

COMPREHENSIVE ASSESSMENT OF LAKE GUSINOYE, REPUBLIC OF BURYATIA, BASED ON WATER, SUSPENDED PARTICULATE MATTER AND BOTTOM SEDIMENTS GEOCHEMISTRY

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ABSTRACT. Lake Gusinoe, the second largest lake in the Republic of Buryatia, is a key source of domestic and industrial water supply for the city of Gusinozersk and nearby areas. It also serves as a recreational site and as a cooling reservoir for the coal-fired Gusinozerskaya Thermal Power Plant. The lake is exposed to prolonged anthropogenic impact from adjacent pollution sources, including the power plant, overburden dumps of the Kholboldzhinsky coal mine, and a municipal solid waste landfill. This study aims to assess the current hydrochemical state of Lake Gusinoe based on a field survey conducted in July 2019. Sampling of water, suspended matter, and bottom sediments was carried out along three transverse and one longitudinal profiles covering the entire lake area, as well as in inflowing rivers and the plant's discharge channel. Parameters analyzed included physico-chemical characteristics, major ions, nutrients, heavy metals, and metalloids (HMMs). Aeration of the water column observed during the study period was caused by wind-driven mixing and upwelling, while oxygen depletion was noted near the wastewater discharge zone. Nutrient levels indicated mesotrophic conditions, approaching eutrophic. Wind forcing facilitated a more uniform distribution of water mineralization and major ions across the greater part of the lake's surface area. Increased water mineralization and sulfate, chloride, and sodium concentrations were confined to the northern part of the lake, where the main anthropogenic sources of readily soluble salts are located. Among HMMs, dissolved Zn, Sr, Mo, and Cu predominated, with maximum concentrations exceeding sanitary norms in the northeastern part of the lake, adjacent to pollution sources. Suspended matter was depleted in HMMs relative to regional lithospheric clarks, whereas bottom sediments showed higher concentrations, indicating continuous pollutant accumulation, especially in the eastern part of the lake.

KEYWORDS: cooling reservoir, major ions, heavy metals and metalloids, nutrients, Gusinozerskaya TPP, wastewater

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INTRODUCTION

Lake Gusinoe is the second largest water body in the Republic of Buryatia. It serves as an important source of domestic and industrial water supply, a recreational site, and a cooling reservoir for the coal-fired Gusinozerskaya Thermal Power Plant (TPP), which operates on lignite extracted from local deposits. The lake's catchment area belongs to one of the most densely populated parts of the Selenga River basin (Ulzetueva et al. 2015). The Gusinozersk industrial complex, one of the largest in Buryatia, has

developed in the vicinity of Gusinozersk and includes energy, processing, and transport enterprises. Persistent pollution sources for the lake include drainage water from unreclaimed overburden dumps and abandoned mines of the Kholboldzhinsky coal deposit, atmospheric emissions and wastewater discharges from the TPP, and municipal sewage from the city of Gusinozersk and the village of Gusinoe Ozero. The Gusinozerskaya TPP alone accounts for 86.65% of total surface water consumption in the Republic of Buryatia. In addition to significant thermal impact on the northern part of the lake, the TPP operation

results in chemical pollution through stormwater runoff and discharges from ash disposal sites. In recent years, increasing recreational and tourist pressure on the lake and its watershed has also been reported (Babikov et al., 2018).

The diverse and intensive use of Lake Gusinoe has prompted studies of its chemical composition. Initial research dates back to the 1930s, coinciding with the development of local lignite deposits on the lake's northeastern shore. Scientific interest in the lake increased significantly following the launch of the Gusinozerskaya TPP. Hydrological and hydrochemical data are available in works by Samarina & Khudyakova, 1969; Bogdanov, 1977; Obozhin et al. 1984; Adushinov et al., 1994; Domyseva et al., 1995. Over the past decade, environmental studies have intensified in response to growing anthropogenic pressure, as evidenced by numerous publications on various aspects of the lake's hydrology and hydrochemistry (Chebunina et al., 2016; Tsydygov et al., 2017; Khazheeva & Plyusnin, 2018; Zhigzhitzhapova et al., 2019; Dagurova et al., Lukyanova et al., 2020; Tsybekmitova et al., 2020; Bazarova & Kuklin 2021; Kosheleva et al., 2022). However, many of these studies have focused on limited areas of the lake and examined only a narrow range of hydrochemical indicators.

A full-lake hydrochemical survey, including bottom sediment sampling, was conducted in 2020 (Radnaeva et al., 2022; Bazarzhapov et al., 2023). This research allowed for the assessment of changes in water levels and physico-chemical characteristics of Lake Gusinoe from 1951 to 2021. Elevated concentrations of total dissolved solids, sulfates, sodium, fluoride, and oxidant-resistant organic fractions were recorded near wastewater discharge points. Seasonal peaks of iron and manganese concentrations were also observed. Nevertheless, a more comprehensive understanding of the lake's current condition requires integrated studies of all components of the aquatic landscape, including not only dissolved substances but also their presence in suspended matter and bottom sediments.

To address this need, the present study sets out the following objectives: to assess the physico-chemical parameters of lake waters during the summer period and the hydrological factors affecting their spatial distribution; to determine the concentrations and spatial variability of major ions; to evaluate contamination levels by heavy metals and metalloids (HMMs) in water, suspended matter, and bottom sediments; and to assess nutrient levels and the trophic status of the lake during the summer.

A field survey was conducted in summer 2019, during which physico-chemical parameters, major ion concentrations, nutrients, and HMMs (in dissolved and suspended forms, as well as in bottom sediments) were determined, allowing for a comprehensive assessment of the current environmental status of Lake Gusinoe.

STUDY OBJECT

Lake Gusinoe is located in the center of the Gusinozersk intermountain basin. The reservoir stretches from northeast to southwest. The length of the lake is 24.8 km, the average width is 8 km, the average depth is 15 m, with a maximum depth of 26 m. The catchment area of the lake is 924 km², the area of the water surface is 164 km², and the ratio of the catchment area to water surface (5.7) characterizes the lake as a reservoir with a small specific watershed. The location of the lake in an intermountain basin determines the predominance of winds of the northeastern or southwestern directions, coinciding with the longitudinal axis of the lake.

The central pool of the reservoir, 22–24 m deep, has a rounded shape with a sharp drop in depth. At a distance of 100 m from the shore, the depth is 15–19 m. The maximum depth of the southern pool reaches 21 m, but the southern coast is relatively flat and has a beach. From the south, the Tsagan-Gol River flows into the lake. It is the largest tributary in terms of water discharge. The village of Gusinoe Ozero, with a population of about 2.5 thousand people, whose municipal wastewater is discharged into the Tsagan-Gol River, is located along the southwestern coast.

The northern pool of the lake is smaller in area and its maximum depths do not exceed 10 m. The northeastern shore is occupied by the Gusinozerskaya TPP with a capacity of 1190 MWh and Gusinozersk, a town with 25 thousand inhabitants. Domestic wastewater from the biological treatment plant in Gusinozersk is discharged into the Zagustai River, which is the longest tributary (44 km) flowing into the lake near the TPP. To the west of the power plant, the Tobkhor River, which flows near the power plant ash dump cards, enters the lake.

The rivers that belong to the catchment of Lake Gusinoe flow down from the slopes of the Khambinsky ridge. The Tsagan-Gol River flows into the lake from the southwest, and the Zagustai and the Tobkhor rivers, as well as smaller rivers and numerous streams, flow into the lake from the northeast. The only river that flows out of the lake is the Bayan-Gol River, which flows into the Selenga, the largest tributary of Lake Baikal. The groundwater system of the study area belongs to the Gusinozersk artesian basin of the Transbaikalian type. The groundwater is formed mainly due to atmospheric precipitation and, partly, due to the infiltration of river water. The upper strata, composed of river alluvium, contain low-mineralized (0.1–0.3 mg/l) water of the Ca-HCO₃ type. The lower strata of the Lower Cretaceous age contain artesian water of the Na-SO₄ type with mineralization up to 1.2–3 g/l.

According to the ratio of water inflow to water volume ($K_w < 0.5$), Lake Gusinoe belongs to the reservoirs of the slow water exchange type. The water balance and morphometric characteristics of the lake contribute to the accumulation of the entering chemical substances and also define the importance of intra-reservoir processes in the transformation of these chemicals.

Lakes located near sources of anthropogenic pollution typically experience negative impacts on both their water bodies and catchment areas (Basha et al., 2010; Kara et al., 2014; Al Naggat et al., 2018; Ćipranić et al., 2019; Kosheleva et al., 2022; Zhao et al., 2022; Vithanage et al., 2022). In 2020, emissions from energy sector enterprises in Gusinozersk amounted to approximately 45–50 thousand tons, accounting for 84% of the city's total atmospheric emissions (Bityukova et al., 2021). The main pollutants include ash particulates containing a wide range of HMMs, carbon and nitrogen oxides, sulfur dioxide, volatile organic compounds, and benzo[a]pyrene. A comparison of the actual and calculated ash composition (based on the coal's properties and ash content) showed that over half of the studied HMMs can condense onto aerosols and volatilize with the flue gases emitted by the thermal power plant (Sycheva & Kosheleva, 2023).

The intensity of airborne deposition of contaminated fine particulate matter over the lake depends on meteorological conditions – wind direction and speed, as well as the amount and duration of precipitation (Potemkin et al., 2011; Khazheeva & Plyusnin, 2016; Bortin et al., 2023). Pollution of the lake's water surface and its catchment occurs both during dry periods, due to wind erosion, and during snowmelt or rainfall events.

Atmospheric precipitation filtering through ash dumps contaminates surface and groundwater with suspended solids, petroleum products, and HMMs.

Lake Gusinoe is the source of water supply for the city of Gusinoozersk and the village of Gusinoe Ozero, as well as smaller settlements located on the coast of the reservoir. Wastewater discharge into the lake and diffuse runoff from the catchment area into the lake are a constant source of pollution. The treatment plants use physical, biological treatment and chlorination, but due to equipment deterioration and overload, the quality of treatment is low.

MATERIALS & METHODS

Physico-chemical parameters of water (temperature, electrical conductivity, dissolved oxygen content) were determined by probing the water column every 1 m with

a YSI Pro30 thermoconductometer and a Pro YSI Pro ODO oximeter. The probing was carried out at 19 stations along 3 cross-sections and one longitudinal profile, in the discharge channel of the TPP, in the Bayan-Gol River flowing from the lake, and in the major lake tributaries (the Zagustai, Tobkhor, and Tsagan-Gol, in their upper and lower reaches) (Fig. 1).

