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Climate Change Affects the Vulnerability of Belarusian Lakes to External Impact

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Abstract: The investigation of lakes' vulnerability to external impacts is essential for understanding and potentially mitigating the threats they face. By studying how lakes are affected by external factors, such as pollution, climate change and human activities, we can assess the health of the ecosystem and predict how it may respond to future changes. The purpose of this research is the analysis of climate change's influence on the vulnerability of Belarusian lakes to external impact. The vulnerability indices were calculated using the randomized aggregate method. The dependences between parameters were defined on the basis of correlation and regression analysis. We investigated the vulnerability of 149 Belarusian lakes. Classifying the lakes allowed us to divide them into three types, with high, medium and low vulnerability to external impact. All the types include 2–3 subtypes. On the basis of classification, we created a zoning scheme for Belarus on the vulnerability of lakes to external impact. A forecast of lake vulnerability for three SSP scenarios to 2100 was conducted. In the SSP_1 scenario, the vulnerability of stratified lakes will increase insignificantly. The vulnerability of homothermous lakes will not change. In the SSP_2 scenario, the vulnerability of lakes will first increase then decrease. Lakes with high and medium vulnerability will be classed as medium- and low-vulnerable. In the SSP_5 scenario, the vulnerability of lakes will decrease more significantly than in the other scenarios.

Keywords: lake; Belarus; lake vulnerability to external impact; climate change

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1. Introduction

Climate change has the potential to disrupt lake ecosystems directly through changes in temperature, wind, and precipitation, and indirectly through watershed effects and in concert with anthropogenic stressors, such as nutrient pollution and land-use change. The issues of the influence of meteorological and climatic conditions on thermodynamic processes in lakes have been studied quite well, but the aspects of the transition of quantitative indicators of the functioning of lake ecosystems to qualitative ones have yet to be studied in detail. The mechanism of the lake response to changes in climatic conditions in the catchment is not entirely clear [1].

The establishment of the limits of permissible load on the lakes is impossible without a comprehensive analysis of the hydro- and thermodynamic indicators.

The general features of the dynamics of the ecological state of lakes, as well as the physical and geographical patterns of the processes occurring in them under climate change, are described in the previous works [1–6]. The average water surface temperature of the lakes in Switzerland increases by 0.29 °C per decade, the UK—by 0.35 °C, Finland—by 0.39 °C, and Austria—by 0.43 °C [2]. During the ice-free period from 1981 to 2000, the water temperature in Lithuanian lakes increased by an average of 0.1–1.1 °C [7]. The average growth rate of winter surface temperature per decade varies from 0.14 °C in Austria to

0.26 °C in the UK, and the bottom water temperature ranges from <0.10 °C in Finland to 0.34 °C in the UK per decade [2].

The research of surface water temperature in Polish and Belarusian lakes showed that the temperature in all studied lakes is characterized by a positive trend at the level of 0.044 °C year^{-1}. The largest index was noted in Chervonoe Lake—0.066 °C year^{-1}, and the smallest 0.029 °C year^{-1} for the deep Lake Hańcza. A positive trend in the average monthly surface water temperatures is also observed, ranging from 0.015 °C year^{-1} in January to 0.069 °C year^{-1} in May [8].

A transformation of the thermal regime is also taking place in the large lakes of Europe, Asia and North America [1,3,5]. The water temperature in Lake Onega, Ladoga and Baikal during 2000–2009 exceeded the long-term average value (4.3 °C) by 0.3–0.7 °C over a decade. The maximum growth rates of the average temperature are observed in July and August, i.e., during the period of maximum warm-up. In Lake Superior, the summer water surface temperature (July–September) has increased by 3.5 °C over the past 100 years, with the most significant warming in the last three decades. In 1979–2006, the average rate of increase in water surface temperature was 1.1 °C per decade. In the lakes Michigan and Huron, the water surface temperature during this period increased by 0.65 °C per decade and 0.86 °C per decade, respectively. All this causes increased evaporation from the water surface, the eutrophication of lakes and the deterioration of the water quality and recreational resources.

In 2003–2005 in Europe, the CLIME (Climate and Lake Impacts in Europe) project was implemented. The aim of the project was to assess the direct and indirect consequences of regional climate change on the dynamics of lake ecosystems in Europe. This assessment was based on the development of a set of models for simulating the reaction of lakes to predicted climate change on the one hand, and on the other hand, on the analysis of historical patterns of change in the lakes located in three regions of Europe: northern (Estonia, Finland, Sweden), western (Ireland, UK), and central (Austria, Germany, Switzerland). The authors showed the features of thermodynamics and changes in the trophic state of lakes in different climatic conditions. Since the implementation of the project, adjustments have been made to the climate change scenarios, respectively, and the assessments of their consequences are also constantly being improved [9]. A temperature increase leads to changes in mixing regimes of lakes [4,6].

The works of M. Scheffer, S. Carpenter, and E. Jeppesen are devoted to the assessment of the stability, the vulnerability of lake ecosystems and the study of their equilibrium states. M. Scheffer revealed the existence of two main stable states: oligotrophic and eutrophic, while there are several alternative stable combinations of components of the lake ecosystem in the eutrophic [10–12].

In Russia, Poland and other countries, the interest of researchers is directed to a quantitative (score-index and integral) assessment of the resistance and vulnerability of lakes, and changes in the parameters of the natural regime and anthropogenic eutrophication [13–15]. A peculiar indicator of the climatic vulnerability of lakes is the complex index developed by N.V. Myakisheva. It takes into account the peculiarities of the response of lakes with different morphometries to changes in air temperature and precipitation [16].

In the Sixth Assessment Report of the IPCC (2021), which includes a physical base of climate change, the consequences of climate change for lakes are described. The most important of these are a shift in the timing of the beginning of freeze-up to later dates and the end to earlier ones; an increase in the temperature of the surface layer of water; the redistribution of water supplies over land; and the emergence of new lakes due to melting glaciers and permafrost, as well as the disappearance of existing ones due to evaporation [17,18].

Besides the physical parameters, climate change affects the biological parameters of lakes. The depletion of oxygen reserves and changes in the mixing regime cause algal blooms, a decrease in the ability to self-purify and the death of aquatic organisms [19,20]. The complex of measures (basin approach, the optimization of water consumption, the treatment and reuse of wastewater) is too general and does not take into account the individual characteristics of a particular ecosystem. Therefore, it is necessary to develop recommendations for different types of lakes, taking into account all the conditions for the functioning of the lake ecosystem.

