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Effect of Climatic Fluctuations on the Structure and Functioning of Ecosystems of Continental Water Bodies

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Abstract—Climatic fluctuations are among the most important factors that cause changes in terrestrial and aquatic ecosystems. This review considers the principal mechanisms of the influence of climate changes on the structure and functioning of ecosystems of water bodies and shows the need to take these mechanisms into account when developing strategies for conserving the biological resources of aquatic ecosystems. Climatic fluctuations affect aquatic ecosystems through changes in temperature, surface runoff of nutrients and other substances and their ratios, the intensity of water mixing during the circulation period, and other mechanisms. Additional nutrients received in rainy periods from the catchment area and directly with precipitation stimulate the growth of primary producers and cause the risk of the further eutrophication of water bodies. An increase in temperature promotes the growth of potentially toxic phytoplankton species and exacerbates the problem of green tides, the massive development of multicellular algae in the coastal zone. Organic substances coming from the catchment area during wet periods stimulate a microbial loop in aquatic ecosystems. In shallow lakes, climate fluctuations can cause changes in food webs and the ecological regime. Climate-induced changes in the composition of producer communities often weaken pelagic–benthic relationships in aquatic ecosystems. In some cases, climate changes have contributed to the invasions of alien species. The natural dynamics of ecosystems affected by climate fluctuations deserves close attention and requires the development of special adaptive management of aquatic biological resources. In some cases, it is necessary to take more severe measures for the protection and restoration of water bodies, which would take into account adverse changes in natural factors.

Keywords: climate, nutrient load, productivity, food webs, ecological regime, ecosystem management

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Climatic fluctuations are among the most important factors causing changes in terrestrial and aquatic ecosystems, as well as in the composition and structure of their constitutive communities of organisms (Stenseth et al., 2002; Golubkov and Alimov, 2010; Bogatov and Fedorovskiy, 2016). Most climate models predict a significant increase in temperature at mid and high latitudes (Ruosteenoja et al., 2011). In northern and alpine lakes, the average annual water temperatures may rise up to 10°C in the next decade (Thompson et al., 2005). However, despite the abundance of evidence on the impact of climate changes on the hydrological characteristics of water bodies and watercourses, their impact on the functioning of water-body ecosystems currently remains insufficiently studied. The purpose of this review is to systematize various mechanisms of this influence and show the need to take these mechanisms into account when developing strategies for the conservation of biological resources of aquatic ecosystems. Since climate changes lead to stable changes in weather conditions, a discussion of the mechanisms of its influence, in addition to the results of long-term studies, involved data on the influence of weather conditions on various characteristics of aquatic ecosystems. Important characteristics of weather conditions include climatic indices developed in recent decades, such as North Atlantic Oscillation (NAO) and Arctic Oscillation (AO). Positive values of these indices imply the prevalence of strong westerly winds carrying warm and humid Atlantic air to the north of the European continent. Winters are getting milder and rainfall is increasing. On the contrary, negative values of these indices are associated with colder winters and lower precipitation in winter and summer (Hurrell, 1995).

Ecological systems function through the dynamic interaction of flows of energy, matter, and information (Alimov et al., 2013). This review discusses ecological mechanisms of the effect of climatic fluctuations on the structure of biological communities and their productivity, as well as on the supply and circulation of nutrients in aquatic ecosystems.