Major ions were determined using the Kapel capillary electrophoresis system (Komarova & Kamentsev, 2006). Alkalinity was determined by the acidimetric method. Water samples for the analysis of the total and dissolved forms of nutrients (phosphorus, nitrogen, and silicon) were taken from three horizons (from surface horizon, below the thermocline, and from bottom horizon). The contents of nutrients were analyzed using the spectrophotometric method following standard procedures (Sapozhnikov et al., 2003). The calculation of the trophic index based on total phosphorus TSI(TP) it was carried out according to Eq. (1):

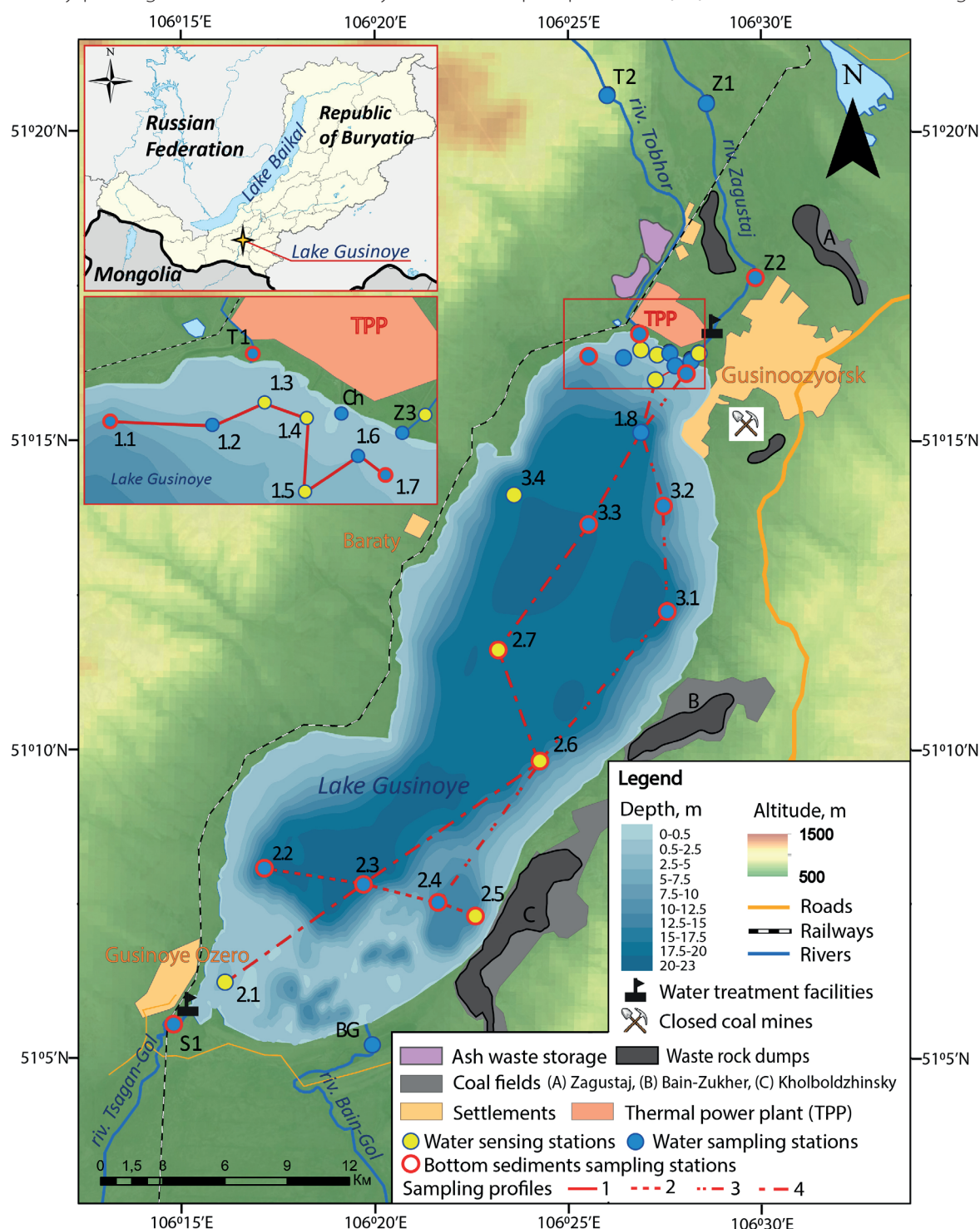


Fig. 1. Sampling stations on survey profiles in Lake Gusinoe, July 2019

$$TSI(TP) = 14.427 \ln(TP) + 4.1504 \quad (1)$$

where TP is the total phosphorus content in the water, mg/m^3 (Carlson, 1977).

The total nitrogen trophic index $TSI(TN)$ was calculated using Eq. (2):

$$TSI(TN) = 54.45 + 14.43 \times \ln(TN) \quad (2)$$

where TN is the total nitrogen content in the water, mg/m^3 (Kratzer & Brezonik, 1981).

Water samples for the determination of HMMs concentrations were taken at 10 stations, and the bottom sediments were sampled at 13 stations along the same profiles. Water samples were divided into liquid and solid phases: suspended particles were separated from the true solution using the Millipore vacuum filtration system with a membrane filter of $0.45 \mu\text{m}$ pore diameter. The filters were then dried to determine the content of suspension and the concentrations of suspended HMMs. Bulk concentrations of As, Cd, Pb, Zn, Co, Mo, Cu, Sb, Cr, V, Mn, Sr, and Ag in water, suspension, and bottom sediments were determined in the certified laboratory of the Institute of Microelectronics Technology Problems and Particularly Clean Materials of the Russian Academy of Sciences. The inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma – atomic emission spectrometry (ICP-AES) methods were applied according to the certified protocols (NSAM 499-AES/MS, 2015) using the X-7c mass spectrometer (Thermo Elemental, the USA) and the iCAP-6500 atomic emission spectrometer (Thermo Scientific, the USA).

For the ecological and geochemical assessment of the trace element composition of bottom sediments, clarkes of concentration:

$$CC = C_i / K \quad (3)$$

and clarkes of dispersion:

$$DC = K / C_i \quad (4)$$

were calculated, where C_i is the concentration of a pollutant in the lake bottom sediments, mg/kg , and K is the clark of the lithosphere (Rudnick & Gao, 2003). The coefficients of environmentally hazardous contamination of water, suspension, and bottom sediments by particular HMMs:

$$Kh = C_i / MPC_i \quad (5)$$

were calculated, showing the excess of the concentration C_i of an element i over the corresponding standard. The standards for soils (HN 2.1.3684-21, 2021) were used, since the MPCs of pollutants are not yet developed for bottom sediments.

RESULTS & DISCUSSION

Distribution of physico-chemical parameters in the lake

Water temperature and hydrological structure of the lake. The thermal regime of a body of water largely depends on weather conditions. In July 2019, the weather in Buryatia was hot and dry, with an average daily temperature of $25\text{--}34^\circ\text{C}$. Rainfall began only in the third decade of July, and the temperature dropped to $17\text{--}20^\circ\text{C}$. The analysis of the water temperature distribution in Lake Gusinoye during the expedition showed that the temperature reached 22.9°C at the outlet of the thermal power plant discharge channel, decreased to 20°C at a distance of 300 m from the outlet (station 1.7), and was $18\text{--}19^\circ\text{C}$ on the surface layer of the northern basin (stations 1.1–1.5). At the same time, the water temperature at the surface was $21\text{--}22^\circ\text{C}$ in the central (stations 2.5, 2.6, 3.1–3.3) and southern basins (2.1–2.4). The warming effect of water discharge from the TPP is clearly visible in the surface layer up to 300–500 m in the coastal shallow zone (Fig. 2).

During the expedition, the water mass of most of the lake was mixed to depths of 10–12 m. At the same time, near the northeastern shores, the depth of the thermocline zone was only 1–3 m (stations 1.2–1.5). In the central pool (stations 2.6–3.4), the thermocline was located at the depth of 11–12 m; in the southern pool (stations 2.2–2.5) it was located at the depth of 13–14 m (Fig. 2), i.e., there was a significant decrease in the thermocline depth in the northern pool and an increase of its depth in the south.

The northeast wind caused a flow of warm water masses to the southern pool and upwelling of colder masses of the hypolimnion into the epilimnion. A similar phenomenon is typical for large lakes elongated in the direction of the prevailing winds (Moiseenko et al., 2002). The temperature of the epilimnion of Lake Gusinoye was $20\text{--}23^\circ\text{C}$. Thus, water of the same temperature occupied most of the lake's volume. The even water temperature down to fairly deep layers and the absence of a density gradient in this volume contribute to the mixing of the entire epilimnion with a steady wind.

A deepening of the thermocline up to 20 m in cooling reservoirs is observed in summer (Suzdaleva & Goryunova, 2014), since warm waters entering the lake from the canal have a lower density and spread in the surface layer of water, increasing the volume of the epilimnion. Deep water intakes of the Gusinozerskaya TPP, located in the northeastern part of the lake, lead to a decrease in the volume of the hypolimnion, and the discharge of warm water to the surface leads to an increase in the thickness of the epilimnion. The even water temperature and the absence of a density gradient to a depth of 10–12 m contribute to mixing and uniform distribution of the components of the chemical composition of water.

