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LAKES TO EXTERNAL IMPACT THE FORECAST OF VULNERABILITY OF BELARUSSIAN UNDER THE CLIMATE CHANGE

***Abstract*:** The article is devoted to the forecast of changes in the vulnerability of lakes in Belarus to external impact in conditions of climate change. The method of E.A. Primak, adapted for lakes of Belarus, was made use of calculate the integral vulnerability indices. Based on the analysis of 14 parameters of the natural regime (morphometric indicators and the rate of external and internal water exchange) and environmental quality characteristics (hydrochemical indicators), the integral indices of the vulnerability to external impact are calculated for 149 lakes of different types. The author describes the classification of lakes in Belarus based on the value of the integral index of vulnerability to external impact, as well as the characteristics of water exchange, thermal stratification and position in the relief. Among all the lakes, classes with a high, medium and low degree of vulnerability were identified. A forecast of the dynamics of the vulnerability of lakes of different types to external impact in accordance with the climate change scenarios RCP2.6, RCP 4.5 and RCP 8.5 was made.

***Key words*:** lake, vulnerability to external impact, water exchange, climate change scenario
***Słowa kluczowe*:** jezioro, podatność na wpływy zewnętrzne, wymiana wody, scenariusz zmian klimatycznych

Introduction

In conditions of changes in the natural environment and intensive anthropogenic pressure, conservation of lake ecosystems is one of the important problems of limnology and hydroecology. The determination of permissible norms of impact on lakes is impossible without a thorough analysis of the relationship between all components of limnosystems and the quantitative assessment of vulnerability to external influences.

The investigation of the resistance of lakes to changes in the parameters of the natural regime and anthropogenic eutrophication has been the subject of many works. At the same time the theory of the existence of several stable states of the lake ecosystem corresponding to different trophic levels is actively being developed. Oligotrophic and eutrophic are the main, but in the eutrophic lake several variants of the equilibrium combination of biotic and abiotic factors are possible [Scheffer 1993, Jeppesen 1998, Scheffer 2001, Scheffer, Carpenter 2003]. An important aspect in this case is the absence of local pollution sources on the catchment that constantly affect the ecosystem and unbalanced its natural stable state.

The most reasonable concept of the stability of aquatic ecosystems proposed by V.N. Mikhailov and K.K. Edelstein implies the sustainability of an aquatic ecosystem, its ability to withstand external natural and man-made influences and internal processes that disrupt the structure and normal functioning of the entire ecosystem or separately its abiotic and biotic parts. With this approach lakes that are unable to maintain their properties at a certain time interval of functioning will be vulnerable [Mikhailov, Edelstein 1996, Datsenko 2007]. This definition was the basis of works of V.V Dmitriev, A.N. Ogurtsov, E.A. Primak et al. They developed a methodology for integral assessment of the resistance of lakes to external impact and their ecological well-being. The authors distinguish adaptive stability, characteristic of lakes and regenerative, characteristic of rivers [Primak 2009, Dmitriev, Ogurtsov 2012, Dmitriev, Ogurtsov 2013, Dmitriev, Fedorova, Biryukova 2016], which is due to the different water residence time to their original state when the anthropogenic impact ceases. The high rate of internal and external water exchange remove and oxidize the eutrophic substances.

The investigation of the thermal regime of lakes in Belarus is associated with the names of O.F. Yakushko, L.V. Guryanova, A.A. Volchek, E.A. Kozlov, P.I. Kirvel et al. They identified the features of heat distribution in lakes with different morphometry [Yakushko 1971, Guryanova 1988], water temperature growth trends that are similar in pace to those in other European regions [Volchek 2016, Kirvel et al. 2018],

The works of V.F. Loginov, I.S. Danilovich, V.I. Melnik et al. are dedicated to climate change research in Belarus [Partasenok, Gayer, Melnik 2015]. However, comprehensive analysis of the influence of climatic conditions on the ecological state of lakes at the present stage has not been carried out.

The research of the ecological sustainability and resistance of Belarusian lakes to external impact connected with names of O.F. Yakushko, G.M. Bazylenko and L.V. Guryanova, A.A. Novik et al. [Guryanova, Bazylenko 1985, Guryanova, Bazylenko 1986, Drabkova, Prytkova, Yakushko 1994, Yakushko, Novik 2005, Sukhovilo, Vlasov, Novik 2018]. The resistance of lakes in Belarus to changes in catchment, climatic conditions and anthropogenic impact was assessed mainly from the standpoint of the influence of the lake morphometry and individual hydrodynamic parameters on it. An integral assessment of the vulnerability of lakes in Belarus, which has a specific quantitative expression and allows more objective comparison of them by this indicator, was not performed. Therefore, this line of research is of particular relevance, since in addition to assessing the natural vulnerability of lakes, it is possible to develop a classification of lakes in Belarus by the value of the integral index of vulnerability to external influences. The purpose of the study was to assess and forecast the vulnerability of lakes in Belarus to external influences in the context of climate change.

Materials and methods

As the objects of study 149 lakes were selected. They located on the territory of all geomorphological regions of Belarus differing in the genesis of basins, morphometric characteristics and stages of natural evolution. The map of the location of the investigated lakes is shown in fig. 1.