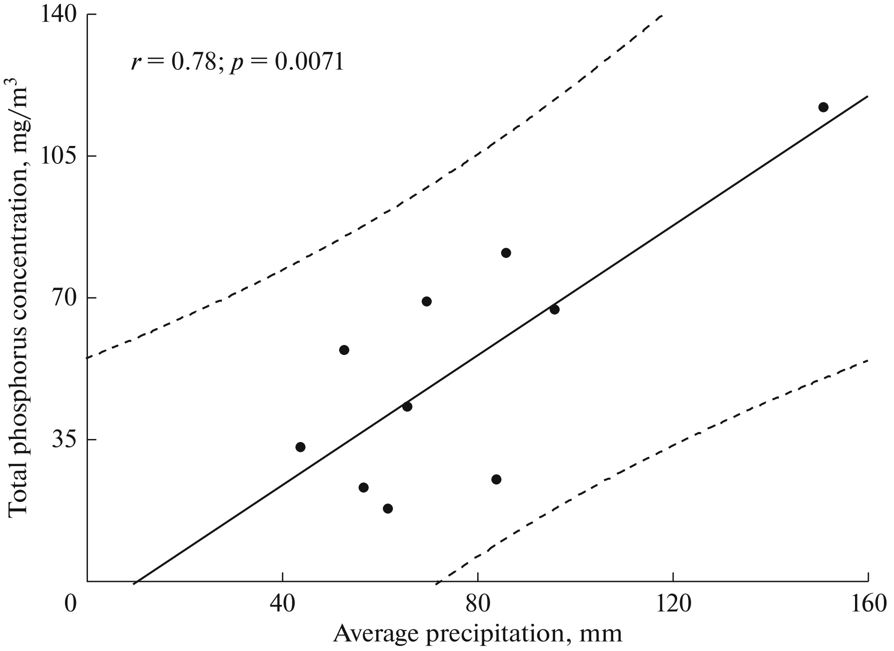

Fig 1. Relationship between the average amount of atmospheric precipitation in July and the concentration of total phosphorus in the Neva River Estuary in 2003–2005 and 2008–2016 (from Golubkov, M.S. and Golubkov, S.M., 2018).

CHANGES IN SUPPLY OF SUBSTANCES FROM THE CATCHMENT AREA

The most important group of factors responsible for the dynamics of aquatic ecosystems is the changes caused by climatic fluctuations in the supply of nutrients and other substances from the catchment area. It is important to understand that similar climatic phases (for example, climate warming) can have different consequences in different climatic zones. According to most climate models, climate warming leads to higher precipitation in the northern regions and the tropics and lower precipitation in midlatitudes (Eggleton, 2018). For example, annual precipitation in Finland is expected to increase by 12–22% by the end of the 21st century (10–40% in winter and up to 20% in summer) (Ruosteenoja et al., 2011). At the same time, an increase in winter temperatures can have a significant impact on the winter–spring dynamics of surface runoff, because constant thaws reduce the snow cover thickness and, as a consequence, reduce the onset time, intensity, and duration of spring floods. As a result of these changes, the winter river runoff increases, while the spring one decreases (Teutschbein et al., 2017).

An increase in surface runoff due to higher atmospheric precipitation leads to a greater supply of nutrients to water bodies. Positive relationships between precipitation, runoff, phosphorus load, and phosphorus concentration have been described for many aquatic systems (Gentry et al., 2007; Withers and Jarvie, 2008; Huttunen et al., 2015; Golubkov, M. and Golubkov, S., 2020). For example, as a result of long-term observations, it was shown that the concentration of total phosphorus in the Neva River Estuary in midsummer is directly proportional to the amount of precipitation (Fig. 1) and the number of rainy days in the region (Golubkov, M. and Golubkov, S., 2018, 2020). Also, its concentration correlated positively with the air temperature in winter and negatively with the summer air temperature; that is, it was higher in years with mild winters and cool rainy weather in summer (Golubkov, M. and Golubkov, S., 2020).

The supply of nutrients to water bodies depends on the composition of soils in the catchment area and the mobility of chemical elements under different conditions. For example, phosphorus turnover depends on changes in temperature and soil moisture regime, and phosphorus losses in soils are affected by changes in the duration and intensity of precipitation (Schoumans et al., 2015). Soil anoxia, which occurs during continuous rains, can lead to the dissolution of Fe–P associations in the soil profile over time and enhance the leaching of phosphorus into water bodies (Uusitalo et al., 2015). Field studies also showed that the catchment area with waterlogged soils has a greater risk of phosphorus loss if it has a positive balance of phosphorus and soil with a high percentage of organic matter (Roberts et al., 2017).