The study of the influence of climatic conditions on the water resources of Belarus is the subject of the works of V.F. Loginov, O.F. Yakushko, A.A. Volchek, I.I. Kirvel, B.P. Vlasov, P.I. Kirvel and others. They noted the tendencies of water temperature growth, similar in pace to those in other European regions [21]. However, a comprehensive analysis of hydrological indicators in connection with new data on the scale of possible climatic changes [18] was not carried out.

The investigation of the ecological sustainability of Belarusian lakes was carried out by O.F. Yakushko, G.M. Bazylenko and L.V. Guryanova, and A.A. Novik et al. They used the morphometric and hydrodynamic characteristics of lakes [22,23]. For an integral assessment of the vulnerability and adaptation of lakes to changing climatic conditions, it is necessary to take into account the entire set of indicators, led by the dynamics of the water mass as a link between morphometry, hydrochemical processes and biological productivity.

The resistance of a lake is its ability to keep its properties and parameters of regimes quasi-constant under the conditions of external and internal loads acting on it at a certain time interval of functioning. The lake vulnerability is its inability to maintain the specified properties for a certain time interval of functioning. With this approach, the least vulnerable to changes in any properties will be the system endowed with these properties to the greatest extent [14]. It follows from the definitions that these concepts are used together and can be independent characteristics of the variability of lake ecosystem.

External impact is understood as anthropogenic impact on the hydrochemical, hydrodynamic or thermal regimes of lakes, as well as changes in the natural environment that can change the parameters of lakes.

Many works are devoted to the study of the stability and vulnerability of lakes to changes in the parameters of the natural regime and anthropogenic eutrophication. At the same time, the theory of the existence of several stable states of a lake ecosystem, closely related to the concept of its plasticity and corresponding to different trophic levels of a lake, is being actively developed. The main ones are oligotrophic and eutrophic, but in a eutrophic lake, several variants of an equilibrium combination of biotic and abiotic factors are possible, based on the dominance of phytoplankton or macrophytes in the primary production [10–12]. An important aspect here is the absence of local sources of pollution in the catchment area that constantly affect a lake and remove it from a stable state. The spatial regularities of Swiss lakes' vulnerability were investigated by Vinnå et al. (2021) [24]. According to this research, mountain lakes are less vulnerable to climate change than lakes located in lowlands.

The resistance of a lake ecosystem is defined as its ability to withstand external natural and anthropogenic influences, as well as internal processes that disrupt the structure and normal functioning of the entire ecosystem, or separately its abiotic and biotic parts [14,15]. According to this approach, lakes that are not able to maintain their properties for a certain time interval of functioning are vulnerable. This definition of the resistance and vulnerability of aquatic ecosystems was based on the research of V.V. Dmitriev and E.A. Primak et al. They developed a methodology for the point-index and integral assessment of the stability of lakes to external influences and their ecological well-being. An ecologically prosperous lake ecosystem is an ecosystem with optimal and diverse production, existing indefinitely in a changing environment [15]. Their methodology is not suitable for small lakes in Belarus. The area of Belarusian lakes does not exceed 79.6 km^2, and 91% of them are smaller than 1 km^2 [25]. All of them, due to their morphometric and hydrochemical characteristics, will be in the vulnerable group.

In Poland, an approach has been developed, aimed at a point-index assessment of the resistance of lakes to changes in the catchment, expressed in the rate of natural eutrophication [13]. It is based on the criteria for assessing the catchment as a "supplier" of substances into a lake (the specific catchment, the density of the river network, the type of water balance, the average slope of a small catchment, the size of the catchment effectively involved in the matter supply, the granulometric composition of underlying rocks, and the type of land use of a small catchment) and the criteria for assessing the lake resistance to the impact of the catchment area (the average depth, the proportion of hypolimnion in the volume of the lake, the coefficient showing the ratio of water volume to the length of the coastline, the coefficient of water exchange, the Schindler index (capacity of the lake depression) and the coefficient reflecting the ratio of the active bottom area under the epilimnion and the volume of the epilimnion). From the values obtained for each point, the average is deduced. It characterizes the position of the lake in typification according to the rate of natural eutrophication [13].

The geosystem approach to lake science in Belarus is associated with the research of B.P. Vlasov, N.D. Grishchenkova, and N.V. Gagina. When considering the territorial structure of lakes, two approaches are distinguished. In the first, they are considered as a "lake-catchment" system, in the second, as a "lake-an administrative-territorial unit" [26].

The purpose of the research is the analysis of climate change impact on the vulnerability of Belarusian lakes to external impact by 2100, according to IPCC scenarios.

2. Materials and Methods

The informational basis for the study was the results of a comprehensive survey of lakes in Belarus conducted by the Laboratory of Lake Research (1971–2017), the materials of the Republican Center of Hydrometeorology, Control of Radioactive Pollution and Environmental Monitoring (1971–2023), data from Sixth Assessment Report of IPCC, as well as the materials obtained during expeditionary work on the lakes of Belarus in 2017–2023 with the participation of the authors. Of all the investigated lakes in Belarus, 149 were selected. The main criteria for the selection of lakes were the following:

(1) Our knowledge of the lakes (the availability of morphometric, hydrodynamic, hydrochemical characteristics, data on the distribution of water temperature with depth).
(2) A relatively proportional ratio of lakes of different types that are at different stages of evolution (the objects of study are represented by all types and subtypes, in accordance with the complex typification of Belarusian limnologist O.F. Yakushko. The largest percentage of lakes is made up of eutrophic lakes with various characteristics. Most of them are shallow. It should be noted that among the small shallow lakes, there are unique vulnerable reservoirs with small forest catchments, characterized by high transparency, low pH (less than 7) and the content of dissolved substances, and these are places of growth for protected species of macrophytes (Cherbomyslo, Bolshoye Ostrovito). Therefore, studying the response of the geosystems of these lakes to climate change seems very relevant.

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 (the Glubokoe district).

The hydrochemical indicators in the studied lakes differ significantly. The mineralization of them varies from 5 (Lake Bredno, the Rossony district of Vitebsk region) to 407 (Lake Beloe, the Bereza district of Brest region) mg/dm^3. A total of 50% of the lakes have a mineralization of 200–400 mg/dm^3, and 39.8% have 100–200 mg/dm^3. An 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, the Polotsk district) [26]. A schematic map illustrating the geographic location of the research objects is shown in Figure 1.

The methodology for assessing lake vulnerability was based on the randomized aggregate method. Figure 2 shows a schematic of the calculation of the integral indices of lake vulnerability to external impact.