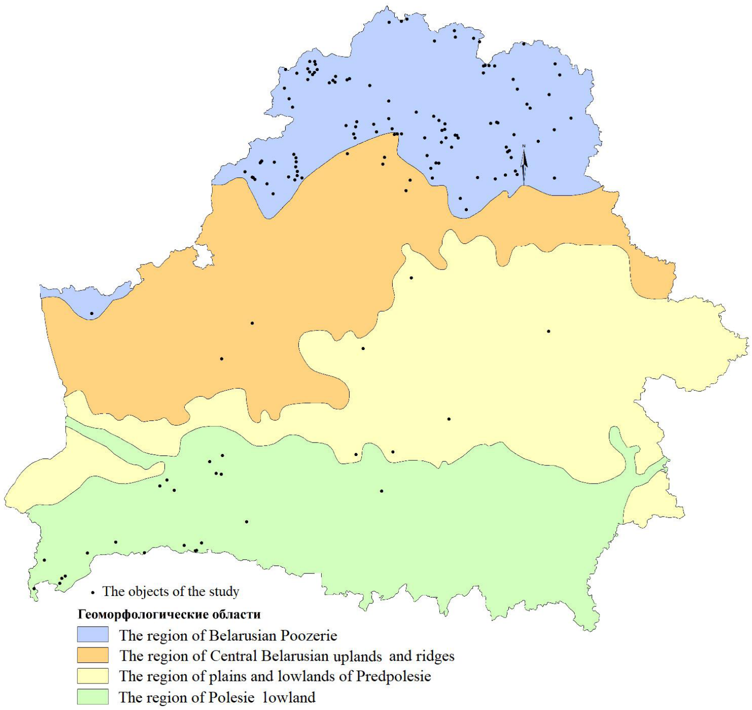

Fig. 1. Map of the location of studied lakes
Ryc. 1. Mapa lokalizacji badanych jezior
Source: compiled by the author.

The source materials were data from a comprehensive survey of lakes in Belarus conducted by the Research Laboratory of Lake Science of the Belarusian State University [Vlasov et al. 2004], stock data from the Republican Center for Hydrometeorology, Radioactive Contamination Control and Environmental Monitoring [State Water Cadastre 1964–2019; The surface water quality yearbook on hydrochemical indicators on the territory of the Republic of Belarus 1983–2019], as well as the materials of the author's own field studies, which made it possible to update the base of hydrochemical and thermodynamic data.

The area of the lakes varies from 0,027 km^2 at Lake Svyatoe, located in the Soligorsk district, to 79,6 km^2 at Lake Naroch. The volumes vary from 0,14 to 710,4 million m^3. The maximum depths range from 0,6 m in Lake Sudoble to 53,6 m in Lake Dolgoe (Glubokoe district).

The hydrochemical indicators in studied lakes differ significantly. The mineralization of them varies from 5 (Lake Bredno, Rossony district of Vitebsk region) to 407 (Lake Beloe, Bereza district of Brest region) mg/dm^3. 50% of the lakes have increased mineralization (200–400 mg/dm^3), 39,8% – medium (100–200 mg/dm^3). The important indicator in assessing the ecological state of a lake is its transparency. In the summer period it ranges from 0,3 (hypertrophic lakes with a disturbed regime) to 9,5 m (Lake Glubokoe, Polotsk district) [Vlasov et al. 2004].

The methodology for the integral assessment of the resistance of lakes to external impact proposed by V.V. Dmitriev and E.A. Primak and based on the application of the randomized aggregate method cannot be applied to the lakes of Belarus, as it was developed for large lakes. It was adapted for small Belarusian lakes. The index obtained was called "integral index of resistance to external impact".

As the main indicator we took the vulnerability index which is the opposite of the resistance index. In fact, the integral vulnerability index is an index adapted for the territory of Belarus and inversed of the lake sustainability index proposed by E.A. Primak. In this case, rationing is performed according to formulas 1 and 2. This index reflects the degree of vulnerability of the lake which exposed to external factors.

The minimum and maximum values of quantitative indicators peculiar to Russian lakes are not applicable to small lakes of Belarus, therefore, when calculating the regional extremes of morphometric, dynamic and hydrochemical characteristics were taken. In addition, some parameters have been changed. Among the criteria for assessing the vulnerability of lakes to changes in the parameters of the natural regime are changes in level fluctuations and temperature stratification. We studied lakes with a natural level regime and small level fluctuations during the year (up to 60–80 cm). It allows us to avoid using amplitude of lake level fluctuations was not taken into account when assessing vulnerability. The indicator of the presence or absence of thermal stratification was replaced by the value of thermal stability in the summer period. It was calculated using the thermodynamic model LakeAnalyzer [LakeAnalyzer]. The average temperature of the water mass in the summer period was not taken into account due to the strong inverse correlation with the maximum depth.

The set of criteria for assessing the vulnerability of lakes to changes in water quality parameters has also been significantly changed. Since for most lakes in Belarus there are no data on the content of suspended solids and BOD_5; they were not used in the vulnerability assessment. As an alternative we used the general mineralization, pH, transparency and the content of nutrients: nitrate nitrogen and phosphate phosphorus.

The list of indicators used for an integral assessment of the vulnerability of lakes in Belarus to external impact as well as the limits of their fluctuations is given in tab. 1.

Table 1

Criteria for an integral assessment of the vulnerability of Belarussian lakes to external impact and the limits of their fluctuations

Tabela 1

Kryteria integralnej oceny wrażliwości białoruskich jezior na oddziaływanie zewnętrzne i granice ich fluktuacji

Parameter	Units	min	max
Surface area	km^2	0,027	79,6
Volume	mln m^3	0,14	710,4
Maximum depth	m	0,6	53,6
Residence time	years	0,02	34,63
Dynamic load	m^3/m^2	0,1	48,8
Specific catchment	–	0,44	817,36
Thermal stability in summer	J/m^2	-0,2	1084,26
Transparency	m	0,3	9,5
Mineralization	mg/dm^3	16,6	407,2
$P0_3^{4-}$	mgP/dm^3	0	3,57
NO_3^{2-}	mg/Ndm^3	0,001	1,8
NH_4^+	mgN/dm^3	0,001	3,9
Bichromate oxidation	mgO^2/dm^3	5,75	129,3
pH	–	4,5	9,5

Source: Compiled by the author based on his own calculations.