Rainy weather also facilitates the washout of additional amounts of nitrogen and dissolved organic compounds, including humic substances and organic particles, into water bodies from the catchment area (Markensten, 2006; Wilk-Wozniak et al., 2016; Teutschbein et al., 2017). At the same time, it was shown that, while in northern Europe climate warming will lead to the greater runoff of nutrients and other substances into water bodies, in Central Europe, on the contrary, the runoff will decrease (Teutschbein et al., 2017). Atmospheric precipitation itself is a source of additional amounts of nutrients, in some cases making up a significant fraction of their input to the reservoir (Boulion, 2017). Climatic changes can also affect the ratio of nutrients in the surface runoff, since it is known that, at low latitudes, the ratio of total nitrogen to total phosphorus (N : P) in water bodies is on average lower than at high latitudes (Abell et al., 2012).

Current climate changes are accompanied by more serious natural hazards, including more frequent extreme floods (Frolov, 2014; Bogatov and Fedorovskiy, 2016, 2017; Naz et al., 2018), which cause a manifold increase in the runoff of nutrients and organic matter into streams and water bodies during the flood period (Sharpley et al. 2015). Moreover, periodic droughts associated with climate warming increase the likelihood of forest fires, after which the runoff of substances from the catchment area also increases many times over (Bogatov and Fedorovskiy, 2016).

EFFECT OF CLIMATIC FLUCTUATIONS ON PRIMARY PRODUCERS AND MINERALIZATION OF ORGANIC MATTER BY PLANKTON

Additional nutrients supplied during rainy periods from the catchment area and directly with atmospheric precipitation stimulate the development of primary producers and pose a risk of further eutrophication of water bodies. Therefore, humidification of the climate in the northern regions of the temperate zone usually results in the higher primary productivity of water bodies (Jeppesen et al., 2009; Schoumans et al., 2015; Sharpley et al., 2015; Golubkov, M. and Golubkov, S., 2020). Some water bodies of the humid zone (zone of increased moisture) exhibited a positive correlation between the NAO and AO indices and the phytoplankton concentration (Maximov et al., 2012; Sharov et al., 2014; etc.). At the same time, it should be taken into account that the threshold concentrations of nutrients causing the eutrophication of water bodies are directly proportional to their flushing rate due to the dilution of wastewater by natural runoff (Rast and Thornton, 2005). Therefore, with aridization of the climate in more southern regions, a decrease in the flushing rate of water bodies characterized by high anthropogenic load with nutrients can lead to their eutrophication. Thus, a significant increase in phytoplankton productivity was observed in the most polluted reservoirs of the Middle Volga in the summer of anomalously warm and low-water 2010 (Kopylov et al., 2012).

The promptness of phytoplankton response to an increase in precipitation may depend on the conditions in the lake catchment area. In the northern regions, where soil thaws slowly in spring, additional nutrient runoff may occur not in spring, but in the second half of the growing season. As a result, an increase in phytoplankton productivity and a subsequent rise in zoobenthos productivity are observed with a delay of one year: in the next growing season (Maximov et al., 2012).

In deepwater lakes, windy weather (positive anomalies in NAO and AO) promotes more intensive mixing of water during the period of homothermy and the extra influx of nutrients from the bottom horizons into the trophogenic layer of water. For example, for large deepwater lakes in Italy, it was shown that the phosphorus content and the concentration of chlorophyll *a* in the epilimnion in summer depends on the strength of the wind in winter, which determines the depth of mixing of water during the winter homothermy and the amount of phosphorus that comes from the bottom layers of water, enriched with nutrients, into the surface horizons (Salmaso et al., 2003).

The duration of the ice cover, the time of its onset, and the intensity of water mixing have a significant effect on the intensity of the spring blooming of water in the reservoir. Therefore, weather conditions in winter and spring are of paramount importance for the productivity of reservoirs. However, wet windy weather does not always increase phytoplankton productivity. In Fennoscandia, if the lake is located on a swampy catchment area, an increase in precipitation leads to the inflow of additional amounts of humic substances into the water body, reducing the water transparency and thereby limiting the primary production of the water body (Markesten, 2006; Maximov, 2012). On the other hand, it was shown that humic acids entering the reservoir can stimulate the primary production of plankton (Chukov et al., 2010).