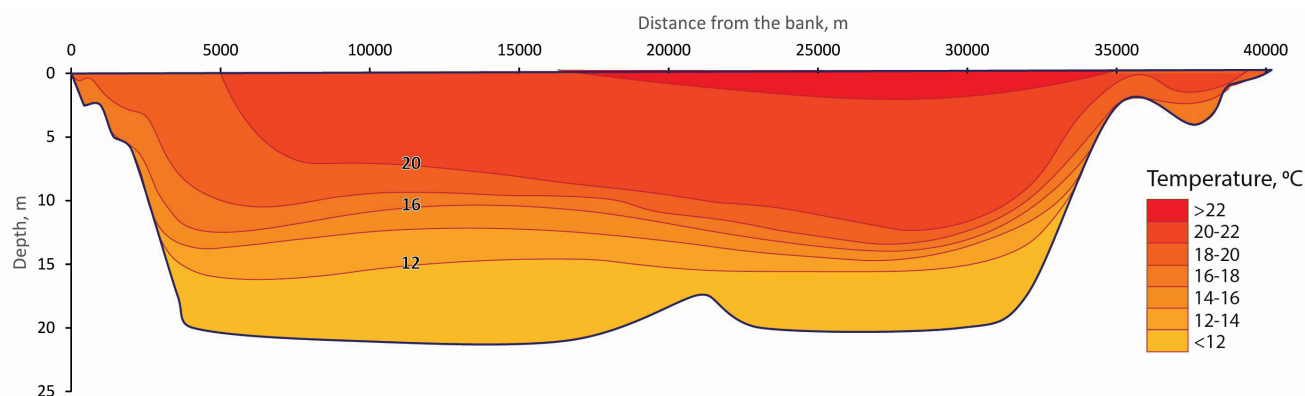


Fig. 2. Distribution of water temperature in Lake Gusinoye along profile 3 (stations 1.6, 1.5, 1.8, 3.3, 2.7, 2.6, 2.3, 2.1), July 25, 2019

In addition to the northeast wind, there are also winds from the south and southwest. Their long-term impact is manifested in the surge of water into the northern part of the lake. There is an effect of "locking" warm waste waters in the northern pool and overheating of the water column above the standards, i.e. above 28°C (Tsydypov et al., 2017).

According to field measurements conducted by scientists from the Baikal Institute of Nature Management of the SB RAS, the difference in water temperature between the discharge canal and the lake water in summer was 11–14 °C, and in winter 14–16°C. The vertical distribution of temperature in the discharge channel itself depends on the season of the year. The difference in water temperatures in the discharge canal near the power plant and at its mouth is minimal in summer (1.8–2.5°C), and maximal in winter (11.2–12.8°C). In winter, in the area where warm waters are discharged, a "polynya" (large air hole in ice cover) with an area of 0.04 to 0.9 km² remains unfrozen until February with a water temperature of 14°C; towards the edges of the "polynya" the temperature gradually decreases, but remains positive (Chebunina et al., 2016; Tsydypov et al., 2017). Reverse temperature stratification, typical of the winter period, does not form; in the "polynya" convection encompasses the entire volume of water to the bottom. Such a distribution was referred to as "winter homothermy" (Lapin et al., 2014).

Oxygen and pH. In the upper layer, mixed to a depth of 10–12 m, aeration reached 89–93% (7.9–8.4 mg/l); below the depth of 12 m, the saturation of water with oxygen decreased to 65–70%; in the bottom layer of the hypolimnion, it was about 60%. The lowest oxygen content (5.6 mg/l) was recorded at stations 2.4 and 2.5 in the near-bottom layers at depths of 15 m and 12 m.

The long period of high temperatures that preceded the observations contributed to the development of photosynthesis in the surface layer, an increase in pH and oxygen content, and the maintenance of oxidizing conditions in the epilimnion. Destruction processes in the near-bottom layer caused a decrease in oxygen content and a decrease in pH.

Near the mouth of the Tsagan-Gol River, the oxygen saturation level dropped below 62%, which was caused by the flow of wastewater from the treatment facilities of the village of Gusinoe Ozero. Pollution of the coastal zone in the southwestern part of the lake is enhanced by insufficiently treated municipal wastewater and diffuse runoff from landfills and private residential buildings, especially during the period of snow melting and rainfall. Insufficient treatment of wastewater containing large amounts of easily oxidized organic substances led to a decrease in the amount of oxygen that is consumed in oxidation processes. Note that as oxygen reserves in the bottom layers of the lake are depleted, at depths of more than 20 m, oxidizing conditions can change to reducing conditions, which, as shown in numerous studies (Zhao et al., 2017; Efimova et al., 2019; Grechushnikova et al., 2020), might cause a release of inorganic phosphorus, iron, and manganese from bottom sediments into the water.

The concentrations of dissolved oxygen in the zone of thermal impact from the Gusinozerskaya TPP in all hydrological seasons were higher than the background values. In the warm period of the year, this may be due to the increased rate of photosynthesis, and in winter, during the period of freeze-up, constant aeration is provided by the "polynya" in the area of warm water discharge (Tsydypov et al., 2017).

The water of cooling ponds located in a zone of moisture deficit is sometimes subjected to alkalization.

One of the most important reasons for this process is the technogenic input of nutrients and easily oxidized organic matter (Shavrak et al., 2012). In the water of Lake Gusinoe, despite the slow water exchange, alkalization was not observed owing to the strong wind and wave effects on the surface layers of the reservoir, preventing the concentration of organic compounds. The pH values in the lake water during the research period ranged from 7.6 to 8.45, decreasing from the surface to the bottom. The patterns of the vertical pH distribution are similar in different parts of the reservoir, which is due to the similarity of biochemical reactions and water exchange processes in the lake.

Mineralization and content of the main ions of the salt composition

According to the classification of (Alekin, 1970), the waters of Lake Gusinoe and its tributaries are characterized by average mineralization; during the survey period, water mineralization was 310–355 mg/l with an electrolytic conductivity of 433–451 µS/cm. The parameters varied across the water area and in the water column of the lake. In the surface layer of water (up to 1 m), the highest mineralization was observed in the northern pool (Fig. S1), which coincided with the temperature distribution. Near the northeastern shore of the lake, insignificant depth of the thermocline and wind-induced negative surge were observed, which might contribute to the entry of more mineralized cold waters of the hypolimnion into the epilimnion. The mineralization of water in the bottom layers of the lake was higher than in the surface layers, increasing with depth. The highest mineralization of water was recorded not at the deepest stations, but in the bottom layers of the reservoir near the settlements – Gusinozersk (station 1.8) and Gusinoe Ozero (station 2.1).

Hydrocarbonates dominated among the anions; the cationic composition was mixed, with a slight predominance of sodium. The content of major ions in the water column of the lake is distributed fairly evenly with depth. Despite the small variations, the spatial distribution of dissolved substances reflects the hydrological processes occurring in the lake (Table S1). The higher concentrations of dissolved substances were found in the northern part of the lake (stations 1.1–1.8), where technogenic sources of easily soluble salts are concentrated. There, increased mineralization and higher levels of sulfates and chlorides were registered, which may be related to wastewater discharges from Gusinozersk treatment facilities and groundwater discharge from closed pits and mines.

A specific feature of the chemical composition of the water of cooling reservoirs located in a zone of moisture deficit is a gradual increase in the mineralization of water, derived not only from evaporation processes but also from the changes in the ratios between the major ions caused by the inflow of highly mineralized waters in the bottom layers. The chemical composition of the water of Lake Gusinoe is formed in the process of interaction in the "water-rock" system, therefore it reflects the geochemical specialization of the host rocks of underground aquifers. Due to the arid climate, the contribution of surface runoff and precipitation is relatively small compared to underground runoff into the lake, which is supplied by the discharge of confined aquifers associated with coal seams and groundwater under the overburden rocks of the Kholboldzhinsky coal mine (Zhambalova et al., 2020).

The increased content of sulfates in precipitation falling on the lake surface in winter is usually associated

not only with emissions from the Gusinozerskaya Power Plant but also with the burning of coal and oil products in residential areas located along the shores of the reservoir. After snowmelt, sulfates enter the lake, increasing the mineralization of its surface layers. Despite the remediation, Kholboldzhinsky mine dumps undergo weathering and generate surface runoff. The influx of meltwater from the mine causes a rise in mineralization in the surface layers of the lake along the coastline. For example, during the flood period in 2015, the maximum water mineralization (365 mg/l) was observed in the zone influenced by meltwater runoff derived from coal mine dumps; at other stations, the mineralization varied in the range of 217–278 mg/l (Khazheeva & Plyusnin, 2018).

A local increase in sulfate content was found in the area affected by the TPP. During the expedition, an increase in diffuse runoff into the lake was observed due to precipitation, which led to a decrease in sulfate content

in the lake's surface layer near station 3.3. A local maximum in sulfate and sodium (Fig. 3) content was observed in the southwestern part of the lake, where a railway line, industrial facilities, fuel and lubricant stores, and various waste dumps are located close to the lake, from which these ions enter the lake through diffuse runoff. Near station 3.2, increased concentrations of the major cations Na, Ca, and K were observed in both the surface and bottom layers; the increase in ion concentrations was likely due to the influx of mineralized water from deep underground horizons along faults and fractures. The tributaries flowing into Lake Gusinoye form a mixing zone of river and lake waters, where, as a result of dynamic and convective mixing, the content of the major ions equalizes to the values characteristic of lake waters. In the southern part of the lake, the influence of the Tsagan-Gol River inflow is detectable (Table 1, Fig. 3).

Water in the Tsagan-Gol River is much less (5 times) mineralized than the lake water; therefore, when it flows

Table 1. Concentrations of the major ions (mg/l) in waters of the tributaries of Lake Gusinoye

Major ions	Tsagan-Gol mouth	Zagustay upper reaches	Zagustay mouth	Tobkhor upper reaches	Tobkhor mouth	Bayan-Gol, source from the lake	Discharge from the TPP
hydrocarbonates	45.9	47.6	202	reaches	140.3	170.2	180.6
sulfates	15.9	13	66.7	28.1	54.1	47.7	52.2
chlorides	3.4	0.6	7.9	11.6	7.1	7.8	8.6
calcium	12.4	13.6	32.6	0.3	31.8	30.3	31.3
magnesium	2.8	2.3	15.8	8.2	12.3	14.5	14.6
sodium	3.1	3.7	44.5	2.3	37.5	45.8	44.1
potassium	1.2	0.3	2.4	4.6	3	3.9	3.7
mineralization	84.6	81.1	371	0.6	286	320	335
discharge, m ³ /sec	2.87		1.09	55.7		0.113	