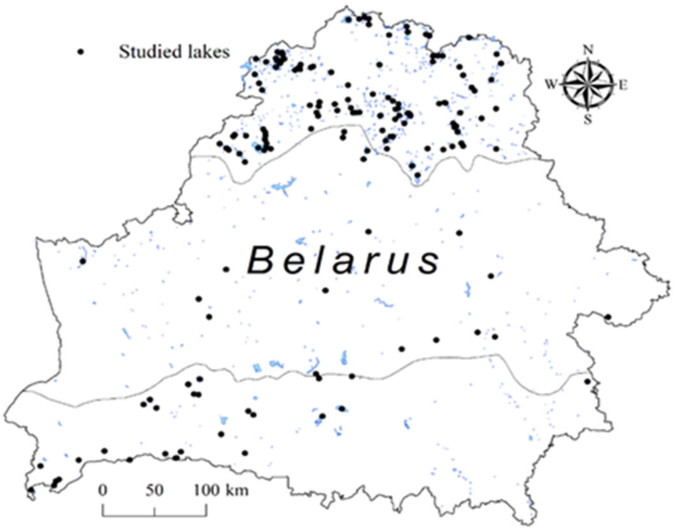

Figure 1. Schematic of the location of studied lakes.

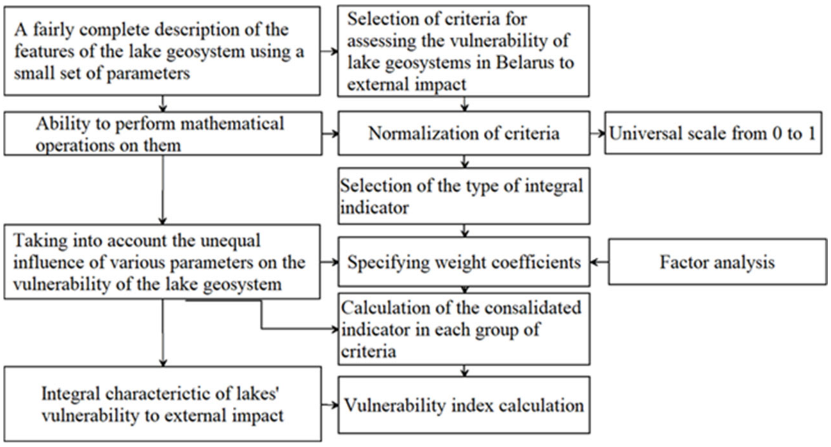

Figure 2. Algorithm of calculation of integral indices of lake vulnerability to external impact.

The integral assessment of the vulnerability of lakes to external influences was carried out in 6 stages. At the first stage, a system of criteria was selected. We used 14 parameters divided into 2 groups (Table 1).

Table 1. Criteria for assessing the vulnerability of Belarusian lakes to external impact.

Parameter	Units	Min	Max
Criteria for assessing the vulnerability of lakes to changes in the parameters of the natural regime			
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
Criteria for assessing the vulnerability of lakes to changes in water quality parameters			
Transparency	m	0.3	9.5
Mineralization	mg/dm^3	16.6	407.2
$PO_4{}^{3-}$	mg/dm^3	0	3.57
$NO_3{}^{-}$	mg/dm^3	0.001	1.8
$NH_4{}^{+}$	mg/dm^3	0.001	3.9
Bichromate oxidation	mgO_2/dm^3	5.75	129.3
pH	–	4.5	9.5

The first group includes 7 morphometric and hydrodynamic characteristics of lakes. Some methods of estimation of the lakes' vulnerability or resistance to external impact involve the use of only these parameters. However, using only morphometric and hydrodynamic characteristics is not enough. Undoubtedly, they form the background for limnic processes. If all the studied lakes were influenced only by natural factors, and the concentration of dissolved substances was close to the background, the criteria for assessing vulnerability to changes in natural conditions alone would be sufficient. Since almost all bodies of water are to one degree or another subject to anthropogenic influence, it is advisable to take into account the changes occurring under its influence. Initially, we considered many more characteristics from both groups, but as a result of additional calculations, only those listed in the table remained. 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—a value equal to 0. A conversion is performed in [27]. The variation in normalized criteria is always in the range from 0 to 1.

At the third stage, the form of the integral indicator was chosen. This depends not only on the criteria from Table 1, but also on their significance, determined by the weight coefficients w_i, the sum of which should be equal to 1.0 ($0 \leq w_i \leq 1$).

At the fourth stage, a weight estimate for w_i was introduced. This estimate was made in *Statistica 10 (Statsoft, Tulsa, OK, USA)*. To calculate weight coefficients, we carried out an indetermined factor analysis (principal component method). As a result, 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 other—a factor equal to 0.1 (Table 2).

Table 2. Weight coefficients of individual indicators used in assessing the vulnerability of Belarusian lakes to external impact.

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	PO_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

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.

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 [16], the second—0.3, because the criteria for assessing the vulnerability of lakes to changes in the parameters of the natural regime form the backdrop to all limnological processes.

A prediction of the vulnerability of lakes to external impact in the future was made for 3 different IPCC scenarios. We have identified relationships between the meteorological characteristics in the catchment areas of lakes, as well as their hydrological and hydrochemical parameters. On this basis, vulnerability assessment parameters for future climate conditions and integral vulnerability indices were calculated.

According to the SSP1–2.6 scenario, the emissions of greenhouse gasses will be low. CO_2 emissions cut to net zero around 2075.

Scenario SSP2–4.5 assumes intermediate GHG emissions. CO_2 emissions will be near current levels until 2050, then a fall is expected, but they will not reach net zero by 2100.

According to the SSP5–8.5 scenario, the emissions of greenhouse gasses will be very high. CO_2 emissions will increase 3 times around 2075 [17]. The changes in water temperatures and lake water regimes under these scenarios are described below.

3. Results and Discussion

The vulnerability indices vary from 0.223 (Lake Naroch, Myadel district, Minsk region) to 0.886 (Lake Bolduk, the same place). The investigation of the distribution of lakes with varying degrees of vulnerability, depending on the genesis and age of the relief, showed that lakes located within moraine hills and kam massifs have the greatest vulnerability. The share of lakes with a high degree of vulnerability reaches 100% here. Lakes with a predominantly medium degree of vulnerability are located on alluvial lowlands, as well as the fluvioglacial and moraine plains of the Poozerian (Wurm) age. These territories contain lakes with varying degrees of vulnerability, but the share of lakes with an average degree of vulnerability varies from 50 to 87.5% [28], which is reflected in Table 3.

Table 3. Proportion of lakes with varying degrees of vulnerability to external impact, depending on the type of relief.

