., 2010, Raschet srednei glubiny ozer Karelii pri otsutsvii batimetricheskikh dannykh (Estimation of average depth of Karelian lakes in the absence of bathymetric data), Izv. RGO 142(3): 43-47 (in Russian).