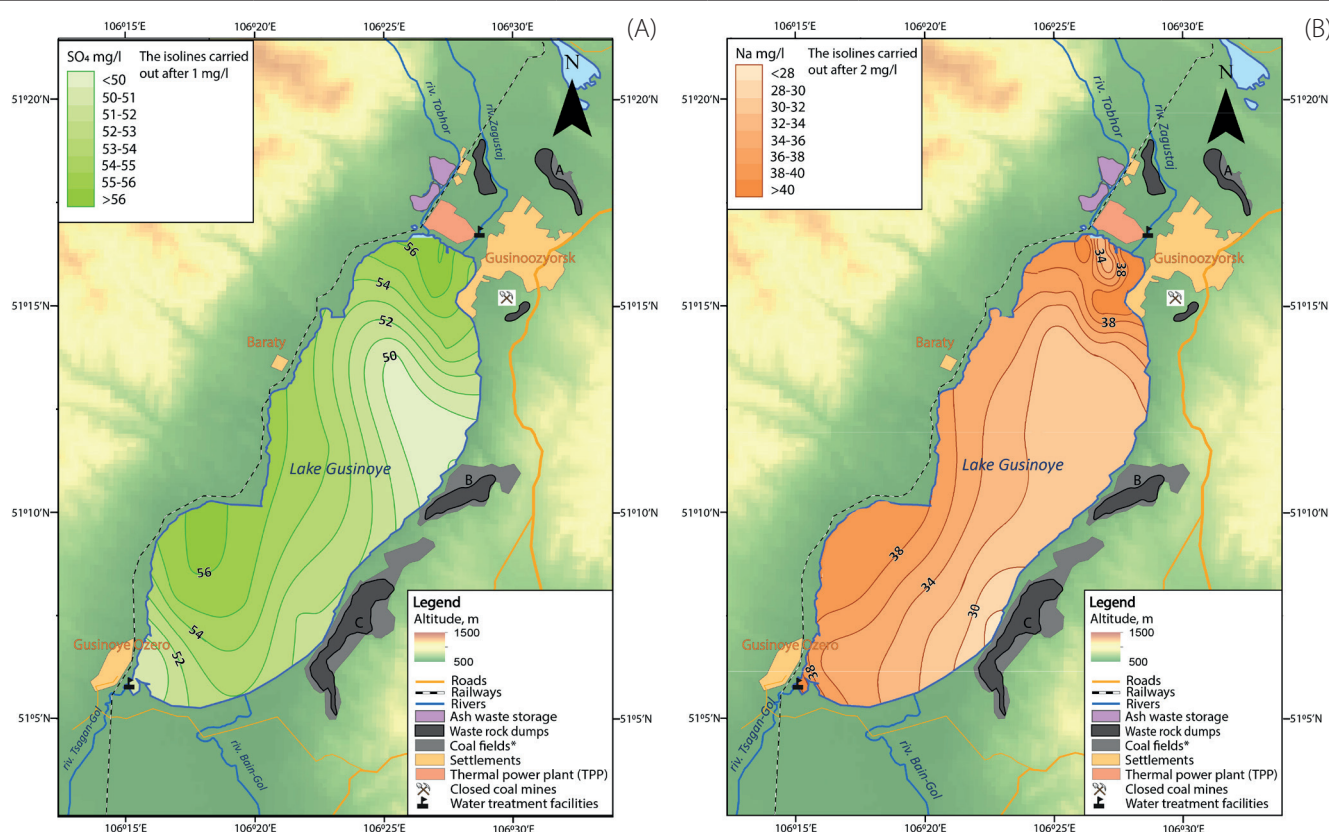


Fig. 3. Distribution of sulfates (A) and sodium (B) (mg/l) in the surface layer of Lake Gusinoye, July 2019

into a reservoir, it spreads for some time in the surface layer. Being colder and denser, the water of the Tsagan-Gol River descends below the epilimnion and spreads into the bottom layer, where it mixes with lake water.

The Zagustay and Tobkhor rivers flow into Lake Gusinoe in its northern part. The water in the Tobkhor River is less mineralized than the water of the Zagustay River (Table 1), which may be caused by the shallower depth of the channel incision and the volume of groundwater entering its bed. In the downstream direction, the mineralization and the content of major ions in the water of the Tobkhor River increase almost 5 times. Water mineralization of the Zagustay River also increases 4.5 times. The two rivers are characterized by a change in the ratio between calcium and sodium ions: the proportion of the latter increases during the low-water period (Fig. 4).

In addition, in the middle reaches of the Zagustay River, the channel is partially blocked by overburden dumps from the Zagustay coal mine, from which sulfates, chlorides, and sodium migrate into the river, increasing the concentration of these ions towards the river mouth. The Tobkhor River in its lower reaches goes around the cards of the ash and slag dumps of the Gusinozerskaya TPP, from which drainage waters of sludge pulp containing high concentrations of easily soluble salts enter the river through a collector channel.

The flow of water from the main tributaries into Lake Gusinoe creates local zones of relatively low (the Tsagan-Gol River) or relatively high (the Zagustay River) water mineralization and major ion concentrations. The size of the mixing zone of river and lake waters depends on seasonal fluctuations in water flow.

In the 1980s and 1990s, changes in water mineralization and the ratio of major ions were caused by the development and subsequent closure of the Kholboldzhinsky open-pit mine and coal mine, as well as the opening of the Gusinozerskaya TPP and the impact of its wastewater on the lake (Bogdanov, 1977; Obozhin et al., 1984; Adushinov et al., 1994). From the 1990s to the present, no noticeable increase in water mineralization has been registered (Radnaeva et al., 2022). However, an increase in the content of sulfates and chlorides was noted, which led to a change in the ratio between the major anions (Khazheeva & Plyusnin, 2018; Lukyanova et al., 2020). The relative content of sulfates increased from 6.5 to almost 13%-eq, and the relative content of chlorides rose from 1.7 to 3%-eq (Fig. S2). This finding is confirmed by the studies of Radnaeva et al. (2022), who noted a gradual increase in sulfate and

sodium concentrations in the lake water, which may be caused by rising groundwater levels. Thus, the impact of multiple anthropogenic factors on the ionic composition and content of highly soluble salts has so far manifested only in certain parts of the lake and has not affected the entire water body.

Heavy metals and metalloids

Dissolved forms of heavy metals and metalloids. Among the dissolved forms of Mn, Cu, Zn, Sr, Mo, Pb, and As analyzed in the water of Lake Gusinoe, the highest concentrations were shown by Sr: the concentrations varied from 958 to 991 µg/l, increasing with depth. The concentrations of Mo in the surface horizon varied from 14.9 to 16.0 µg/l and in most of the lake's water area they increased with depth, reaching a maximum value of 31.1 µg/l in the eastern part of Lake Gusinoe, at station 3.1 (Fig. 5). The exception was station 1.2 located in the impact zone of the Tobkhor River, where the highest Mo content (16.0 µg/l) was registered in the surface horizon. The concentrations of dissolved Zn were in the range of 0.73–36.1 µg/l, they varied quite strongly throughout the lake (Fig. 5).

Over the major part of the reservoir, the concentration of Zn decreased with depth. The maximum value in the surface horizon (3.4 µg/l) was registered near the Gusinozerskaya TPP, at station 1.1, and in the bottom horizon (36.1 µg/l), at station 2.4, in the southeastern part of the lake due to discharge of groundwaters draining overburden dumps of the Kholboldzhinsky coal mine (Table S2). The Mn concentration varied in the range of 0.24–1.7 µg/l, the maximum value of 1.7 µg/l was found in the northern part of the water area, at the confluence of the Zagustay River. In the northern part of the lake, the Mn concentration decreased with increasing depth; in the southern part of the lake, on the contrary, the Mn concentration, as a rule, increased with depth: at stations 2.4, 3.1, the concentrations of this element at a depth of 21 m were 3 times as much as in the surface horizon.

The content of dissolved Cu varied between 0.87–1.5 µg/l with a maximum value of 1.5 µg/L in the surface layer at station 1.6 in the northern part of the lake. The lowest concentrations among the studied HMMs were observed for As and Pb. The concentrations of As displayed very low variability within the water area and little change with respect to depth; As concentrations were in the range of 1.0–1.2 µg/l. The Pb concentrations varied from 0.03 µg/l in the surface layer at station 3.3 to a maximum of 0.18 µg/l

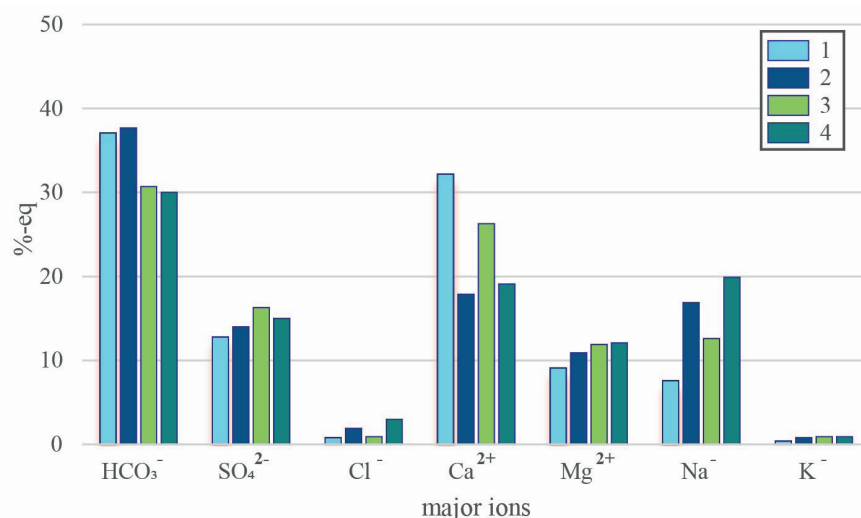


Fig. 4. Relative content of the major ions (%-eq) in the water of the Zagustay River in its upper reaches (1) and at the mouth (2), and in the water of the Tobkhor River in its upper reaches (3) and at the mouth (4)