Relief	Average Catchment Area, km^2	Percentage of Low-Vulnerable Lakes	Percentage of Medium-Vulnerable Lakes	Percentage of Vulnerable Lakes
Ridged-hilly and ridged marginal glacial formations of the Sozhian (Riss) age	140.00	100.00	0.00	0.00
Wavy and gently undulating fluvioglacial plains and lowlands of the Sozhian (Riss) age	9.04	0.00	0.00	100.00
Ridged-hilly marginal glacial formations of the Poozerian (Wurm) age	6.20	100.00	0.00	0.00
Ridged-hilly marginal glacial formations of the Poozerian (Wurm) age	51.58	25.00	31.25	43.75
Hilly and wavy moraine plains of the Poozerian (Wurm) age	154.93	40.00	46.67	13.33
Kam massifs of the Poozerian (Wurm) age	23.77	33.33	0.00	66.67
Hilly fluvioglacial plains and lowlands of the Poozerian (Wurm) age	235.56	53.57	42.86	3.57
Flat and gently undulating lacustrine–glacial lowlands of the Poozerian (Wurm) age	273.45	50.00	26.92	23.08
Flat lacustrine–alluvial lowlands of the Poozerian (Wurm) age	265.30	47.06	52.94	0.00
Alluvial lowlands and river valleys of Poozerie (Wurm)–Holocene age	87.20	25.00	50.00	25.00

As we can see in Table 2, the least vulnerable lakes are those located within the fluvioglacial lowlands and plains. Within Poozerie, the least vulnerable to external impact are the lakes confined to the fluvioglacial and lacustrine–glacial lowlands and plains, with the exception of acidotrophic lakes (Cherbomyslo, Bredno). The least vulnerable are the lakes of the Sozh moraine uplands, the Poozerie kam massifs and moraine uplands.

This is due to the increase in the catchment area and the acceleration of external and internal water exchange when moving from hills to plains. The catchment area determines the permissible phosphorus load in a lake and allows us to predict the trophic state of a lake in conditions of anthropogenic influence [29,30].

Figure 3 reflects the change in the indices of vulnerability to external influences in lakes with the same water volume (about 15 million m^3), using the example of lakes Batorino, Voloso Yuzhny, and Berezovskoe. These lakes differ in the genesis of lake depressions, surface area, depth, catchment area, etc.

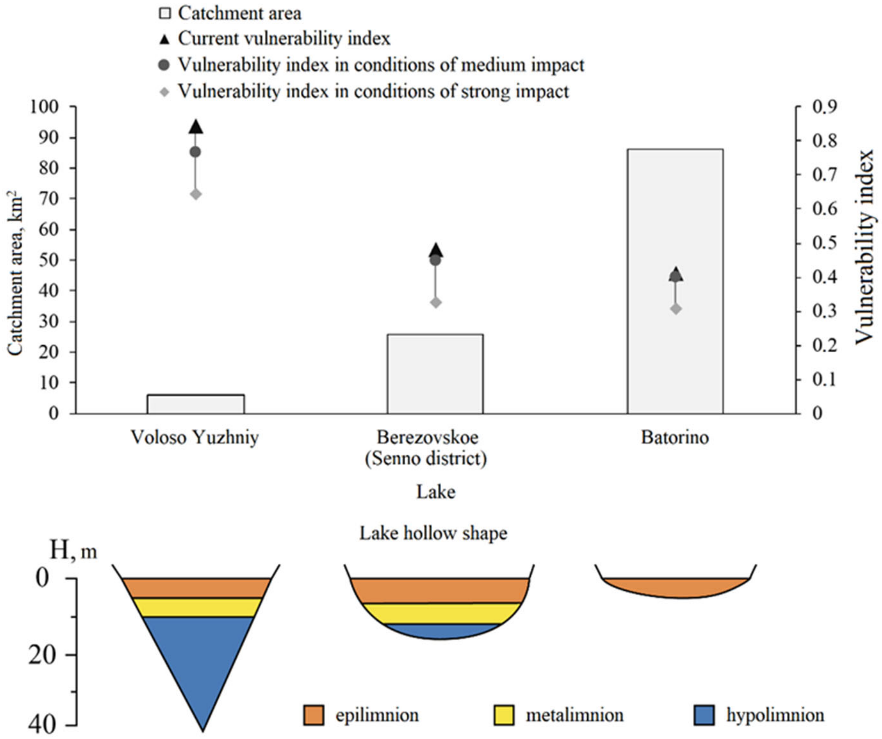

Figure 3. Comparison of vulnerability indices for lakes with the same water volume, but different catchment area and depression shape.

As the figure shows, there is the inverse relationship between the catchment area and the lake vulnerability to external impact. A large catchment area not only contributes to a decrease in the lake's vulnerability, but also smooths the consequences of anthropogenic impact, which is expressed by a decrease in the amplitude of fluctuations of the integral index of vulnerability to external impact in conditions of water pollution. The typification of Polish lake geoecosystems and the assessment of the natural resistance of the lake to the pressure from the alimentation area is also taken into account. Another set of indicators used by the author allowed her to arrive at similar results. The deep stratified lakes in Poland are more vulnerable to external impact than large shallow water bodies [13].

According to our approach, degraded lakes are less vulnerable than those not degraded, because more vulnerable lakes degrade faster than those that are invulnerable. For example, Lake Lyadno and Lake Bobritsa (Vitebsk region) are located 300 m from each other. Lake Lyadno is a wastewater receiver, whilst Lake Bobritsa develops in conditions close to natural. These water bodies differ in area (0.58 and 2.25 km^2, respectively), and the water volumes differ by 4.4 times: 19.11 and 4.35 mln m^3. The other morphometric characteristics are similar. Their maximum depths are 22 and 23 m, and their catchment areas are 14.2 and 16.5 km^2, respectively. The residence time of Lake Bobritsa is over 6 years, Lyadno—only 1.6 years. Due to the pollution of Lake Lyadno with wastewater, the mineralization of the water in it is higher than in Lake Bobritsa, by 100 mg/dm^3 (278.8 and 171.1 mg/dm^3, respectively), and the pH by 1.5 (9.3 versus 7.8). The concentration of nutrients is also higher (nitrates—3.5 times), transparency, on the contrary, is lower (1.1 m, while in Lake Bobritsa it is 3.7 m). The index of vulnerability of Lake Bobritsa is 0.542, Lyadno—0.447. Hence, Lake Bobritsa is more vulnerable than Lake Lyadno.

Because of the strong effect of the catchment on the first stages of the development of lake geoecosystems, lakes with large catchments become eutrophic and less vulnerable faster than the small ones. Mesotrophic lakes, the catchments of which are characterized by a small area, have largely retained their natural properties. At the current stage of the functioning of lakes with large catchments, their vulnerability is much lower than it was in the late glacial and Holocene.