The integral assessment of the vulnerability of lakes to external influences was carried out in 6 stages. At the first stage, a justified system of criteria was selected, which made it possible to diagnose the vulnerability of lake. Each of the parameters from tab. 1 is necessary, and all parameters together are sufficient to describe the quality (non-additive property) of the system under consideration. All of them are divided into two types. An increase in the values of the characteristics of the first type leads to an improvement in the state of the ecosystem and an increase in its vulnerability (for example, transparency), and an increase in the values of the characteristics of the second type leads to a decrease in vulnerability (area, volume of water mass, content of dissolved substances). In addition, there are characteristics whose critical values (pH = 7,0) divide the measuring scale in the characteristics into two intervals with opposite properties of the influence of the variable on the state of the water body. At the same stage, vulnerability classes were introduced and the measurement ranges of the studied parameters were analyzed.

At the second stage, the initial characteristics were normalized. For conditions that maximize vulnerability, for each criterion there corresponds a value equal to 1, for conditions that minimize vulnerability – equal to 0. Such a conversion is performed as follows:

For the criteria of the first type, the translation rule in the form (1) was used:

$$q_i = q_i x_i = \begin{cases} 1, & \text{if } x_i \le \min_i \\ \left(\dfrac{x_i - \min_i}{\max_i - \min_i} \right)^{\lambda} & \text{if } \min_i \le x_i \le \max_i \\ 0, & \text{if } x_i > \max_i \end{cases} \quad (1)$$

For the criteria of the second type, the translation rule in the form (2) was used:

$$q_i = q_i x_i = \begin{cases} 0, & \text{if } x_i \le \min_i \\ \left(\dfrac{\max_i - x_i}{\max_i - \min_i} \right)^{\lambda} & \text{if } \min_i \le x_i \le \max_i \\ 1, & \text{if } x_i > \max_i \end{cases} \quad (2)$$

where q is the normalized value of the parameter; x_i is the current value of the criterion;
$\max_i$ ($\min_i$) - the maximum (minimum) occurring value of the criterion;
λ is a parameter that determines the specific form of functions (1) and (2): (λ <1– convexity up, λ> 1 – convexity down). In this case, λ = 1, because according to a study by E.A. Primack, taking into account nonlinearity only slightly affects the accuracy of calculations.

The range of variation of q_i is always in the range from 0 to 1. Thus, the initial parameters in various measurement scales are reduced to a single dimensionless scale, after which mathematical values can be performed on their values in order to obtain the integral indicator. At this stage the minimum and maximum values of the parameters from each rating scale of the initial characteristics were also specified.

At the third stage, the form of the integral indicator Q (q, w) was chosen. The indicator Q depends not only on the indicators q_i, but also on their significance determined by the weight coefficients w_i, the sum of which should be equal to 1.0 ($0 \le w_i \le 1$). As an expression for an integral indicator, a linear (or nonlinear) convolution of indicators of the form (3) was used:

$$Q = Q(q, w) = Q(q_1 \dots q_m, w_1 \dots w_m) = \sum_{i=1}^{m} q_i w_i \quad (3)$$

which is a weighted arithmetic mean of the values of qi and determined by the parameter vector w = (w_1 ... w_m), non-negative components of which are weight coefficients that specify the significance of individual criteria for an integral assessment of the level of vulnerability. The introduction of an additional condition for normalizing weights (w_i + ... + w_m = 1) allows us to accept the value of the parameter w_i as an estimate of the relative significance of the indicator q_i.

At the fourth stage, weights estimates for w_i were introduced. As a rule, drawing up a plan of assessment studies is itself the primary "weighing" of parameters, components and their properties. But it is not enough, since the influence of the selected factors is unequal, as a result of which it becomes necessary to introduce different significance factors. In most cases the following methods are applied to take into account the "weight" of each of the criteria of the quality of the natural environment: the weight of all selected parameters is taken equal; the weight of the most important parameters increases or the weight of the secondary indicators decreases by a conditional number of times; weight is determined using expert judgment; the weight of each index is determined using additional calculations. In the course of this study, the importance of individual indicators was determined using additional calculations. We conducted a factor analysis (principal component method). As a result, it was found that in the group of criteria for assessing the vulnerability of lakes to changes in the parameters of the natural regime, the most "significant" are the area and volume, as well as the strength of thermal stratification, expressed through thermal stability. In the group of criteria for assessing the vulnerability of lakes to changes in water quality parameters, transparency, mineralization, and bichromate oxidation are of the greatest weight. These indicators were assigned weighting factors equal to 0,2, the rest – 0,1.

The weights of individual indicators are given in tab. 2.

Table 2

Weight coefficients of individual indicators used in assessing the vulnerability of Belarusian lakes to external impact

Tabela 2

Współczynniki wagowe poszczególnych zastosowanych wskaźników w ocenie wrażliwości białoruskich jezior na oddziaływanie zewnętrzne

Criteria for assessing the vulnerability of lakes to changes in the parameters of the natural regime							
Indicator	Area	Volume	Maximum depth	Residence time	Dynamic load	Specific catchment	Thermal stability in summer
Weight coefficient	0,2	0,2	0,1	0,1	0,1	0,1	0,2
Criteria for assessing the vulnerability of lakes to changes in water quality parameters							
Indicator	Transparency	Mineralization	pH	$P0_3^{4-}$	NO_3^{2-}	NH_4^+	Bichromate oxidizability
Weight coefficient	0,2	0,2	0,1	0,1	0,1	0,1	0,2

Source: Compiled by the author based on his own calculations.