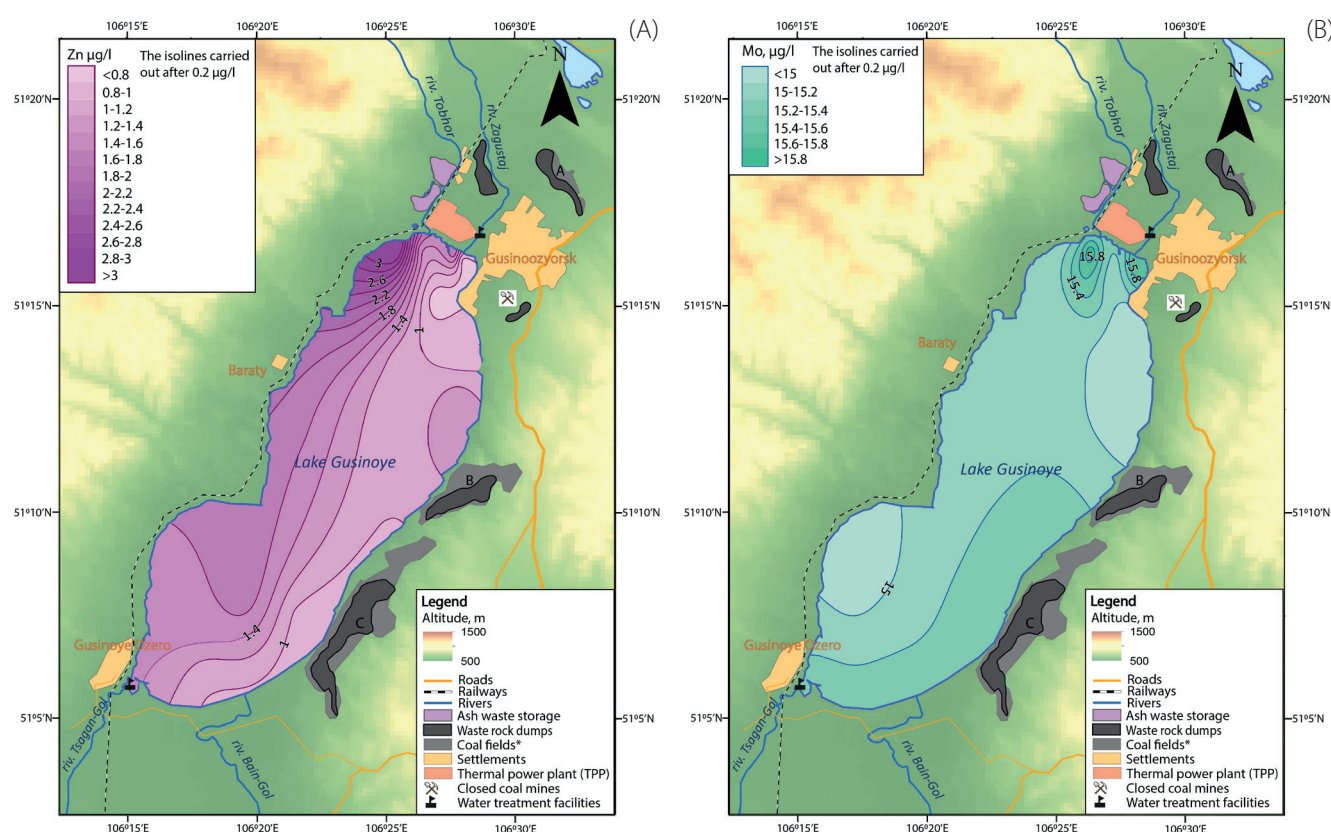


Fig. 5. Distribution of Mo (A) and Zn (B) (µg/l) in the surface layer of Lake Gusinoe, July 2019

at station 1.2 in the northern part of the lake at a depth of 5 m, which are related to the influence of the tributaries and discharges from the TPP.

The comparison of the results of the present study with the findings of the research conducted in 2021 (Bazarzhapov et al., 2023) which focused on seasonal changes of chemical composition of water and bottom sediments of Lake Gusinoe, showed that in the summer of 2021, the average concentrations of dissolved forms of Pb and Mn were higher, and the concentrations of Zn and Cu, on the contrary, were lower. The Mn concentrations in the lake in 2021 were 2.5 times as much as the concentrations observed two years earlier. Since 2019 they increased from 0.81 to 1.9 µg/l. The increase in Pb concentrations (from 0.08 to 0.11 µg/l) was less distinct. The concentration of Cu in 2021 was much lower compared to the previous period (the difference with 2019 observations was almost 2 times); they dropped from 1.09 to 0.58 µg/l, and Zn decreased from 3.07 to 2.5 µg/l (the difference was 1.2 times). At the same time, the results of the research of (Bazarzhapov et al., 2023) showed that the summer period is characterized by rather low concentrations of dissolved HMMs compared to other seasons of the year (autumn, spring, and winter).

Suspended forms of heavy metals and metalloids. In the suspended sediments, all the studied elements – Mn, Cu, Zn, Sr, Mo, Pb – were below the clarke values estimated for the upper part of the Earth's crust. The highest concentrations were displayed by Mn; its concentration varied in a wide range – from 24.4 to 395 µg/g. In general, the northern part of Lake Gusinoe is characterized by higher levels of Mn: in the area where the Tobkhor River flows into the lake at station 1.6, its content reached 212 µg/g. At this station, Cu and Sr also showed the maximum concentrations. The Mn content in suspended sediments increased with the depth of the reservoir and degree of dispersion of bottom sediments, with the exception of station 3.2, where the concentration of Mn in the surface layer was 395 µg/g, and at a depth of 21 m it decreased

to 43.4 µg/g. A similar vertical distribution for station 3.2 was found for Cu (surface-bottom concentrations, 4.0–1.1 µg/g), Zn (8.0–2.5 µg/g), Sr (15.3–7.7 µg/g) and Mo (0.63–0.19 µg/g). These patterns in distribution may be associated with the influence of surface runoff generated from the waste landfill and the abandoned coal mine, whose locations are the closest to station 3.2. The increase in the influx of polluted water into the lake was driven by heavy rainfall in June–July 2019, when 117 mm of rain was recorded over 22 days.

The concentrations of Sr in the suspended matter varied from 7.4 to 17.9 µg/g; the highest concentration was detected in the area influenced by the discharge zone of the power plant, at station 1.6. The concentration of Zn varied between 3.2–11.7 µg/g and, as a rule, increased with depth, with the exception of stations 1.2 and 3.2. The highest concentrations of Zn 10.5–11.7 µg/g were found in the bottom layer in the northern part of the lake. The content of Pb in the suspended matter was 1.1–11.4 µg/g, with the highest concentrations observed along profile 1, where the Tobkhor and Zagustay rivers reach the lake, and at the discharge zone of the Gusinoozerskaya Power Plant. Over most of the water area, the Pb concentrations showed slight variations in the range of 1.1–3.2 µg/g. The Cu concentrations varied in the range of 1.0–7.4 µg/g. The patterns of Cu distribution have not been identified either with respect to the depth or to the water area. The lowest concentrations in suspended matter were recorded for Mo (0.17–0.75 µg/g); the concentrations of this element increased with depth throughout the entire water area, except for station 3.2.

Heavy metals and metalloids in bottom sediments. The bottom sediments of Lake Gusinoe were analyzed to determine Ag, Mo, As, Cu, Sr, Zn, Sb, Pb, V, Co, and Cr concentrations. Compared to the clarke values for the upper part of the earth's crust, bottom sediments are enriched in $\text{Mo}_{9.2}, \text{Ag}_{3.8}, \text{Sb}_{2.5}, \text{Sr}_{1.5}, \text{Zn}_{1.5}, \text{Pb}_{1.4}, \text{As}_{1.3}, \text{Cu}_{1.1}$ (lower index is CC value), and depleted in $\text{Cr}^{3.1}, \text{Co}^{1.7}, \text{V}^{1.3}$ (upper

index is *DC* value). The maximum relative enrichment was observed for Ag at station 2.6 (*CC* = 26) in the eastern part of Lake Gusinoe, which might be due to the influence of overburden lignite dumps located on the shore.

In general, the northern part of the lake showed the lowest concentrations of almost all studied HMMs, which can be explained by the high speed of water delivery through the discharge channel of the power plant and the deposition of elements far from the discharge site. The exceptions are As and Sb, for which the highest concentrations, reaching 12 mg/kg and 1.3 mg/kg, respectively, were found at station 1.1, in the northwestern part of the water area.

The highest concentrations in bottom sediments of Lake Gusinoe were displayed by Sr (222–772 mg/kg), Zn (39–117 mg/kg), Cr (4.6–44 mg/kg), Cu (3.5–46 mg/kg), V (21–96 mg/kg) and Pb (15–29 mg/kg). Mo and As concentrations were in the range of 2.0–14 mg/kg, and the lowest concentrations were found for Ag (0.07–1.4 mg/kg) and Sb (0.41–1.3 mg/kg). The maximum Sr concentration, equal to 772 mg/kg, was detected in the eastern part of the lake, where the Kholboldzhinsky coal mine is located, and decreased towards the western part of the reservoir to 370 mg/kg. The highest concentrations of Ag, Mo, Pb, and Cr were found at station 2.6, in the eastern part of the lake. The bottom sediments in the central part of the lake, at stations 2.3 and 2.7, displayed the maximum concentrations of Zn, V, and Co. The highest concentrations of Cu were determined in the northeastern part of Lake Gusinoe, at station 3.2.

The analysis of the spatial distribution of the HMMs in bottom sediments revealed the accumulation of pollutants in numerous depressions of the bottom, while in shallow water the accumulation of HMMs was less obvious. Bottom sediments in the deep-water areas of the lake have a greater capacity for the accumulation of HMMs, since they are represented by black silts with a high proportion (up to 51%) of fine particles (less than 10 µm in diameter). These sediments contain a relatively high amount of organic matter (5.1–6.9%) in contrast to sandy or sandy loam sediments of shallow areas with a lower content of organic matter (0.9–4.3%).

The comparison of the results obtained for bottom sediments by (Bazarchapov et al., 2023) revealed that the average content of Pb, Mn, Cu, and Zn in sediments in July 2021 was significantly lower than in 2019: the concentration of Pb decreased by 3.4 times, Cu by 1.8 times, and Zn and Cr by 1.4–1.5 times. No significant seasonal changes in HMMs concentrations in bottom sediments were reported.

The study of the HMMs concentrations in bottom sediments of Lake Gusinoe and its tributaries conducted by (Dampilova et al., 2022) showed significant discrepancies with our results, which might indicate high geochemical heterogeneity of the lake and river sediments. In the eastern part of the lake, at the location where wastewater enters the lake from the overburden dumps of the Kholboldzhinsky coal mine, the concentrations of Cu, Zn, and Cr in the bottom sediments were reported to be higher (2.9, 2.8, and 2.3 times, respectively) than the concentrations established in the present research. At the same time, the concentrations of Pb turned out to be twice lower. A comparison of the trace element composition of the bottom sediments in the central part of Lake Gusinoe showed that, according to the results of our study, the concentration of Pb was 7.2 times, Cu 1.4 times, and Zn 1.6 times as high as the concentrations reported by (Dampilova et al., 2022). The only element that showed comparable concentrations in the bottom sediments was Cr.