The impact of climatic factors on lakes has its own regional differences. In Poozerie, the northern region of Belarus with the lowest summer air temperatures and high wetting factor, the main factor contributing to the transition of lakes to a qualitatively new state is the rise in water temperatures. In Polesye (in the south of Belarus), the driest region of the country, in addition to an increase in water and air temperatures, leading to an increase in evaporation, there is a decrease in the amount of precipitation in a warm season. Therefore, the climatic vulnerability of shallow Polesye lakes is high and is expressed by a reduction in the area of the water surface, which is currently observed in the example of lakes Chervonoe and Vechera.

The anthropogenic impact on lakes also differs in Poozerie and Polesye. In the catchments of Polesye lakes (Vechera, Chervonoe), a network of reclamation canals is widespread. In Poozerie, the most severely altered lakes experience pollution from industrial and agricultural lands.

If the relief of the catchment area is an azonal factor that determines the vulnerability of a lake to external impact, then climatic conditions play a defining role for other zonal factors (vegetation in catchments, hydrochemical characteristics, etc.). As a result of their interaction in the lake ecosystem, a certain combination of its components is formed. It affects the value of the integral index of its vulnerability.

By combining the types of relief from Table 2 (National atlas of Belarus, 2002) with similar morphometry characterized by the presence of lakes with the same degree of vulnerability to external impact, territories with a predominance of high-, medium- and low-vulnerable lakes were identified. The boundaries of them are shown in Figure 4.

During the analysis of the distribution of lakes with varying degrees of vulnerability to external impacts over the territory of the physical–geographical provinces, a number of regularities were identified. Within the northern part of Belarus (Poozerie), lakes with medium and high vulnerability prevail. The largest lakes (Osveyskoe, Naroch, Ezerishche, Snudy, etc.) are classified as weakly vulnerable, with the calculated values of the indices equal to 0.223–0.441. On the lacustrine–glacial lowlands, the share of lakes with a low degree of vulnerability reaches 50%, on the lakeside end–moraine hills—25%. The share of lakes with a high degree of vulnerability increases with an increase in the hypsometric level and reaches 66.7% on kam massifs. Within the moraine hills, it is already lower, but it is here that the lakes are distinguished by variation, both in genesis and morphometric features, and in hydrochemical characteristics, which provides a wide range of fluctuations in their vulnerability to changes in natural conditions and anthropogenic load. The minimum share of lakes with a high degree of vulnerability (3.6%) in Poozerie is typical for fluvioglacial plains.

In the west and east of Belarus, lakes with a medium level of vulnerability prevail on the plains, and lakes with a high degree of vulnerability are found on the uplands (Svityaz). However, the total number of lakes here is small, so a detailed analysis of the spatial dynamics of lake vulnerability is difficult. Lakes of the fluvioglacial plains and lowlands of Predpolesye are characterized by a low degree of vulnerability (Sudoble with a vulnerability index of 0.321 and Dikoe with an index of 0.367). This is facilitated by the shallowness of the lakes and large catchments, which create conditions for intensive vertical and horizontal water exchange, due to which there is a uniform distribution of dissolved substances throughout the water mass, and their subsequent oxidation. Lakes with a medium degree of vulnerability include Glukhi and Sergeevichskoe, in which water exchange is slower.

Table 4. Related works on the parallel machine scheduling problem.

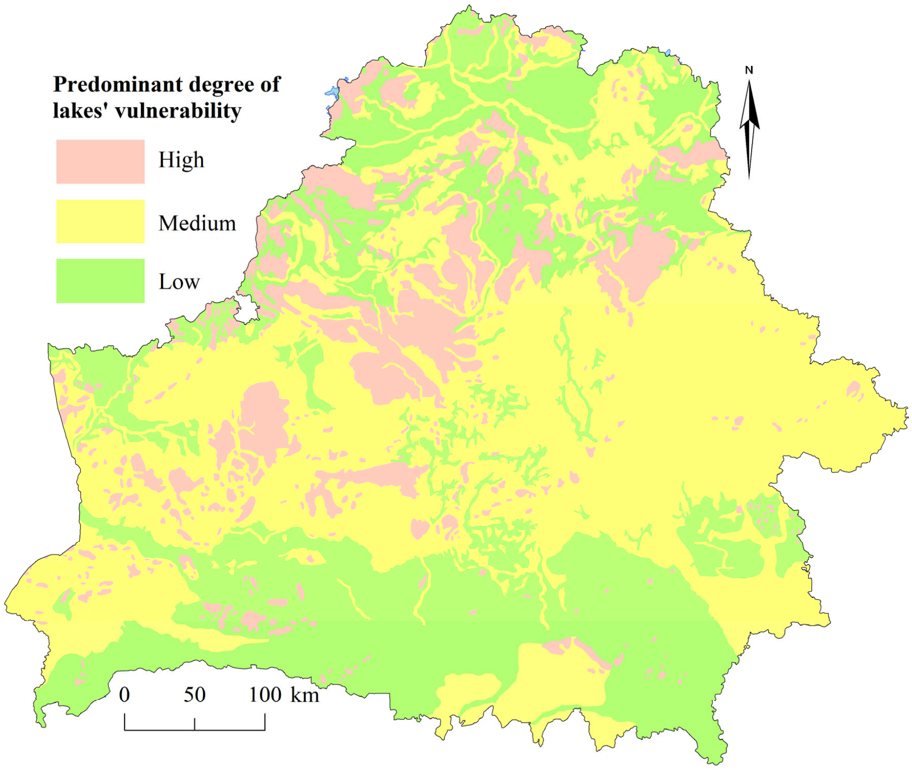

Figure 4. Spatial distribution of lakes with varying degrees of vulnerability on the territory of Belarus.

There are lakes of all types of vulnerability in Polesye, with a predominance of those that are weakly vulnerable [28]. There are no significant differences in the altitude position and vertical division of the catchments of the lakes; therefore, morphometry, hydrodynamics, and hydrochemical characteristics play an important role in the formation of the resistance of lakes to the effects of external factors. Lakes Beloe in the Ivanovo district and Gorodischenskoye in the Pinsk district are distinguished by a high degree of vulnerability. This is due to the small catchments and slow water exchange. However, the real residence time in Lake Gorodishchenskoye is higher, due to the presence of a hydraulic connection with the river. Yaselda, therefore, is most likely to be attributed to the second type. The catchment area of Lake Beloe is only 0.6 km^2, covered with forest and swamp. It is characterized by low mineralization (about 70 mg/dm^3), the acidic reaction of the environment and a rather high transparency for Polesye lakes—2.5–5 m (in summer), which makes it similar to shallow Poozerie lakes with weak water exchange, a low content of dissolved matters, and a high transparency. Lakes Vechera, Orekhovskoe, Selyakhi are characterized by a medium degree of vulnerability. Lakes with a low degree of vulnerability include the large lakes Vygonoshchanskoe and Chervonoe, with catchments located mainly on lacustrine–alluvial lowlands, as well as lakes Beloe (Brest region), Bobrovichskoe, etc.