At the fifth stage, for the left and right boundaries of each class according to the approved rules, the values of the integral indicator Q were calculated and an assessment scale for it was constructed.

$$\overline{Q}^{(i)}(I) = \overline{Q}(q^{(j)}; I) = \overline{Q}(q^{(j)}; \overline{w}(I)) = \frac{1}{N(m,n,I)} \sum_{i=1}^{N(m,n,I)} [Q^{(t)}(q^{(j)})] \quad (4)$$

Moreover, in RAM, the transition to Q (q; I) = MQ (q; I) is realized in the form (4):

$$[S^{(j)}(I)]^2 = \frac{1}{N(m,n,I)} \sum_{i=1}^{N(m,n,I)} [Q^{(t)}(q^{(j)}) - \overline{Q}^{(j)} I]^2 \quad 5)$$

with accuracy estimate Q (q; I) (5):

At the sixth stage, according to the available data, the values of the integral indicator were determined according to the rules for constructing the main classification model. A consolidated indicator of the criteria of the first group is assigned a weight coefficient of 0,7, the second – 0,3.

The next task was to create the classification of Belarusian lakes according to these indicators. Classification of lakes was carried out on the basis of calculated vulnerability indices. Subclasses were distinguished taking into account the morphometry of the lakes, the residence time of water and thermal stratification. The boundaries of the classes of vulnerability of lakes to external impact are shown in tab. 3.

Table 3

The values of the integral index of the vulnerability of lakes in Belarus to external impact

Tabela 3

Wartości integralnego wskaźnika podatności jezior na Białorusi na wpływ zewnętrzny

Class of vulnerability	Low degree of vulnerability	Medium degree of vulnerability	High degree of vulnerability
Values of integral vulnerability index	0,000–0,441	0,442–0,548	0,549–1,000

Source: Compiled by the author based on his own calculations.

Results and its discussion

The adjusted classification of lakes according to the vulnerability level of external influences, which is taken as a basis in forecasting, includes 3 classes and 8 subclasses of lakes:

1. *Lakes with a high degree of vulnerability*. The calculated indices of vulnerability of lakes of this class vary from 0,549 to 0,886. The class is subdivided into two subclasses:

1.1. *Small-area stratified lakes with long water residence time situated on uplands and plains*. Among these are the Balduk, the Dolgoe and the Rudakovo.

1.2. *Small-area stratified lakes with long water residence time situated on lowlands*. This subclass includes the Bredno and the Cherbomyslo.

2. *Lakes with a medium degree of vulnerability*. Composite indices of their vulnerability to external influences ranges from 0,442 to 0,548. Such class is subdivided into three subclasses:

2.1. *Large and middle-area stratified lakes with long water residence time situated on uplands and plains*. The Strusto, the Richie and the Genno are the typical instances of this subclass.

2.2. *Small-area stratified lakes with long and medium water residence time situated on plains and lowlands*. Among representatives of the subclass are the Setovskoe, the Sominskoe, the Iodovo, etc.

2.3. *Small-area stratified lakes with medium water residence time situated on plains and lowlands*. This subclass includes the Vechera, the Besumenik, the Dobeevskoe, the Yelnya.

3. *Lakes with low degree of vulnerability* The indices of vulnerability range from 0,223 to 0,441. This class of lakes is also subdivided into three subclasses:

3.1. *Small-area feebly stratified and unstratified lakes with intensive water residence time situated on plains and lowlands*. This subclass includes the Sinsha, the Mnuta, the Nedrovo, the Bolshaya Osmota, the Oltush and the Lukovskoye.

3.2. *Variably sized unstratified lakes with medium water residence time situated on lowlands*. Vygonoshchanskoye and Chervonoe lakes are the instances of this subclass.

3.3. *Large-area feebly stratified lakes with long water residence time situated on lowlands*. This subclass includes the Snudy, the Myadel, the Naroch, the Drivyaty and etc.

In classes of lakes with low and medium degree of vulnerability disturbed lakes subjected to anthropogenic eutrophication are singled out. Vulnerability indices ranges from 0,326 to 0,485. Lakes of varied morphometry are occurred here, trophic status of them in the period before anthropogenic eutrophication also differentiated. Today the degree of lakes vulnerability is stipulated not by their natural specifics, but by the long-term impact of human economic activity on them (the Miorskoe, the Leskovichi, the Potekh etc.). Moreover, the level of productional processes in such lakes is unstable throughout the year, which is a trait of a fragile ecosystem [Drabkova 1994].

Depending on the period of water exchange, morphometric characteristics, and features of stratification, the response of lakes to climatic changes will vary. In order to identify the patterns of long-term dynamics of the integral indices of the vulnerability of lakes to external influences and to predict their state under the conditions of climate change, 7 reference lakes belonging to different subclasses of vulnerability were identified. The absence of lakes belonging to subclass 2.3 is explained by the commonality of their properties with the lakes of subclass 3.2. The main morphometric characteristics of the reference lakes are given in tab. 4. Based on the analysis of the long-term dynamics of the vulnerability indices of the reference lakes and the forecast of changes in air, water, and annual precipitation, a forecast was made of the change in the vulnerability of Belarus lakes to external impact until 2100.

Table 4

Morphometric characteristics of reference lakes
and their place in the classification of vulnerability to external impact

Tabela 4

Charakterystyka morfometryczna jezior referencyjnych i ich miejsce
w klasyfikacji podatności na wpływy zewnętrzne

Lake	Area km^2	Volume mln m^3	Maximum depth m	Residence time of water years	Subclass of vulnerability
Voloso Yuzhny	1,21	15,1	40,4	13,2	1,1
Bredno	0,28	0,54	4,7	6,9	1,2
Richi	12,8	131	51,9	5,7	2,1
Kroman	0,92	12,2	26,5	0,5	2,2
Sinsha	2,53	8,1	7,1	0,02	3,1
Wygonoshchanskoe	26	32,1	2,3	3,6	3,2
Naroch	79,6	710,4	24,8	12	3,3

Source: Compiled by the author based on Lakes of Belarus: handbook.