Organic matter coming from the catchment area serves as an additional source of nutrients for bacteria, as well as animals of zooplankton and zoobenthos (Karlsson et al., 2012; Wilk-Woźniak et al., 2016; Golubkov et al., 2019b). In rainy years, their input into water bodies can significantly increase, which stimulates processes of the mineralization of organic matter in ecosystems (Jansson et al., 2008; Golubkov et al., 2017, Golubkov, M. and Golubkov, S., 2020, Williamson et al., 2020).

Climate warming affects the species composition of phytoplankton. It is suggested that a higher water temperature reduces the role of diatoms and golden algae in phytoplankton and increases the role of cyanobacteria, dinophytes, and green algae (Elliot et al., 2006; Jarvinen et al., 2006; Jeppesen et al., 2009; Kopylov et al., 2012; Klais et al., 2013; Sharov et al., 2014). However, it should be borne in mind that, in certain species of these groups of algae, the temperature factor may invoke different responses (Golubkov et al., 2019a). In addition, rearrangements in the phytoplankton structure can be caused not so much by an increase in temperature as by other factors accompanying warming: changes in the concentration of nutrients and suspended substances, the flushing rate of water bodies, the light conditions of phytoplankton development, the timing and features of ice melting, and the mixing conditions of the water column (Weyhenmeyer et al., 1999; Rast and Thornton, 2005; Klais et al., 2013; Golubkov et al., 2019a). For example, the predominance of dinoflagellates over diatoms during the spring bloom of phytoplankton in Lake Erken, Sweden, was observed in the years when blooming began under the ice with thin snow cover in early spring (Weyhenmeyer et al., 1999). This was explained by the fact that diatoms quickly settled in the absence of turbulence under the ice, while actively floating dinoflagellates remained in the trophogenic layer.

Climatic changes can stimulate the development of cyanobacteria through changes in the ratio of nutrients in the surface runoff. In contrast to the humid zone, where, as a rule, the element limiting the primary production is phosphorus, the development of phytoplankton in low latitudes with a more arid climate is often limited by nitrogen (Abell et al., 2012). It is known that a decrease in the N : P ratio in water below a certain limit causes massive development of nitrogen-fixing cyanobacteria, many of which release toxic substances, cyanotoxins. Therefore, climate aridization can stimulate the development of these unwanted microorganisms and cause summer deaths of fish and other animals, as was observed in the steppe zone of Canada (Bariĉa, 1980). The large growth of cyanobacteria was observed in the reservoirs of the Middle Volga in the anomalously warm and dry year of 2010 (Kopylov et al., 2012).

Climatic factors also affect bottom producers. The past decades have been characterized by the worsening problem of so-called green tides, large growths of multicellular algae of genera *Ulva, Cladophora,* and *Spirogyra* in the coastal zone of water bodies (Gladyshev and Gubelit, 2019). One of the features of green tides is that the organic matter created by algae is poorly utilized in the food chains of coastal water bodies (Golubkov et al., 2018). As a result, huge amounts of decomposing biomass can accumulate at the shore line, contaminating coastal water bodies. Studies have shown that the biomass of these algae is affected positively by the water temperature and negatively by the wind speed; the mean seasonal biomass also negatively correlates with the NAO index (Gubelit, 2015).

EFFECT OF CLIMATIC FLUCTUATIONS ON FOOD-WEB DYNAMICS AND ECOLOGICAL REGIME OF WATER BODIES

In some cases, weather conditions affect the dynamics of food webs and lead to a change in the ecological regime of the water body. For example, in the shallow freshwater lake Botshol in the Netherlands, climate warming and humidification caused frequent changes in its ecological regime (Rip et al., 2007). In the first half of the 20th century, in a relatively dry climate, the prevailing ecological regime was characterized by the domination of bottom producers (chara algae) and high water transparency. With the warming and humidification of the climate in the second half of the 20th century, in years with high atmospheric precipitation, this regime was becoming unstable and replaced by a regime with high phytoplankton biomass, low water transparency, and low biomass of bottom producers. Opposite changes were observed in Lake Balaton in Hungary, where the arid years of 2000–2003 were characterized by a decrease in the water level; the extensive growth of benthic vegetation, primarily filamentous algae; and a decrease in the phytoplankton productivity (Padisak et al., 2006).