A common feature of the highly vulnerable and weakly vulnerable lakes of Poozerie is a low specific catchment area and, consequently, a relatively low salinity. The low vulnerability of lakes Naroch, Osveyskoe, Lukomskoe, and Drivyaty to external impact is due only to the large volume of water mass and active internal water exchange. Therefore, the indicator of the specific catchment area served as a factor in the unification of districts in the province. The allocation of provinces was carried out on the basis of calculating the proportion of lakes with a low specific catchment area (less than 10) [16]. The zoning algorithm is illustrated in Figure 5.

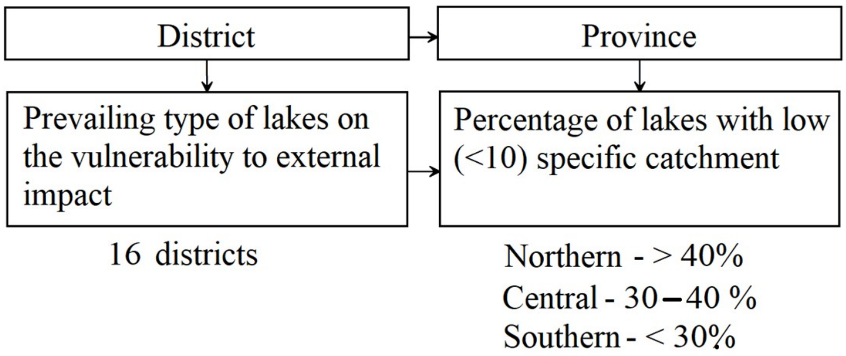

Figure 5. Algorithm for zoning the territory of Belarus according to the degree of vulnerability of lakes to external impact.

The main criterion that determines the relationship between a lake and its catchment area is the specific catchment indicator, i.e., the ratio of their areas. The lakes of the north, center and south of Belarus have differences in this indicator, which determines the allocation of three provinces in the system of zoning lakes according to the degree of vulnerability: north, central and south.

Based on the calculations, a schematic map of the zoning of the territory of Belarus was created according to the degree of vulnerability of lakes to external influences (Figure 6).

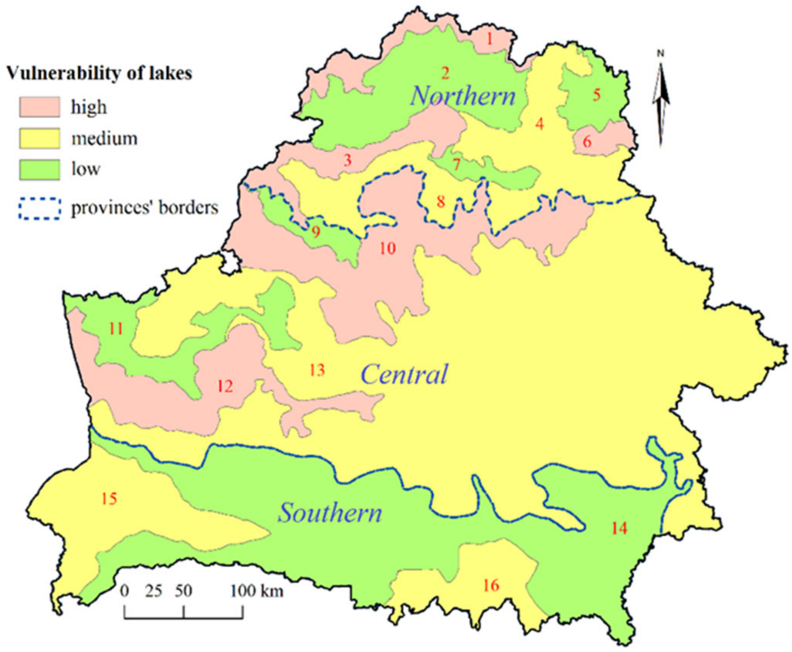

Figure 6. Note: Numbers on the schematic map indicate: 1—Braslav–Gorodok district; 2—Polotsk–Disna district; 3—Sventsiany–Ushachi district; 4—Shumilino district; 5—Surazh district; 6—Vitebsk district; 7—Lepel district; 8—Naroch–Chashniki district; 9—Vileyka district; 10—Oshmyany–Minsk–Orsha district; 11—Neman district; 12—Volkovysk–Novogrudok district; 13—Central Belarusian district; 14—Polesye district; 15—Brest district; 16—Lelchitsy district.

The northern province, with a share of lakes with a specific catchment of <10 exceeding 40%, is located in the north of Belarus and covers the area of 39,595.0 km^2. It consists of eight districts. The districts with a predominance of lakes with a high degree of vulnerability are Vitebsk, Braslav–Gorodok and Sventsiany–Ushachi, confined to moraine heights and ridges. The lakes of medium vulnerability prevail within the Shumilino and Naroch–Chashniki districts. The lakes of the Polotsk–Disna and Lepel districts are characterized by low vulnerability. The central province is isolated on the basis of the calculated share of lakes with small specific catchments in the range of 30–40%. It has the largest area of 14,947.9 km^2. It consists of five districts with varying degrees of lake vulnerability with a dominant medium. Highly vulnerable lakes prevail within the Volkovysk–Novogrudok and Oshmyany–Minsk–Orsha districts. The largest region (central-Belarusian) is distinguished by an average degree of lake vulnerability. A low lake vulnerability is typical for the Vileika and Neman districts.

The southern province is characterized by a share of lakes with small specific catchments less than 30%, which includes three regions (Polessky, with a predominance of lakes with a low degree of vulnerability; and Brest and Lelchitsy, with a predominance of lakes with a medium degree of vulnerability) and covers the area of 53,098.3 km^2. Territories with lakes of a high degree of vulnerability here occupy an insignificant area; therefore, they do not form districts. The obtained zoning scheme made it possible to generalize the spatial patterns of the distribution of different types of lakes throughout Belarus and can be used for the rational use and determination of the permissible norms of anthropogenic impact on lakes and adjacent catchment areas.

Vulnerability indices are not constant. When morphometric, hydrological and hydrochemical parameters change, indices change too. For example, disturbed lakes are found among water bodies with medium and low vulnerability (Boloyso, Lyadno, etc.). Their vulnerability indices are at least 0.100 lower than those in other lakes with a similar morphometry and water exchange period. Disturbed lakes are situated near towns or farms. They are receivers of wastewater from industrial plants and agricultural facilities. Seventy years ago, the vulnerability indices of these lakes were higher.