In accordance with the climate change scenario RCP2.6, the average summer air temperature will increase by 1,3°C. This will lead to an increase in the temperature of the surface layer of water by about 2°C. In shallow unstratified lakes, the bottom temperature will also increase by 2°C. The thermal stability of their water mass will not change significantly. In deep lakes during the summer stagnation period, intensification of thermal stratification is expected due to an increase in surface temperature, which will cause its decrease at the bottom. In Lake Naroch and other large lakes with depths of more than 15 m there is a tendency to lower bottom water temperature in summer. Over 50 years they decreased by an average of 0,5°C, but over the period from 1992 to 2017 they decreased by 1,5°C, and before that there were cyclic fluctuations, almost not expressed at present. This pattern is typical for periods of climate warming and it is associated with stronger heating of the epilimnion and the increase in thermal stability. With climate change according to the RCP2.6 scenario, the integral indices of the vulnerability of lakes to external impact will increase with the exception of shallow lakes as shown in Fig. 2 and 3. Some stratified lakes (Bobritsa, Strusto), currently belonging to the class of lakes with an medium degree of vulnerability, will pass into a class with a high vulnerability to environmental changes and anthropogenic impact. It is also possible to pass Lake Snudy into a class of lakes with the middle degree of vulnerability. The position of the remaining lakes in the classification will correspond to the current one. The vulnerability of shallow lakes will not change due to the lack of stratification and the prevalence of internal mechanisms in the formation of vulnerability.

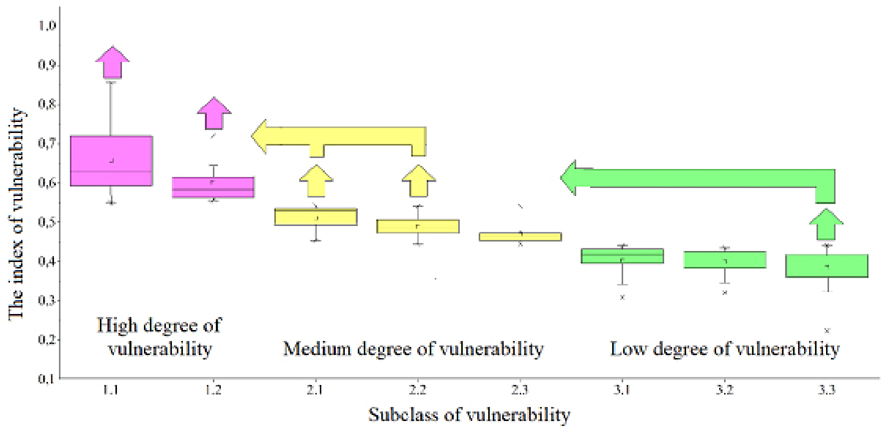

Fig. 2. The forecast of changes in the vulnerability of lakes in Belarus to external impact according to scenario RCP2.6
Ryc. 2. Prognoza zmian wrażliwości jezior Białorusi na oddziaływanie zewnętrzne według scenariusza RCP2.6
Source: compiled by the author based on the processing of his own data.

An increase in air temperatures in winter by an average of 1,6–1,7°C will shift the start and end dates of ice formation to later and earlier dates, respectively, which will improve the aeration of the water mass. Moreover, in the lakes of the Brest region, stable ice formation will rarely form.

The amount of precipitation will increase by 3–5%, so changes in the period of water exchange will be insignificant. As a result, at the current level of influence of human economic activity on lakes, a significant change in their trophic status is highly improbable.

According to the most probable scenario RCP4.5, winter air temperature will increase by an average of 3,1 °C. In winter ponds located in this territory will not have ice cover, as no obstacles will be created for aeration of the water mass.

With an increase in the average air temperature in summer by 2,5–2,8°C by 2100, the water temperature in the lakes of Belarus will increase by 2,8–3,3°C and will reach 23–25°C, the maximum will exceed 30°C. A typical example of such temperature distribution over depth can illustrate thermal stratification observed in Lake Naroch in 2010, when temperature difference from surface to bottom was about 11°C.

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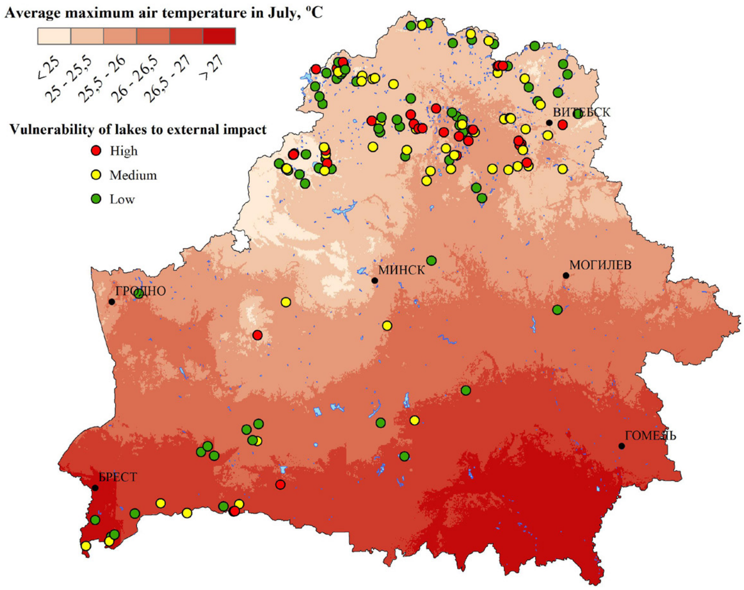

Fig. 3. Spatial patterns of vulnerability of lakes of Belarus to external impact according to the scenario RCP2.6

Ryc. 3. Przestrzenne wzorce podatności jezior Białorusi na oddziaływanie zewnętrzne według scenariusza RCP2.6

Source: compiled by the author on the basis of processed data WorldClim version 1.4 and processing of their own data.