Ecosystems of shallow salt lakes, where changes in weather conditions can initiate a whole cascade of changes at different trophic levels, are especially sensitive to climatic fluctuations (Williams, 2002; Golubkov, M.S. and Golubkov, S.M., 2012; Shadrin and Anufriieva, 2013). Significantly higher water salinity often reduces the number of links in their food chains and gives rise to the trophic cascade (Lin et al., 2017; Golubkov et al., 2018). In years with low atmospheric precipitation and high water salinity, which is favorable for the development of large crustaceans *Artemia* spp., their filtration activity can significantly reduce the primary production of plankton (Golubkov et al., 2007; Golubkov, 2012; Golubkov et al., 2018). For example, hot windless weather in spring and summer in 2005 with negative NAO values led to a significant increase in water salinity and massive growth of *Artemia* in the shallow hypersaline Lake Tobechik (eastern Crimea). The filtration activity of *Artemia*, in turn, reduced the primary production of plankton, increased water transparency, and induced massive growth of filamentous algae at the bottom of the lake (Golubkov et al., 2007; Golubkov, M.S. and Golubkov, S.M., 2012). The production of these algae was far higher than the production of phytoplankton. This, in turn, led to the massive growth of the biomass of benthic animals. On the contrary, in rainy years with low water salinity, *Artemia* were eliminated from the community due to the appearance of predatory forms of zooplankton, which led to an increase in the primary production of plankton and prevented the development of benthic producers due to low water transparency. Thus, a change in weather conditions can cause a shallow salt lake to shift from an ecological regime predominated by planktonic food webs to a regime predominated by bottom food webs, and vice versa. High water salinity also enhances the role of prokaryotic organisms compared to eukaryotic ones, as well as that of anoxygenic photosynthesis and chemosynthesis compared to oxygenic photosynthesis (Shadrin and Anufrieva, 2018). In general, higher water salinity as a result of climate aridization in mid-latitudes can lead to dramatic changes in biodiversity, primary productivity, shortening of the food chain, and reduced efficiency of energy transfer from producers to upper trophic levels in salt lakes (Williams, 2002; Lin et al., 2017; Golubkov et al., 2018; Shadrin and Anufrieva, 2018).

Climatic factors affect the formation of permanent stratification (meromixis) in deepwater salt meromictic lakes. In such lakes, deep in the lake basin, there is a salty water column (monimolimnion), on top of which is a layer of less salty (sometimes fresh) water of lower density (mixolimnion). Due to the difference in density, these layers of water do not mix, which gives rise to the accumulation of organic substances in the monimolimnion, the absence of oxygen, and the accumulation of hydrogen sulfide (Rogozin, 2019). One characteristic feature of such lakes are phototrophic anoxygenic sulfur bacteria, which form stable accumulations at the border of monimolimnion and mixolimnion (Melack and Jellison, 1998; Rogozin, 2019). The depth of the redox zone may depend on weather conditions; in particular, it positively correlates with the air temperature in the previous year (Zadereev et al., 2014). It was also shown that climatic changes, such as no ice cover during warm winters, a decrease in lake depth, or salinization of the mixolimnion during the dry period, lead to the partial or complete disruption of meromixis and the lake becomes holomictic (completely mixed) (Melack and Jellison, 1998; Rogozin, 2019). This is accompanied by an intensive supply of nutrients to the photic zone, which leads to high eutrophication of the water body and changes the composition of phyto-, bacterio-, and zooplankton (Simona, 2003; Rogozin et al., 2017). With the complete mixing of water in the reservoir, purple sulfur bacteria disappear from the community (Rogozin et al., 2017).

In some cases, mixing of the meromictic lakes can result in the release of toxic gases into the atmosphere, as happened in Lake Nyos in Cameroon, when about 1700 local residents died due to the eruption of carbon dioxide (Rogozin, 2019).