Since some of the initial parameters used to calculate the integral indices of lake vulnerability to external impact depend on meteorological and climatic conditions, the indices themselves are also in a close relationship with air temperatures. Figure 7 shows the relationship between the integral index of the vulnerability of Lake Naroch to external impact and the average air temperature for the previous 7 days in 1986–2018. In this case, the correlation coefficient is 0.62 (significant—±0.32).

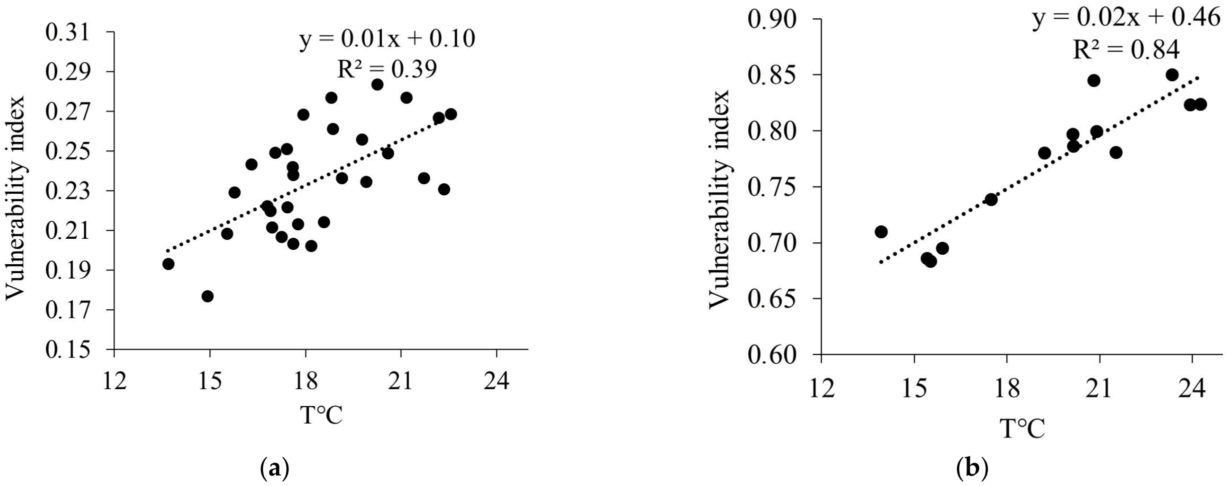

Figure 7. Relationship between the integral index of the vulnerability of Lake Naroch (**a**) to external impact in August and the average air temperature for the previous 7 days, 1986–2018 and Lake Voloso Yuzhny (**b**) to external influences in August from the air temperature for the previous 5 days.

The vulnerability index's connection with the thermal stability of the water mass is closer (the correlation coefficient is 0.80, significant—±0.18). For the deep lake Voloso Yuzhny, the obtained regressions are even more pronounced, as evidenced by Figure 6.

The differences in the period of averaging air temperatures in the catchments of various lakes are due to the greater inertia of the water mass of Lake Naroch compared to Lake Voloso Yuzhny.

For shallow lakes, an example of which is Vygonoshchanskoe, in the formation of vulnerability, the dominant role is assigned to internal factors; therefore, such connections have not been identified for them.

Based on the general tendency for the vulnerability of Lake Naroch to change under the SSP2 scenario, the value of the integral index will not rise above 0.400, i.e., the lake will remain in the weakly vulnerable type.

At the same time, for the highly eutrophic lake Vygonoshchanskoe, such regularity has not been revealed; therefore, its vulnerability is mostly formed by processes in the lake ecosystem, and the role of external factors is insignificant. The greatest danger for water bodies of this type is not an increase in air temperature itself, but a decrease in the amount of precipitation and an increase in evaporation. Now we can see a reduction in the area in the lakes Vechera and Chervonoe in dry summers. As a result, there will be a decrease in water volumes, accompanied by an increase in the lake vulnerability indices. However, a complex of hydrological and hydrochemical conditions will contribute to the preservation of the lake position in the type with low vulnerability to external impact.

On the basis of the obtained regression equations, a forecast of changes in the vulnerability of the lakes of Belarus to external impact was conducted, up to 2100, for three scenarios of greenhouse gas emissions: SSP1, SSP2, SSP5. Under the SSP1 scenario, the number of highly vulnerable lakes will increase, but the spatial patterns of changes in their vulnerability will not change in comparison with the modern ones shown in Figure 6.

Some stratified lakes (Bobritsa, Zhenno), whose geosystems currently belong to the type with a medium vulnerability level, will be classified as the type with high vulnerability to external impact. Their vulnerability indices will increase by 0.550. It is also possible that the geosystem of Lake Snudy will be classified as the type with a medium vulnerability level, with an index value of near 0.450. The position of non-stratified lakes in the typification will correspond to the current one, due to the leading role of internal mechanisms in the formation of vulnerability.

In the SSP2 scenario, due to a decrease in the vulnerability of the lakes, only two types of areas will remain, as shown in Figure 8a. With an increase in the average air temperature in the summer by 1.6–2 °C by 2050, the water temperature in the lakes of Belarus will increase by 2.3–2.8 °C and will be 22–24 °C, and the maximum will exceed 30 °C. In the expenditure part of the water balance, the share of evaporation will increase by 8–20%. With a predicted increase in precipitation by 1–5%, this will cause a decrease in the water levels in the low water of the summer, becoming especially pronounced in the shallow lakes of Polesye. If the negative water balance in the lakes of Central Belarus and Polesye is observed now from May to August, and in Poozerie from June to August, then in the future the period of predominance of the expenditure part of the water balance over the inflow will cover the period from the end of April to September. The vulnerability of lake geosystems to external impacts will change as follows: first, due to increased stratification, it will increase, as in the climate change scenario RCP2.6. This will entail a shift in the production processes to a thinner and warmer epilimnion, a concentration of biogenic elements, a decrease in transparency and a subsequent increase in trophic status, with a diminution in the vulnerability index to external impact.

Only 10 lakes will have high vulnerability indices. Currently, this number, among the objects of study, is 26. Most of the lakes (more than 80 from 149) will be classified as the type with low vulnerability. In SSP2 scenario, in areas where vulnerable lakes prevail now, lakes with a medium vulnerability to external impact will be spread, as well as in the moraine plains of Poozerie. In the plains and lowlands of central and southern Belarus, the vulnerability of most lakes will be low.

In the SSP5 scenario, the territories with low vulnerability lakes will expand (Figure 8b).