In the outcome part of the water balance, the share of evaporation will increase by 10–25% with a predicted increase in precipitation by 1–5%. This will cause a decrease in water levels in the summer low-water season, which is especially pronounced in the shallow lakes of Polesie. If now the negative water balance in the lakes of Central Belarus and Polesie is observed from May to August, and in Poozerie from June to August, then in the future the period of predominance of water flow over the parish will cover April–September. The vulnerability of lakes to external impact will change as follows: first due to increased stratification it will increase, as in the climate change scenario RCP2.6. This will cause a shift in production processes to the epilimnion, a concentration of nutrients there, a decrease in transparency and a subsequent increase in trophic status and a decrease in the index of vulnerability to external impacts (Fig. 4–5).

Lakes with high vulnerability to the external impact will remain only on moraine hills and stony massifs of the Poozerie. Many lakes with an average degree of vulnerability will pass into weakly vulnerable class.

According to the RCP8.5 scenario, winter air temperature will increase by an average of 5,6°C. At the same time, ice cover will rarely form and only in the extreme north-east of Belarus. The dimictic lakes of the rest of Belarus will turn to warm monomictic ones. Of the positive consequences of such a rise in temperature, the absence of winter clutter should be noted. On the positive side, it should be noted that a rise in temperature will lead to the absence of winter clutter.

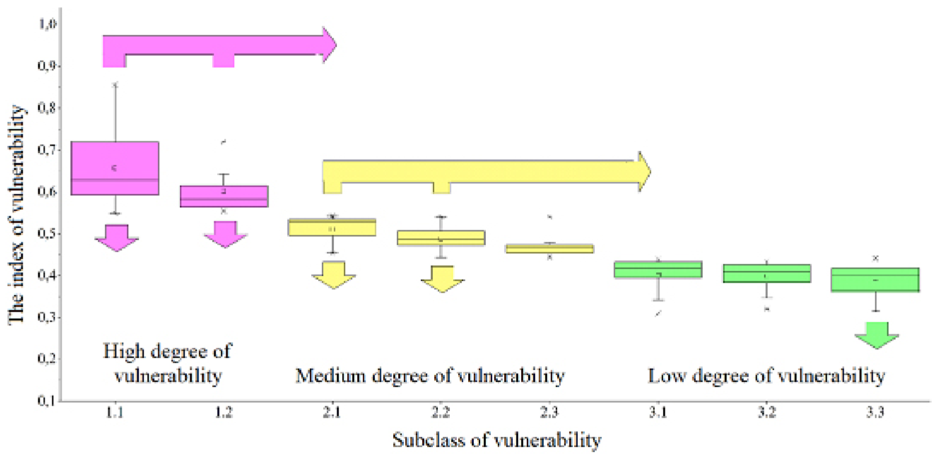

Fig. 4. The forecast of changes in the vulnerability of lakes in Belarus to external impact according to scenario RCP4.5
Ryc. 4. Prognoza zmian podatbości jezior na Białorusi na oddziaływanie zewnętrzne według scenariusza RCP4.5
Source: compiled by the author based on the processing of his own data.

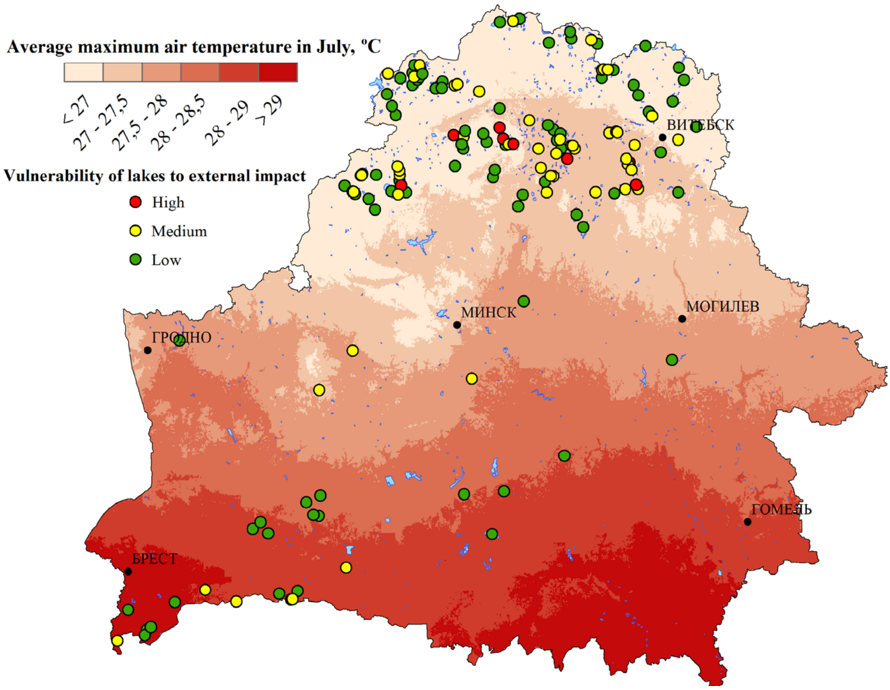

Fig. 5. Spatial patterns of vulnerability of lakes in Belarus to external impact according to the scenario RCP4.5
Ryc. 5. Przestrzenne wzorce podatności jezior Białorusi na oddziaływanie zewnętrzne według scenariusza RCP4.5
Source: compiled by the author on the basis of processed data WorldClim version 1.4 and processing of their own data.

An increase in summer air temperatures of 5,2°C will cause an increase in water temperatures of 6–8°C. The average values of thermal stability and heat reserves of lakes will correspond to the current maximum recorded, and the vertical temperature distribution during the year illustrates Fig. 6.

With an unchanged amount of precipitation in the warm season, the degree of aridity of the climate will increase. As a result a number of Polesie spill lakes can turn into lowland marshes and reduce the area of other lakes.

