Anthropogenic eutrophication of lakes Turgoyak and Bolshoi Kisegach

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Abstract. The article examines the long-term dynamics of three main indicators of the trophic state of water bodies (transparency, phosphorus concentration and oxygen regime) for the natural oligotrophic lakes of the Southern Urals: Turgoyak and Bolshoi Kisegach. These lakes have a similar history of anthropogenic development (water intake and recreation). At the same time, the lakes have a different degree of anthropogenic transformation in connection with different volumes of incoming nutrients, which affect the quality of lake waters and natural recreational potential.

1. Introduction
Lakes Turgoyak and Bolshoi Kisegach were formed at the turn of the Pleistocene-Holocene, about 12-13 thousand years ago [1, 2]. Until the beginning of the XX century, the lakes were not exposed to anthropogenic impact. In their natural state, the ecosystems of these lakes had an oligotrophic type of trophic state. In the process of developing the resources of the lakes (Turgoyak - water intake, recreation, episodic flow of domestic sewage water; B. Kisegach – recreation, water intake, systematic flow of domestic waste water from Lake Maly Terenkul), they change the initial characteristics of their ecosystems. Joint consideration of the dynamics of the ecological state of Turgoyak and B. Kisegach lakes is an important task to identify the intensity of the process of anthropogenic eutrophication of lakes in the Southern Urals. The problems of managing eutrophication processes are of global importance [3].

2. Materials and methods
Comparison of the materials of the authors who in different years explored Turgoyak and B. Kisegach to compare the intensity of anthropogenic eutrophication, we selected the data on water transparency, the concentration of dissolved oxygen in depth, and the total phosphorus concentration for July – August. Field observations and analysis of samples on Lake Turgoyak in 2015-2020 and lake B. Kisegach 1994 - 2020 performed by the author.

The trophic status of the lakes was assessed using the Trophic State Index (TSI), according to the method [4].

3. Results and discussion
According to the results of the expedition of the Institute of Geography of the Academy of Sciences of the USSR in 1965, Turgoyak and Bolshoi Kisegach were named among the oligotrophic lakes of the Southern Urals [5]. These picturesque lakes are located to the west (Lake Turgoyak) and east (Lake B. Kisegach) relative to the Ilmensky ridge and the territory of the Ilmensky state reserve. These are one
of the most capacious and deepest lakes in the Chelyabinsk region, with maximum depths exceeding 30 m (Table 1). In total, the water volume of only these two lakes is about 10% of the total "reserve" of waters of all lakes in the Chelyabinsk region.

Table 1. Morphometric parameters of lakes Turgojak and B. Kisegach [1; 6; 7].

| Lake       | Surface area, km² | Basin area, km² | Volume, million m³ | Maximum depth, m | Average depth, m |
|------------|-------------------|-----------------|--------------------|------------------|------------------|
| Turgojak   | 26.4              | 49.0            | 507.0              | 32.5             | 19.2             |
| B. Kisegach| 14.1              | 114.0           | 202.0              | 32.0             | 14.6             |

Lake Turgojak has been a natural monument since 1969; in 2007, the status of a natural monument was confirmed with an additional protected area of coastal landscapes. Lake B. Kisegach from 1969 to 2008 was also a natural monument. In 2008, the protected status of a natural monument from Lake B. Kisegach was removed.

Lakes from the 1930s to the 1950s are increasingly used in economic activities (water intake and recreation). Lakes B. Kisegach and Turgojak are popular places for beach-bathing and sanatorium-resort recreation. The number of vacationers (mostly unorganized) on the water area and the coast of each of these lakes is about 50 - 100 thousand people per year. The maximum recreational attendance on some days reaches 2000-2500 people/hour, and taking into account the unevenness of rest - up to 7000 people/day [1; 7; 8; 9].

On Lake Turgojak from 1952 to the beginning of the 1990s the water withdrawal exceeded the average long-term water balance of the lake (i.e. more than 5 - 6 million m³/year). Currently, water intake is significantly reduced and does not threaten the secular mass of lake waters [7]. Water intake from the lake B. Kisegach (in 1970-90, in total - about 2 million m³/year) [1], in the 2010s was significantly increased (approximately up to 3 million m³/year, possibly more). In combination with local changes in the catchment area and dry years, this currently (2017 - 2020) leads to a significant decrease in the level of Lake B. Kisegach.

Over the years of active involvement of Turgojak lakes and lakes B. Kisegach in the economic cycle on the lakes there are observed not only cyclical, but also directed negative changes in lake ecosystems. The leading elements of pollution for oligotrophic lakes are biogenic substances - nitrogen and phosphorus compounds. They enter the lakes with sewage water, runoff from disturbed soils, flushing from uncomfortable beaches and directly from bathers. Increased concentrations of biogenic compounds accelerate the eutrophication of the reservoir.

We tracked long-term changes in the leading indicators of the state of the lake ecosystem: transparency along the white disk in summer, total phosphorus concentration in surface and bottom waters, and dissolved oxygen concentration along the deep vertical.

In the long-term development of lake ecosystems, a steady decrease in water transparency is noted (figure 1).

2015 to 2019 there is a progressive decrease in the transparency of the waters of lakes Turgojak and B. Kisegach in the central zone – from 11.5 m to 8 m near Lake Turgojak (a drop of 70%) and from 3.8 m to 2.7 m (2018) near Lake B Kisegach (down 71%). In 2020, the transparency of water bodies is practically returning to the level of 2015; here we can talk about some natural cyclical process, because the reservoirs are not interconnected and there was no fundamental change in the intensity or nature of anthropogenic load during this period. The minimum transparency of the waters of oligotrophic lakes is 6-8 m, since the late 1970s such transparency is no longer typical for the lake. B. Kisegach.
One of the indicators of growing eutrophication is a steady increase in the total phosphorus content; in 2020, a slight decrease in concentrations in surface waters was noted (Table 2).