Environmental hazard of HMMs pollution in Lake Gusinoe. In the water of the lake, an excess of the dissolved forms of Cu, Zn, Sr, and Mo over the sanitary standards (maximum

permissible concentrations) was revealed (MPC, 2016). The greatest excess over the standards was observed for Mo and Sr; their concentrations were higher than the MPC values in 100% of the analyzed water samples. For Mo, the environmental hazard coefficient *Kh* varied from 15 to 31, for Sr, it varied from 2.4 to 2.5. For these elements, the maximum excesses over the MPC (31 and 2.5 times, respectively) were found in the eastern part of the lake, at station 3.1, in its bottom layer. For Cu, the excess over the MPC was detected in 52% of the examined water samples; the maximum value of *Kh* = 1.5 was recorded in the northern part of the lake, in the zone influenced by the Zagustay River. The concentration of dissolved Zn exceeds the MPC only in the bottom layer (*Kh* = 3.6) of the lake, at station 2.4 located in its eastern part, which is affected by the Kholboldzhinsky coal deposit.

Nutrients

During the field research, silicon concentration in the epilimnion of Lake Gusinoe varied between 1.2–1.7 mg/L, and in the water of near-bottom layers, it was nearly twice as high. As a rule, a decrease in silicon concentrations in the surface layers of dimictic water bodies occurs from May to August as a result of the great silicon requirements of diatoms, which dominate the species composition of phytoplankton at the beginning of the growing season (Xiao et al., 2019; Sharapova et al., 2020). The waters of the lake's tributaries contained silicon in concentrations of 4–7 mg/L due to the predominance of their underground feeding. The silicon content increased from the upper reaches to the mouths of the lake's tributaries. The influence of the tributaries is clearly evident in the surface layers of the lake, where they form areas of elevated silicon concentrations (Fig. 6A).

In summer, almost all the nitrogen and phosphorus were present in organic form, and the content of inorganic phosphorus and nitrate nitrogen was close to analytical zero (Table S3). Despite the upwelling caused by the influence of constantly blowing winds, a summer thermocline formed in the lake, which prevented complete mixing of the water column and hampered the supply of nutrients from the bottom layers. The predominance of organic forms of nitrogen and phosphorus was recorded not only in the surface but also in the bottom horizons of the lake.

They probably created competition for phytoplankton for nutrients (inorganic forms of phosphorus and nitrogen) in the substrate. The content of ammonium was noticeably higher in the area where warm waters were discharged from the TPP. The increased water temperature contributed to more active mineralization of macrophytes and dead planktonic organisms and easily oxidized organic substances that entered the lake with the water of the Zagustay River and with wastewater from the treatment facilities of Gusinozersk (Fig. 6A).

The distributions of phosphates and nitrates along profile 3 were rather similar (S3). The enrichment with phosphates was observed in the near-bottom layers of the lake, at depths of 15 m or more. The replenishment of the epilimnion with nutrients in the summer could occur due to the influx from the tributaries or with diffuse surface runoff from the catchment area (Fig. 6B, S4).

The patterns of the distributions showed that in the area of the power plant impact there is a zone of local enrichment in nutrients, but a much larger amount of these elements comes with the Tsagan-Gol River discharge in the southern pool (Figs. 6, 7, S4).

The distribution of organic nitrogen corresponded to the distribution of temperature: the highest contents of nitrogen were observed in places with warm water in the

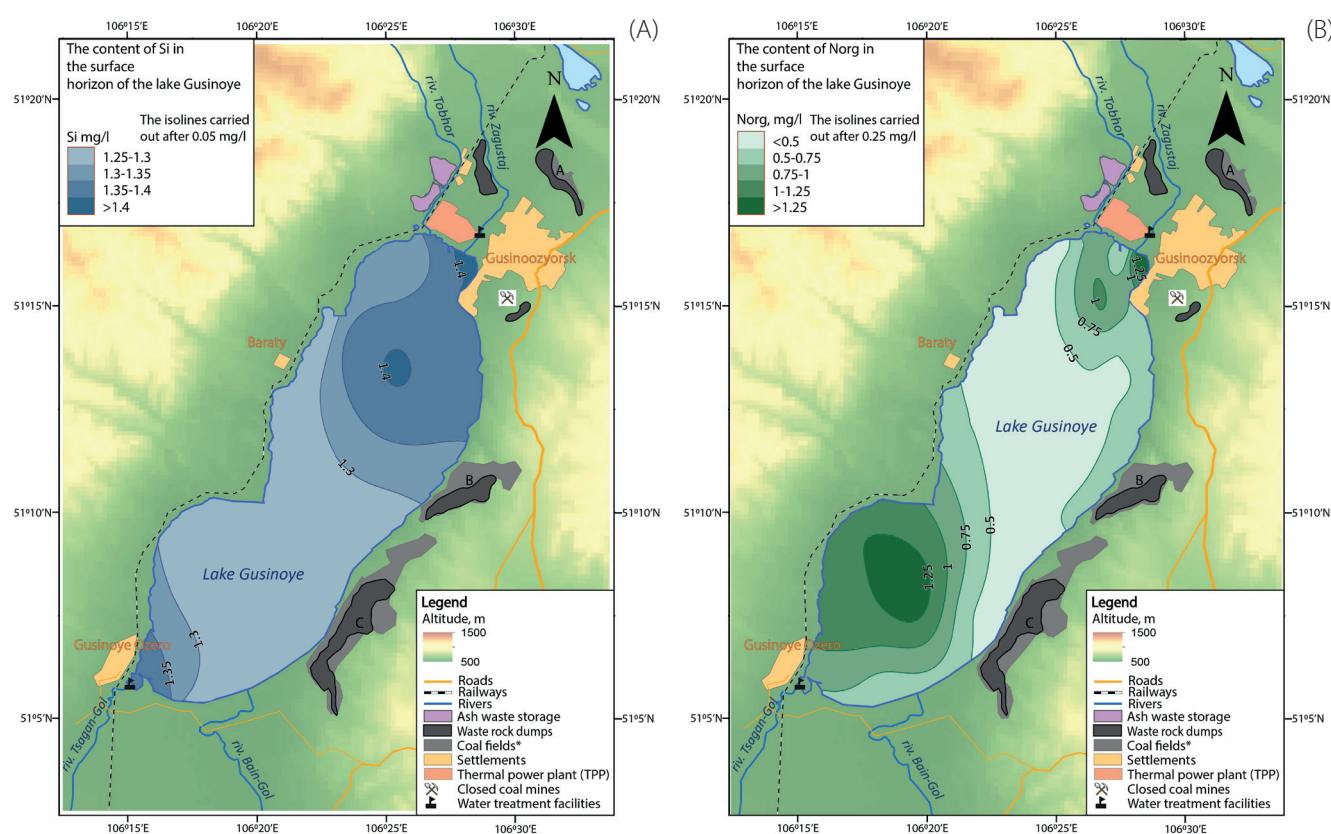


Fig. 6. Distribution of Si (A) and Norg (B) in the surface layer of Lake Gusinoe, July 2019

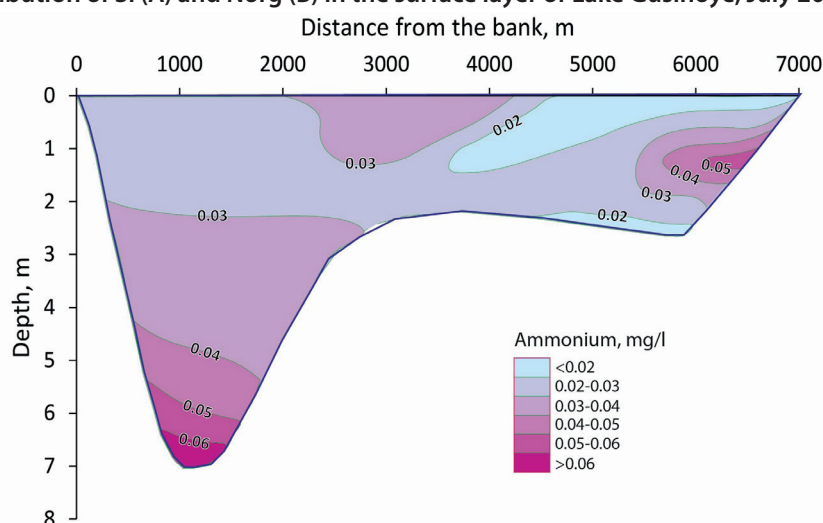


Fig. 7. Distribution of ammonium (mg/l) in Lake Gusinoe in August 2019 along profile 1 (stations 1.1–1.7)

center of the southern pool and in the northern pool in the area of discharge of warm water from the power plant, as well as in the impact zone of the Tsagan-Gol River (Fig. 7). The utilization of mineral nitrogen and phosphorus compounds was also facilitated by the presence of extensive macrophyte thickets in the lake's littoral zone, as confirmed by the distribution of organic nitrogen along the eastern shore of the reservoir. Furthermore, the most important sources of organic compounds of nitrogen and phosphorus are wastewater from the Gusinozerskaya TPP, municipal wastewater from Gusinozersk and the village of Gusinoe Ozero, and diffuse runoff from the southwestern shore of the lake. The similar distribution of these elements on the reservoir's surface (Fig. 3, 6 B) indicates similar sources of nitrogen, phosphorus, sulfates, and sodium.

The contribution of phosphorus and nitrogen to the production capacity of aquatic ecosystems has been assessed in many studies (Soranno et al., 1997; Wilhelm & Adrian, 2008; Adamovich et al., 2016; Erina et al., 2020;

Walumona et al., 2021; Sapelko et al., 2025). For this purpose, the ratio of total nitrogen to total phosphorus (TN:TP) is often used. At a value <10 , the development of algae is limited by nitrogen, and at a value >17 , the growth of algae is limited by phosphorus (Smith, 1982). The TN:TP ratio observed in the epilimnion of Lake Gusinoe varied between 24–64, which indicates that phosphorus was the limiting element. The highest values of this ratio were typical of the epilimnion of the reservoir at stations 1.7 and 1.8. These stations are under the impact of Gusinozersk wastewater and showed increased levels of organic nitrogen, accounting for 86–99% of its total concentrations (Fig. 7).

The assessment of the nutrient limitation using the ratio of inorganic substances that are most accessible to microorganisms – nitrates and phosphates – indicates a more pronounced limitation by inorganic nitrogen. The $\text{NO}_3:\text{PO}_4$ ratio in the northern pool ranged from 0.3 to 1, which may imply a deficit of inorganic nitrogen, which is

necessary for optimal phytoplankton productivity. The highest ratio of nitrates to phosphates (3–7) was observed in the surface layers of the reservoir at stations 3.1–3.3, where the influence of leachates from the coal dumps located on the eastern shore is possible.