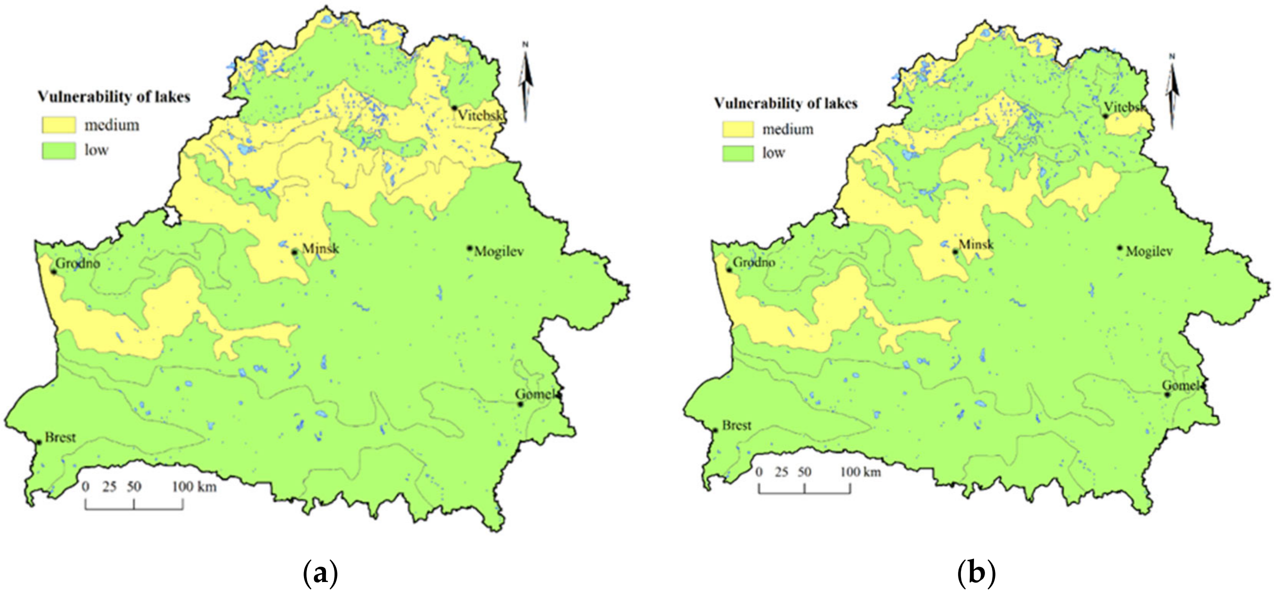

Figure 8. Changes in the vulnerability of Belarusian lakes to external impact according to the SSP2 (**a**) and SSP5 (**b**) scenario.

The lakes of plains and lowlands will turn into a type of weakly vulnerable lake. In mesotrophic lakes, eutrophication processes will occur. They will be expressed by the growth of phytoplankton biomass, and, as a consequence, by the oversaturation of the epilimnion with oxygen and its absence in the hypolimnion. Lake geosystems with a high degree of vulnerability (Dolgoe, Bolduk, Glubokoe) will be entirely classified as the medium-vulnerable type due to their eutrophication. Their indices of vulnerability are estimated at the level near 0.450–0.500. This will require a revision of the existing typification of lake geosystems in Belarus. Lakes with the medium degree of vulnerability will prevail on uplands, and, in their development, a number of shallow lakes of the Polesye will reach the stage of swamps or will experience a reduction in the water area [27]. The appearance of new vulnerable lakes is only possible with the next glaciation or the carrying out of expensive restoration measures.

Thus, the main direction of the influence of climate warming on lakes will be a decrease in their vulnerability to external impact, which will strongly affect lakes with a high degree of vulnerability.

In the research of Råman Vinnå et al., the results from the RCP8.5 (analog of SSP5) scenario showed substantial changes by the end of the century, including a reduction in ice-cover duration, changes in stratification duration (both winter and summer), and the risk of shift in lake mixing regimes. It was noted that lakes at lower and mid-altitudes may risk shifting to monomictic regimes due to climate change. Specifically, seven out of the eight lakes studied at these altitudes showed potential shifts in mixing regimes, indicating vulnerabilities in these ecosystems. The research also highlighted altitudinal variations in the projected trends in lake surface heat fluxes during the 21st century [24]. The results of Woolway and Merchant [6] show that by the end of the 21st century, the temperature of the surface layer of water in temperate lakes will increase by 2.5 °C, and the maximum possible increase is estimated at 5.5 °C. For 100 of the 635 lakes, a weakening of the mixing and a change in its regime are predicted (for example, from polymictic to dimictic for lakes in Belarus and adjacent territories, or from dimictic to warm monomictic for the southern temperate zone).

Additionally, changes in precipitation patterns caused by climate change can lead to altered water levels, affecting habitat availability, visitor activities, and water resource management. For example, low water levels can increase the concentration of pollutants in the water, as well as encourage the growth of harmful algal blooms. The results of our research can be used in the studying of lake vulnerability in other regions with similar climate and relief, in lake restoration, and in planning the optimal structure for the use of resources of lakes and their watersheds

4. Conclusions

Thus, if climatic conditions change according to the SSP1 greenhouse gas emission scenario, by the end of the 21st century, the water temperature in lakes will increase by 2 °C. This will entail a slight increase in the vulnerability of stratified lakes to external impact. According to the most probable scenario, SSP2, the water temperature in lakes will increase by 2.8–3.3 °C, which will first cause an increase, then a decrease in their vulnerability to external impact due to the eutrophication of lakes. The SSP5 scenario assumes an increase in water temperature by 6–8 °C. As a result, there will be a complete restructuring of all lakes, with a decrease in their vulnerability.

The change in the water regime will only significantly affect the state of lakes if the climate changes according to the SSP5 scenario. In other cases, the outflow part of the water balance will change due to an increase in evaporation. There will also be a redistribution of components in water income. Due to the early melting of snow, the flood will shift to an earlier period. The summer low-water period will become longer.

An increase in the vulnerability indices to external impact will occur only under climate change under the SSP1 scenario, as well as in the first two decades under climate change under the SSP2 scenario. Subsequently, a decrease in vulnerability is expected in all lakes due to increased thermal stability and reduced transparency. With climate change under the SSP5 scenario, the equilibrium will shift towards lower vulnerability indices almost immediately. In this case, shallow Polesye lakes will be characterized by a decrease in levels and a strong reduction in area.

To prevent the intensive growth of the trophic status of lakes in conditions of climate change, it is recommended to create protected areas in the catchments of mesotrophic lakes with a high and medium degree of vulnerability, and strictly adhere to the protection regime. The economic use of all other lakes and their catchments should be carried out in the absence of local sources of pollution in compliance with the regime of water protection zones and coastal strips.

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