Table 2. Total phosphorus concentration (ppm/dm$^3$) in the surface waters of the central part of the reservoir (summer).

|       | 1965$^a$ | 2016 | 2019 | 2020 |
|-------|----------|------|------|------|
| Turgoyak | 0.003    | 0.011| 0.018| 0.006|
| B. Kisegach | 0.006    | 0.036| 0.082| 0.03 |

$^a$ according to [5]

In deep waters (at depths of 28-30 m), the current content of total phosphorus in the lake Turgoyak has not undergone significant changes compared to the mid-1960s. (from 0.027 ppm/dm$^3$ in 1965 to 0.032 ppm/dm$^3$ in 2018). On the contrary, on the lake B. Kisegach noted a significant change in the concentration of total phosphorus in not only surface, but also in bottom waters (from 0.011 ppm/dm$^3$ in 1965 to 0.047 ppm/dm$^3$ in 2016).

The study of the oxygen content along the vertical vertical in the lakes for the period from 1965 to 2020 showed that changes took place in the lakes: the oxygen saturation observed in 2020 in Lake Turgoyak is a consequence of the initial stages of eutrophication, but the distribution of oxygen along the depth is generally typical for oligotrophic lakes. In Lake B. Kisegach, oxygen supersaturation of the upper layers is observed (associated with the active reproduction of phytoplankton algae) and oxygen deficiency in the water column and at the bottom (absorption in organic oxidation processes). This type (without the formation of an anaerobic zone in the bottom layers) is characteristic of mesotrophic lakes (Table 3).
Table 3. Depth distribution of dissolved oxygen in lakes, (summer).

| Depth, m | Turgoyak (ppm/dm³; O₂%) |  | B.Kisegach (ppm/dm³; O₂%) |  |
|---------|-------------------------|--|--------------------------|--|
|         | 1965                    | 2020 |                        | 1965 | 2020 |
| 0,5     | 9.1 (94%)               | 9.8 (105%) | 8.1 | 10.2 (112%) |
| 10      | 10.0 (99%)              | 10.8 (110%) | 8.9 | 5.7 (53%) |
| 20-25   | 9.8 (82%)               | 11.8 (109%) | 8.3 | 5.6 (52%) |
| 28-30   | 9.6 (80%)               | 10.1 (85%) | 5.3 | 4.0 (36%) |

* Data on temperature and % oxygen content in the lake B. Kisegach in [5] does not.

4. Conclusion
Evaluating the dynamics of hydrophysical and hydrochemical indicators of the state of lake ecosystems (figure 1, table 2, table 3), we can conclude that since the 1970s to date, one of the oligotrophic lakes (Lake B. Kisegach) has passed to the mesotrophic level (in some cases, a weakly eutrophic level) and the initial natural characteristics have not been restored over the past 50 years.

In general, for the period from 1912 to 1965 TSI for Lake B. Kisegach was 30-32; in 2000 - 2020 - 40-45.

The main reason for the deterioration of water quality and intensive eutrophication of Lake B. Kisegach is the long-term (since 1929) supply of household waste water from the Kisegach sanatorium to the neighboring lakes M. Terenkul and Tabankul, located higher than Lake B. Kisegach. Within a few decades, lakes Tabankul and M. Terenkul were significantly polluted with biogenic substances and changed their trophic status (to polytrophic; occasionally - to hypertrophic). Long-term runoff from these polluted lakes has significantly changed the ecosystem of Lake B. Kisegach. From an oligotrophic lake, it turned into a mesotrophic-weakly eutrophic reservoir. To restore the lake B. Kisegach requires a combination of rehabilitation and preventive measures in the system of lakes Tabankul - M. Terenkul - B. Kisegach. Currently, they can be broken down into stages:

The first stage: cutting off the polluted runoff from Lake M. Terenkul to Lake B. Kisegach; construction of a biopond in the area of the M. Terenkul - B. Kisegach channel (possibly on a part of the coastal water area of the M. Terenkul lake) and the introduction of a purification system for phosphorus compounds and biological effluent (retention of cyanobacterial cells) directly in the channel between the lakes;

The second stage: complex restoration measures in the system of lakes Tabankul - M. Terenkul, consisting of separate interrelated measures (described in detail in [11]).

Lake Turgoyak continues to retain the main characteristics of the waters inherent in oligotrophic water bodies, but tends to increase the trophic state of the lake.

In general, for the period from 1912 to 1965 TSI for Lake Turgoyak was 22-25; in 2000 - 2020 - 26-27.

In Lake Turgoyak, recreation and sewage drainage play a significant role in increasing the trophic status; in the last 4 years, a sharp decrease in transparency has been observed, a massive reproduction of phytoplankton algae is recorded, which was previously completely uncharacteristic for the lake. The long-term trend (figure 1) indicates an increase in the trophic status of the lake from oligotrophic to oligotrophic-mesotrophic.

The self-healing ability for Lake Turgoyak is preserved. An important area is the accounting and regulation of the recreational load (spontaneous tourism on the coast and watershed, beach and bathing holidays). It is also necessary to solve the problem of sewerage of recreation centers located on the shores of Lake Turgoyak.

For Lake Turgoyak, it is recommended to strengthen the implementation of environmental measures provided for by the existing status of the lake as a protected object "natural monument". Lake Turgoyak, according to its water characteristics, remains the last oligotrophic lake in the Southern Urals. It is recommended to increase the legal protection of the lake from anthropogenic impact - to transfer the lake to the status of a specially protected natural area of a higher rank (state reserve, natural park).
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