In mesotrophic lakes, eutrophication processes will occur, expressed in the growth of phytoplankton biomass, and, as a consequence, in the oversaturation of the epilimnion with oxygen and its absence in hypolimnion. The predicted change in the vulnerability of lakes to external impact is shown in Fig. 7–8.

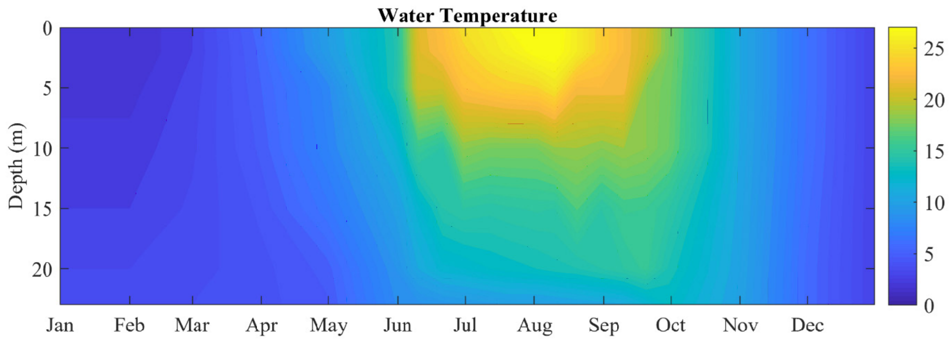

Fig. 6. The predicted annual course of water temperature in Lake Naroch, 2100 (scenario RCP8.5)
Ryc. 6. Przewidywany roczny przebieg temperatury wody w jeziorze Narocz, 2100 (scenariusz RCP8.5)
Source: compiled by the author using the thermodynamic model LakeAnalyzer.

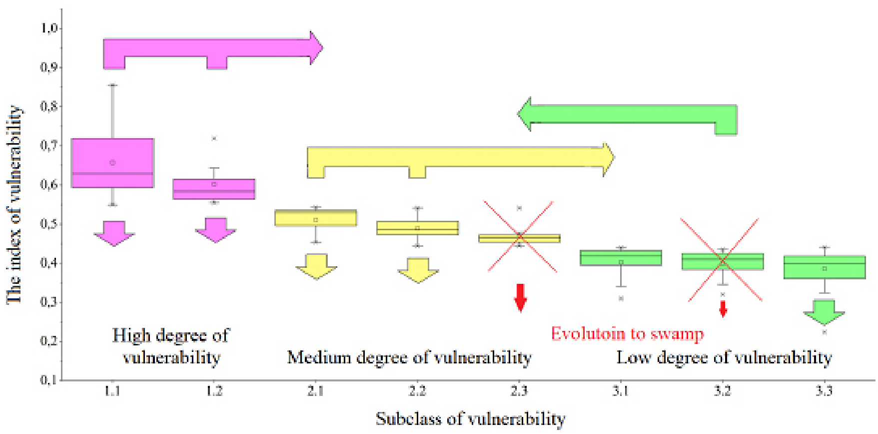

Fig. 7. Forecast of changes in the vulnerability of lakes in Belarus to external impact according to scenario RCP8.5
Ryc. 7. Prognoza zmian wrażliwości jezior na Białorusi na oddziaływanie zewnętrzne wg scenariusza RCP8.5
Source: compiled by the author based on the processing of his own data.

As can be seen from the figures, the transition of unstable lakes to the class of medium-stable, medium-stable to the class of stable is expected. Unstable lakes in their modern sense will disappear due to their eutrophication. Polesie shallow lakes are most likely to have reached the stage of lowland swamps in their development.

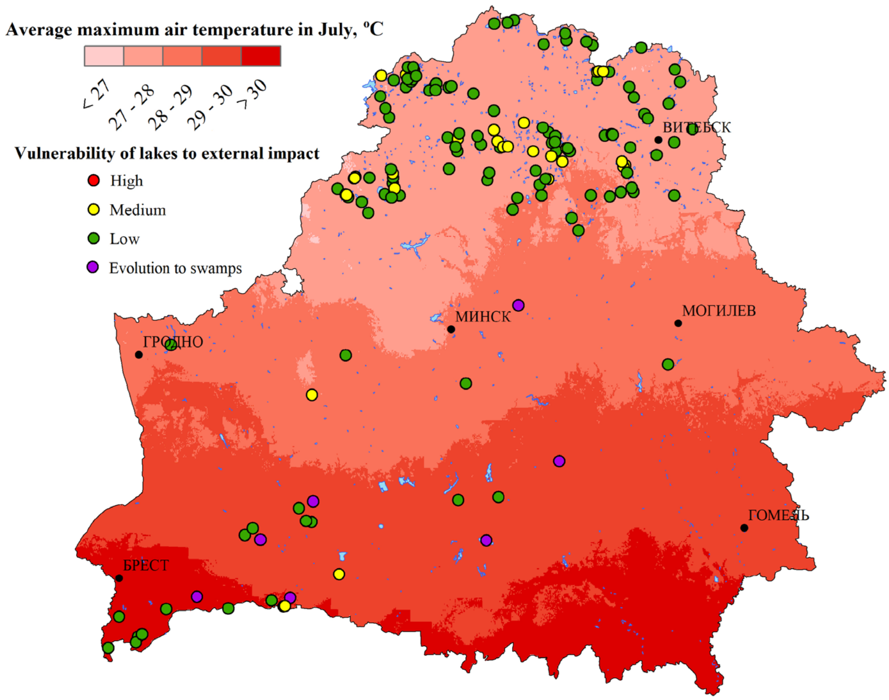

Fig. 8. Spatial patterns of vulnerability of lakes of Belarus to external impact according to the scenario RCP8.5
Ryc. 8. Przestrzenne wzorce podatności jezior Białorusi na oddziaływanie zewnętrzne według scenariusza RCP8.5
Source: compiled by the author on the basis of processed data WorldClim version 1.4 and processing of their own data.