There are a lot of lakes where the organic matter is created not as a result of the photosynthetic activity of phytoplankton but mainly as a result of the activity of submerged macrophytes (Pokrovskaya et al., 1983; Sapelko et al., 2025). In the coastal areas of the shallow northern part of Lake Gusinoye, we observed thickets of underwater macrophytes. The increase in the overgrowth of Lake Gusinoye indicates that the ecosystem is developing according to the macrophyte type and, despite the anthropogenic load, is still capable of maintaining the overall level of productivity (Bazarova & Kuklin, 2021; Bazarova, 2024).

The trophic status of a lake is the most important hydro-ecological characteristic determined by the physico-chemical and biological processes occurring in the aquatic system (Wetzel, 2001). The trophic status of Lake Gusinoye was characterized by Trophic State Indices (TSI), calculated using the contents of total phosphorus TSI(TP) (Carlson, 1977) and total nitrogen TSI(TN) (Kratzer & Brezonik, 1981). The range of values that limit bioproductivity in mesotrophic water bodies is 40–50 (Carlson, 1977). The calculations performed indicate that in the summer of 2019, Lake Gusinoye can be classified as a mesotrophic reservoir because index values were $TSI(TP) = 49.4$ and $TSI(TN) = 50$. Such values indicate that the lake lies on the boundary between mesotrophic and eutrophic water bodies and also imply its probable transition to a eutrophic state. Close values of the TSI(TP) and TSI(TN) indices, as well as the ratio of nitrogen and phosphorus in the epilimnion of the lake, indicate that co-limitation of nitrogen and phosphorus is observed, which is typical of water bodies of the temperate zone.

CONCLUSIONS

During the open-water period, the distribution of physico-chemical characteristics in the surface layers of the lake is shaped by wind influence, which generates drift currents and causes wind-driven downwelling, leading to the formation of upwelling zones. Wind activity promotes a more uniform distribution of water mineralization and major ions across most of the lake's area. Elevated levels of water mineralization and major ion concentrations are confined to the northern part of the lake, where the main anthropogenic sources of highly soluble salts are located. Sulfates, chlorides, and sodium enter the lake with wastewater discharges from Gusinozersk and the village of Gusinoye Ozero, with groundwater inflow from closed coal pits and mines, with diffuse runoff from ash dumps located in the channel of the Zagustay River, and from the territory of the Gusinozerskaya TPP.

During the study period, pollution of the lake with HMMs was identified. Among the dissolved forms of HMMs in the lake water, Sr, Mo, Cu, and Zn predominated. The highest concentrations of these elements, exceeding MPC values, were found in the northern part of the lake and in the area where drainage water from the overburden dumps of the Kholboldzhinsky coal mine discharges into the water body. Suspended matter was depleted in all studied HMMs compared to the Clarke values for the upper continental crust; the highest contents in suspended sediments were found for Mn and Sr, which is attributed to surface runoff from the municipal solid waste landfill and an abandoned coal mine. At the same time, bottom sediments were enriched in Mo, Ag, Sb, Sr, Zn, Pb, and As, compared to average concentrations in the upper continental crust. Concentrations of Cu, Zn, Sr, Mo, and Pb in bottom sediments were higher than in suspended matter. HMMs entering the lake from various sources are deposited and accumulated in bottom sediments, increasing their pollution level and forming anthropogenic HMM anomalies.

The greater part of the lake's water mass is well aerated. However, in coastal zones, oxygen content decreases due to the decomposition of organic matter entering the water body with insufficiently treated wastewater from the city of Gusinozersk and the village of Gusinoye Ozero, as well as with diffuse runoff from landfills and private households within the watershed. The decomposition of remnants of coastal aquatic vegetation also contributes to oxygen depletion. During the study period, almost all nitrogen and phosphorus in Lake Gusinoye were present in organic form. Despite wind-induced mixing and upwelling, the replenishment of the euphotic zone with inorganic nutrients was limited due to their low content in the hypolimnion. The utilization of mineral forms of nitrogen and phosphorus was further facilitated by the presence of extensive macrophyte beds in the littoral zone, which is corroborated by the distribution of organic nitrogen along the eastern coast. In the summer of 2019, Lake Gusinoye was classified as a mesotrophic water body.

A comprehensive study of the lake's water mass together with suspended sediments showed that the current anthropogenic load has not yet led to significant changes in the content of highly soluble salts and HMMs; exceedances of MPCs for individual metals were identified only in the northern part of the lake. However, the gradual accumulation of HMMs in bottom sediments indicates that in the near future they may become a source of secondary pollution for the lake's ecosystem. An unfavorable trend is also observed in the dynamics of nutrient content. Under the influence of increasing municipal load associated with wastewater discharge and diffuse runoff, as well as unregulated tourism, the waters of the northern reach of the lake may transition to a eutrophic state. This could negatively affect the ecosystem of Lake Gusinoye and the quality of water used for domestic and drinking water supply. ■

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Appendix

Supplementary materials to the article by Lyudmila Efimova, Natalia Kosheleva, Anna Lukyanova, Daria Sycheva and Vasiliy Efimov: “Comprehensive assessment of Lake Gusinoye, Republic of Buryatia, based on water, suspended particulate matter and bottom sediments geochemistry”

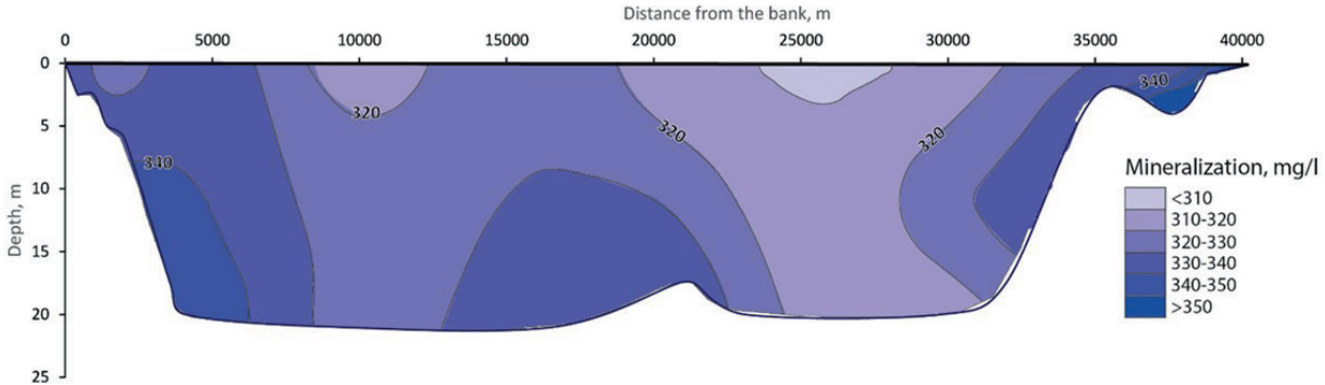


Fig. S1. Distribution of water mineralization (mg/l) along profile 3 (stations 1.6, 1.5, 1.8, 3.3, 2.7, 2.6, 2.3, 2.1), July 25, 2019

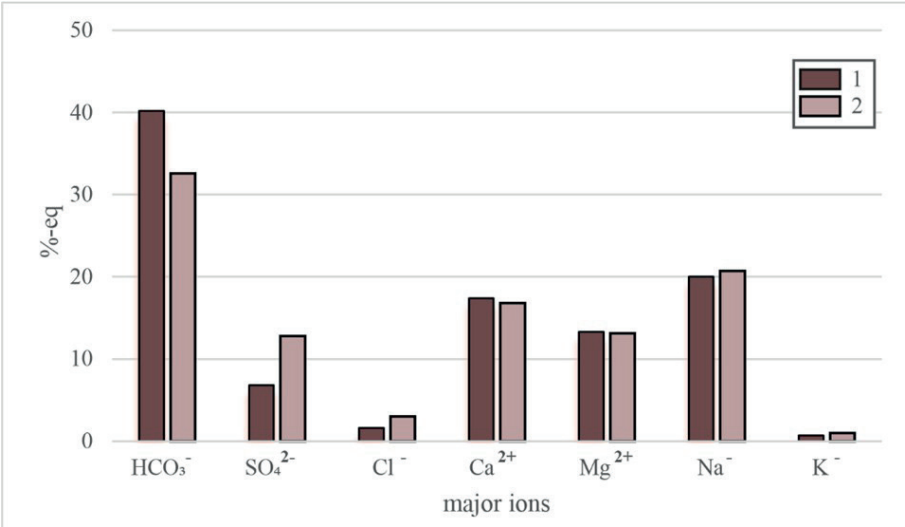


Fig. S2. Relative content of major ions in the water of Lake Gusinoye, %-eq:
a – August 1969 (Adushinov et al., 1994); b – July 2019 (data from MSU expedition, 2019)

Table S1. The content (surface-bottom) of major ions (mg/dm³) in the water of Lake Gusinoye at water sampling stations