Reconstructions in phytoplankton communities caused by climate changes can affect not only zooplankton communities, but also zoobenthos. For example, in recent decades, the Baltic Sea has been experiencing an increase in the proportion of dinoflagellates when compared to diatoms during spring blooms of phytoplankton (Klais et al., 2013). As a result of these changes in the phytoplankton composition, the flow of organic matter from the pelagic to the benthal zone (pelagic–benthic coupling) significantly decreased, since, unlike relatively heavy siliceous diatoms, which rapidly settle to the bottom, actively floating dinoflagellates easily stay in the surface trophogenic layer of water and can be utilized in the pelagic zone of the water body, or settle to the bottom in the form of difficult-to-decompose cysts. All this significantly worsens the nutritional conditions for zoobenthos (Klais et al., 2013; Spilling et al., 2018).

A similar picture is observed in the distribution of cyanobacteria in the water column, many species of which have neutral buoyancy and mainly concentrate in the surface water horizons (Golubkov et al., 2017). Climate warming often enhances the role of cyanobacteria in summer phytoplankton (Elliot et al., 2006; Jarvinen et al., 2006; Jeppesen et al., 2009; Sharov et al., 2014), which in turn reduces the inflow of organic matter to zoobenthic communities (Golubkov et al., 2017).

An increase in the runoff of organic matter, which is associated with warming and humidification of the climate in the northern regions, stimulates the development of the so-called microbial loop and diminishes the role of the grazing food chain, secondary consumers, affecting, in particular, the zoobenthic communities (Eriksson Wiklund et al., 2009). This is due to the fact that bacteria, due to their small size, as well as cyanobacteria and dinoflagellates, have a very low settling rate and, basically, stimulate metabolism in the water column, reducing the ratio of primary production to mineralization of organic matter in the pelagic zone of water bodies (Golubkov et al., 2017; Golubkov, M. and Golubkov, S., 2020; Williamson et al., 2020). It should also be taken into account that the stimulation of the microbial loop negatively affects the productivity of the grazing food chain, including fish (Boulion, 2019), and increases the rate of turnover of nutrients in aquatic ecosystems, which contributes to their eutrophication (Golubkov et al., 2019).

The above examples show that, if climatic changes primarily affect producer communities, the duration of changes in communities depends on the duration of weather changes. If climatic fluctuations affect populations of animals of the upper trophic levels with long development cycles, changes in the trophodynamics of water bodies become longer. For example, the disappearance of the predatory largemouth bass from Lake Wintergreen (United States) in 1978 led to the long-term domination of small planktivorous fish and—as a consequence, due to the trophic cascade—to a decrease in the density of large zooplankton and the eutrophication of the lake. Only after the artificial reintroduction of this predator into the reservoir in 1986 did the changes reverse and the water quality in the lake improved (Mittelbach et al., 1995).

In some cases, changes in aquatic ecosystems caused by climate fluctuations contribute to the introduction of alien species and a decrease in their bioresource potential (Golubkov and Alimov, 2010; Holopainen et al., 2016). Therefore, the degradation of natural communities of zoobenthos in the Neva River Estuary, caused by climate changes, contributed to the introduction of alien *Marenzelleria* polychaetes that are not easily available to fish, which impoverished fish nutrition and resulted in a multiple drop in its catches (Golubkov and Alimov, 2010; Golubkov et al., 2012). On the other hand, the oxygenation of bottom sediments due to the bioturbation activity of poly-

Table 1. Effect of climatic changes on the dynamics of ecosystems of continental water bodies