Thus, the main direction of the influence of climate warming on lakes will be an increase in their trophic status, which will especially affect the mesotrophic and mesotrophic ecosystems with signs of lake oligotrophy. Phytoplankton biomass will increase in both mesotrophic and eutrophic lakes. Outbreaks of algal blooms are currently observed in them. For example, the high biomass of phytoplankton in the mesotrophic lakes Voloso Severny and Voloso Yuzhny in early August 2018 can be explained by high air temperatures for a long time. According to the theory of alternative stable states of the ecosystem of Lake M. Schaeffer, with a decrease in water transparency, there will be a transition from a "macrophytic" steady state to a "phytoplankton" one.

The positive effects of climate warming include an increase in the duration of the mixing period of the water mass, however during long periods of stagnation, oxygen deficiency in hypolimnion will be more pronounced than at present, until its complete disappearance in lakes, the maximum depth of which exceeds 15 m.

Conclusion

Thus, with an increase in water temperature caused by changes in climatic conditions, the development of lake geosystems will occur in the direction of reducing vulnerability to external influences. A decrease in rainfall will increase the vulnerability of lakes by reducing the volume of water mass.

If the climatic conditions change according to the RCP2.6 scenario, by the end of the 21st century, the water temperature in the lakes will increase by 2°C, which will entail an increase in the vulnerability of lakes to external influences due to increased stratification with the same trophic status. Some lakes with an average degree of vulnerability (Bobritsa, Richi) will go into the class of highly vulnerable, the position of others in the classification will remain unchanged. According to the most probable scenario RCP4.5, the water temperature in the lakes will increase by 2,8–3,3°C. In this case, the trophic status of mesotrophic lakes will increase. As a result of this vulnerability to external influences will increase. Lakes with a high degree of vulnerability to the external impact of the lake will remain only on the uplands. The RCP8.5 scenario assumes an increase in water temperature by 6–8°C. Dimictic lakes of Belarus, with the exception of its northeast, will become warm monomictic, which will entail a complete restructuring of their ecosystems with an increase in integral indices of vulnerability to external influences. Shallow lakes in Polesie are most likely to have reached the stage of lowland marshes in their development.

The results can be used in predicting the development of lakes under the influence of natural processes and the anthropogenic factor, managing lake ecosystems, their reclamation, for environmental and recreational purposes, as well as in the educational process in the field of land hydrology, limnology, hydroecology.

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Summary

The article presents a forecast of changes in the sensitivity of Belarus' lakes to external influences in the conditions of climate change. Method E.A. Primak was used to calculate sensitivity integral indices for 149 lakes of different types. Among all lakes, classes with high, medium and low sensitivity were distinguished. A forecast of the dynamics of the sensitivity of lakes of various types to external impact was also prepared in accordance with the RCP2.6, RCP 4.5 and RCP 8.5 climate change scenarios.

The research shows that with the increase in water temperature caused by changes in climatic conditions, the development of lake geosystems will lead to a decrease in susceptibility to external influences. Reducing rainfall will increase the sensitivity of lakes by reducing the volume of water mass.

Streszczenie

W artykule zaprezentowano prognozę zmian wrażliwości jezior Białorusi na oddziaływania zewnętrzne w warunkach zmian klimatycznych. Metoda E.A. Primak została wykorzystana do obliczenia całkowych wskaźników wrażliwości. Na podstawie analizy 14 parametrów reżimu naturalnego (wskaźniki morfometryczne oraz szybkość zewnętrznej i wewnętrznej wymiany wody) oraz cech jakości środowiska (wskaźniki hydrochemiczne) obliczono całkowe wskaźniki podatności na oddziaływanie zewnętrzne dla 149 jezior różnych typów. Spośród wszystkich jezior wyróżniono klasy o wysokim, średnim i niskim stopniu wrażliwości. Sporządzono także prognozę dynamiki wrażliwości jezior różnych typów na oddziaływanie zewnętrzne zgodnie ze scenariuszami zmian klimatycznych RCP2.6, RCP 4.5 i RCP 8.5.

Z badań wynika, że wraz ze wzrostem temperatury wody wywołanym zmianami warunków klimatycznych rozwój geosystemów jeziornych będzie następował w kierunku zmniejszania podatności na wpływy zewnętrzne. Zmniejszenie opadów deszczu zwiększy wrażliwość jezior poprzez zmniejszenie objętości masy wody. Jeśli warunki klimatyczne zmienią się zgodnie ze scenariuszem RCP2.6, to do końca XXI wieku temperatura wody w jeziorach wzrośnie o 2°C, co pociągnie za sobą wzrost podatności jezior na wpływy zewnętrzne w wyniku zwiększonej stratyfikacja o tym samym statusie troficznym. Niektóre jeziora o średnim stopniu wrażliwości (Bobritsa, Richi) zostaną zaliczone do klasy wysoce wrażliwych, pozycja innych w klasyfikacji pozostanie bez zmian. Według najbardziej prawdopodobnego scenariusza RCP4.5 temperatura wody w jeziorach wzrośnie o 2,8–3,3°C. W takim przypadku stan troficzny jezior mezotroficznych wzrośnie. Jeziora o wysokim stopniu wrażliwości na zewnętrzne oddziaływanie jeziora pozostaną tylko na wyżynach. Scenariusz RCP8.5 zakłada z kolei wzrost temperatury wody o 6–8°C. Jeziora Dimiktyczne Białorusi, z wyjątkiem jej północno-wschodniej części, staną się ciepłymi monomiktami, co pociągnie za sobą całkowitą restrukturyzację ich ekosystemów ze wzrostem integralnych wskaźników podatności na wpływy zewnętrzne. Płytkie jeziora Polesia najprawdopodobniej osiągnęły w rozwoju stadium bagien nizinnych.