Climate change	Response of ecosystems		
	Runoff of substances from catchment area	Primary production and mineralization of organic substances	Food chains and spatial structure
Temperature rise	Change in annual runoff dynamics	Decrease in the ratio of primary production to mineralization of organic matter	Weakening of pelagic–benthic coupling due to the reduced role of diatoms in plankton Widening of the redox zone and the enhanced role of purple sulfur bacteria in food chains of meromictic lakes
Climate humidification	Increase in P and N runoff	Increase in primary production of plankton	Predominance of planktonic food webs in ecosystems of water bodies
	Increased organic matter runoff	Decrease in the ratio of primary production to mineralization of organic matter	Enhanced role of the microbial loop and lower productivity of the grazing food chain
Extreme weather events	Increased runoff of substances from the catchment area	Increase in phytoplankton production in deep-water lakes Decrease in phytobenthos production	Reduced role of benthic and increased role of pelagic food webs
Climate aridization	Decrease in P and N runoff	Decrease in primary production and the enhanced role of anoxygenic photosynthesis in shallow salt lakes	Enhanced role of the microbial loop in shallow salt lakes. Disruption of meromixis and the reduced role of organisms of the redox zone in food webs of meromictic lakes
	Decrease in the N : P ratio	Increased likelihood of cyanobacteria blooming	Weakening of pelagic–benthic coupling
	Reduction of organic matter runoff	Increase in the ratio of primary production to mineralization of organic matter in freshwater reservoirs of the humid zone	Reduced role of the microbial loop in freshwater reservoirs of the humid zone Decrease in the number of links and productivity of the grazing food chain in hypersaline lakes

chaetes reduced the internal biogenic load on the estuary water area (Maximov, 2018).

The main changes occurring in the ecological systems of water bodies under climate changes are summarized in Table 1. These data, as well as the examples given, clearly show how diverse and complex the responses of ecological systems are to the current climate warming. These responses affect a variety of processes occurring at different levels of biological organization. Moreover, both climatic changes and the corresponding responses of aquatic ecosystems have significant regional features. All this requires further careful investigation, since no effective environmental policy can be implemented without understanding the mechanisms of these changes.

CLIMATE WARMING AND ENVIRONMENTAL POLICY

The current period is characterized by an extremely difficult ecological situation, because intensive anthropogenic impact occurs against the background of rapid climatic changes, which in certain cases can enhance negative consequences of anthropogenic environmental stress (Williams, 2002; Zillen et al., 2008; Golubkov and Alimov, 2010; Huttunen et al., 2015; Sharpley et al., 2015; Golubkov, M. and Golubkov, S., 2020). Climate changes can reduce the self-purification ability of water bodies, and catastrophic floods can lead to greater washout of pollutants from the catchment area (Wen et al., 2017; Golubkov et al., 2020). In case of greater negative consequences, it is necessary to plan additional measures to preserve the environment. For example, in Northern Europe, where warming and humidification of the climate, as a rule, result in the higher load of nutrients on water bodies, it is proposed to apply phosphorus fertilizers only where it is absolutely necessary, keep track of the amount of phosphorus forms and the rate of its release (fast or slow) from the soil, and reduce the phosphorus content in feed to meet the dietary needs of domestic animals (Schoumans et al., 2015). It was also shown that application of the principles of the EU Water Framework Directive requires periodic revisions of targets for the restoration of aquatic ecosystems, taking into account the changes caused by climate fluctuations (Noges et al., 2007; Schoumans et al., 2015).

The natural dynamics of ecosystems, determined by long-term changes in natural factors, deserves close attention and requires the development of the special adaptive management of biological resources of water bodies. It should be such a management mode that would take into account natural dynamics of the ecosystem, where practical demands are adapted to this dynamics and capabilities of the ecosystem (Golubkov, 2006). Depending on the type of water body, the corresponding management objective may be different. A detailed analysis of the costs and benefits of the environmental policy is needed to determine what is achievable, affordable, and desirable for ecologists and for most of the interested enterprises (Sharpley et al., 2015).

The development of methods and techniques for predicting possible changes in ecosystems is a special task, the solution of which can be accomplished only with knowledge of the processes occurring in ecosystems and the patterns of their qualitative and quantitative changes under changes in the environment. In some cases, it is necessary to take more stringent measures for the protection and restoration of water bodies, which would take into account adverse changes in the natural background occurring under the influence of climate fluctuations.

Russia, as was indicated in the report of Roshydromet on climate changes and their consequences on the territory of the Russian Federation (Frolov, 2014), needs to accelerate the development of strategies for responding to climate changes at various levels: federal, regional, and municipal. A system of adaptation measures of various spatial and temporal scales, based on the results of scientific analysis of climate changes and their consequences, should become a priority part of these strategies.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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