Station No	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.1
The depth, m	6	5	2.5	2.0*	4.5	1.8*	2.5*	11	4.5
pH	8.33-8.28	8.32-8.34	8.23-8.23	8.28	8.34-8.28	8.3	8.32	8.37-8.26	8.29-7.60
HCO ₃ ⁻	179.6-179.6	168.7-180.2	187.1-190.1	182	180.7-184.9	181.8	187	182.5-192.5	169-192.2
SO ₄ ²⁻	55.8-55.9	56.2-56.8	56.4-56.6	57.1	57.0-55.7	56.0	55.3	55.9-55.6	50.1-22.6
Cl ⁻	9.7-9.2	9.4-9.1	11.2-9.1	9.4	9.1-8.9	8.8	8.8	8.9-9.5	8.1-2.8
Ca ²⁺	28.5-28.0	31.3-27.8	24.7-26.4	26.4	23.9-30.5	28.7	29.0	28.5-28.4	28.6-27.4
Mg ₂ ²⁺	16.5-16.2	17.8-16.2	14.0-15.5	14.9	13.8-16.6	17.0	16.7	16.8-17.1	14.9-7.1
Na ⁺	39.0-38.7	41.8-38.3	32.5-35.8	37.2	32.2-39.8	40.6	40.5	41.6-40.8	36.2-14.1
K ⁺	2.6-2.7	2.8-2.6	2.1-2.5	2.7	2.1-2.8	3.1	2.7	2.8-2.9	2.8-1.8
M	336-339	329-334	332-335	318	319-324	326	331	337-347	330-355
The station number	2.2	2.3	2.4	2.5	2.6	2.7	3.1	3.2	3.3
The depth, m	20	22	15.6	12	19	21	19.6	16	21
pH	8.44-7.90	8.44-8.27	8.44-8.0	8.42-8.36	8.44-7.94	8.42-7.91	8.34-7.91	8.42-8.17	8.45-7.91
HCO ₃ ⁻	177.8-189.5	175.4-178.6	180.3-190.4	186.5-189.8	182.2-206	191.5-202.7	183.7-183.9	183.1-184.2	190.9-199.3
SO ₄ ²⁻	55.5-55.7	55.1-51.1	52.9-52.9	51.9-52.4	52.4-51.7	53.8-52.5	49.7-53.1	54.0-54.1	49.7-53.3
Cl ⁻	8.7-9.0	9.3-9.3	8.8-8.9	8.6-8.8	8.5-8.7	9.1-8.8	8.2-8.4	8.2-8.1	7.3-7.7
Ca ²⁺	27.6-28.1	22.0-23.7	22.1-22.1	20.4-22.4	22.2-23.5	23.1-23.5	21.3-22.2	21.7-22.4	21.6-21.2
Mg ₂ ²⁺	16.3-16.4	13.8-13.6	13.1-12.9	12.6-13.6	13.7-14.0	14.2-14.1	13.0-14.4	14.5-14.9	14.0-13.5
Na ⁺	39.0-39.0	34.1-32.1	31.2-29.9	27.9-31.6	31.9-32.4	32.7-32.6	30.8-32.4	32.6-32.2	30.0-28.8
K ⁺	2.7-2.7	2.7-2.8	2.6-2.6	2.1-2.5	2.8-2.7	2.6-2.7	2.6-2.6	3.2-3.0	2.9-2.7
M	328-340	312-327	311-320	310-321	314-329	327-337	310-318	318-320	317-327

Note: *The content of major ions at stations 1.4, 1.6, 1.7 was measured only at the surface.

Table S2. The concentrations of dissolved forms of HMMs in water (surface – bottom) of Lake Gusinoye and in the suspended and bottom sediments at water sampling stations. The MPCs for fishery and clark values for the upper part of the earth's crust (Rudnick, Gao., 2003)

Station No	1.1	1.2	1.6	1.7	1.8	2.2	2.3	2.4	3.1	3.2	3.3	
Depth, m	6	2.5	2.0*	2.5*	20	21	21	17	21	21	20	
Concentrations of dissolved forms of HMMs, µg/l												MPC for fishery
Mn	0.66-0.29	1.1-1.0	1.7	0.8	0.52-1.2	0.63-0.85	0.64-1.3	0.24-0.73	0.43-1.2	1.2-0.74	0.55-0.27	10
Cu	1.4-1.0	1.3-0.93	1.5	0.92	1.1-1.4	0.95-1.0	1.1-1.2	0.98-1.1	1.1-1.2	1.0-0.94	1.1-0.87	1
Zn	3.4-1.2	1.5-0.8	1.7	0.75	0.75-1.5	1.4-0.73	1.7-1.0	1.0-36.1	1.3-2.3	1.0-0.79	1.1-1.0	10
Sr	962-990	961-969	990	971	968-983	969-979	968-985	984-960	963-991	958-970	979-982	400
Mo	15.2-15.8	16.0-15.0	15.4	15.8	15.2-16.2	14.9-15.6	15.1-15.9	15.3-15.4	14.9-31.1	14.9-15.8	15.1-15.4	1
Pb	0.11-0.09	0.13-0.18	0.11	0.06	0.04-0.13	0.08-0.04	0.13-0.04	0.06-0.12	0.08-0.1	0.04-0.05	0.03-0.08	6
As	1.07-1.08	1.1-1.2	1.1	1.1	1.0-1.1	1.0-1.1	1.1-1.2	1.0-1.2	1.1-1.2	1.0-1.1	1.0-1.1	50
Concentrations of HMMs in suspended sediments, µg/g												Clarkes
Mn	31-154	121-162	212	199	41-158	47.6-133	24.4-110	39.7-87.7	-	395-43.4	46.3-74.6	900
Cu	2.4-2.3	3.3-1.1	7.4	2.4	2.5-3.0	1.2-2.3	1.0-1.8	1.3-1.2	-	4.0-1.1	1.1-3.0	28
Zn	9.1-10.5	7.4-4.9	9.2	7.1	4.6-5.5	4.8-5.0	3.2-3.9	4.2-4.4	-	8.0-2.5	7.3-11.7	67
Sr	7.8-13.5	7.8-10.8	17.9	14.6	9.8-13.7	11.6-12.9	8.1-11.4	12.0-15.3	-	15.3-7.7	7.4-9.4	330
Mo	0.17-0.20	0.27-0.62	0.29	0.37	0.28-0.59	0.31-0.56	0.12-0.27	0.17-0.75	-	0.63-0.19	0.17-0.47	1.1
Pb	4.9-11.4	3.9-6.6	10.1	4.6	3.3-4.1	2.8-3.1	2.0-2.2	2.9-3.2	-	1.1-1.2	1.3-2.1	17
Concentrations of HMMs in bottom sediments, µg/g												Clarkes
Ag	0.07	0.01	0.09	0.1	0.06	0.09	1.4	0.28	0.12	0.33	0.1	0.053
Mo	2.3	2.3	10.6	13.4	12.2	9.6	13.9	10.4	10.2	12.7	13.6	1.1
As	11.5	2	5.8	7.4	5.3	5.9	6.5	5.7	4.2	6.9	6.9	4.8
Cu	17.6	3.5	36.5	39.9	28.2	27.1	42.4	34	35.4	46	39.7	28
Sr	222	492	370	462	760	772	467	424	351	705	390	330
Zn	90.8	39	109	118	70.9	84.9	117	121	104	106	112	67
Sb	1.3	0.41	1.1	1.2	0.8	0.92	1.2	1.2	1.0	1.13	1.21	0.4
Pb	22.7	15.7	24.6	25.5	20.2	21.9	29	28.7	21.7	26.1	25.9	17
V	76.2	21.2	83.6	92.4	56.6	68	88.9	95.9	64.4	73.1	86	97
Co	9.5	4.5	11.1	13.1	8.2	10.9	11.8	13.2	8.3	10.3	11.2	17.3
Cr	22.6	4.6	32.2	39	22.2	27.1	44.3	41.1	24.9	30.2	35.3	92

Note: *The concentrations of HMMs were measured only at the surface; "-"no data available.

Table S3. The concentrations (surface-bottom) of nutrients (mg/dm³) in the water of Gusinoe Lake at water sampling stations. The MPCs for fishery

Station No	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.1
The depth, m	6	5	2.5	2.0*	4.5	1.8*	2.5*	11	4.5
Si	1.26-1.34	1.36-1.40	1.38-1.36	1.40	1.26-1.44	1.42	1.42	1.28-1.44	1.38-2.78
PO ₄ ³⁻	0.021-0.012	0.017-0.018	0.014-0.014	0.014	0.014-0.017	0.029	0.017	0.015-0.015	0.019-0.045
P-PO ₄ ³⁻	0.0068-0.004	0.0035-0.0033	0.0047-0.0047	0.0047	0.0045-0.0054	0.0094	0.0054	0.0049-0.0049	0.0063-0.0148
P total	0.021-0.024	0.026-0.025	0.025-0.022	0.022	0.021-0.022	0.029	0.027	0.021-0.025	0.022-0.052
N-NO ₃ ⁻	0.004-0.002	0.004-0.003	0.002-0.003	0.002	0.001-0.004	0.004	0.002	0.002-0.008	-
N-NH ₄ ⁻	0.022-0.063	0.022-0.037	0.048-0.031	0.016	0.010-0.009	0.047	0.042	0.024-0.063	0.015-0.020
N-NO ₂ ⁻	0.003-0.003	0.004-0.003	0.003-0.004	0.004	0.003-0.003	0.004	0.004	0.003-0.004	0.001-0.006
N total	0.5-0.6	1.0-0.6	0.6-0.5	0.6	0.6-0.5	0.6	1.3	1.1-0.7	1.0-0.8
N org	0.47-0.53	0.90-0.56	0.55-0.46	0.58	0.58-0.48	0.55	1.25	1.07-0.63	0.98-0.77
Station No	2.2	2.3	2.4	2.5	2.6	2.7	3.1	3.2	3.3
The depth, m	20	22	15.6	12	19	21	19.6	16	21
Si	1.26-2.23	1.26-2.29	1.28-2.09	1.32-1.54	1.26-2.09	1.26-2.13	1.36-2.21	1.38-1.76	1.48-2.31
PO ₄ ³⁻	0.012-0.062	0.013-0.064	0.015-0.019	0.014-0.018	0.011-0.044	0.013-0.054	0.011-0.049	0.011-0.016	0.012-0.052
P-PO ₄ ³⁻	0.004-0.0202	0.0042-0.0209	0.0049-0.0063	0.0047-0.0059	0.0035-0.0143	0.0042-0.0176	0.0035-0.0159	0.0035-0.0052	0.0037-0.017
P total	0.027-0.041	0.021-0.039	0.021-0.023	-	-	-	0.016-0.039	0.019-0.022	0.017-0.032
N-NO ₃ ⁻	-	0.003-0.008	0.004-0.007	-	-	-	0.043-0.009	0.067-0.026	0.020-0.134
N-NH ₄ ⁻	0.016-0.026	0.017-0.017	0.015-0.023	0.033-0.017	0.011-0.018	0.015-0.022	0.029-0.021	0.019-0.019	0.028-0.034
N-NO ₂ ⁻	0.000-0.001	0.000-0.000	0.001-0.001	0.001-0.001	0.000-0.001	0.001-0.001	0.000-0.000	0.001-0.001	0.000-0.001
N total	1.2-0.5	1.4-0.9	0.6-0.6	-	-	-	0.6-0.8	0.6-0.5	0.5-0.7
N org.	1.18-0.47	1.38-0.87	0.58-0.57	-	-	-	0.53-0.77	0.51-0.45	0.45-0.53

Note: *The concentrations of the nutrients at stations 1.4, 1.6, 1.7 was measured only at the surface; "-"no data available.

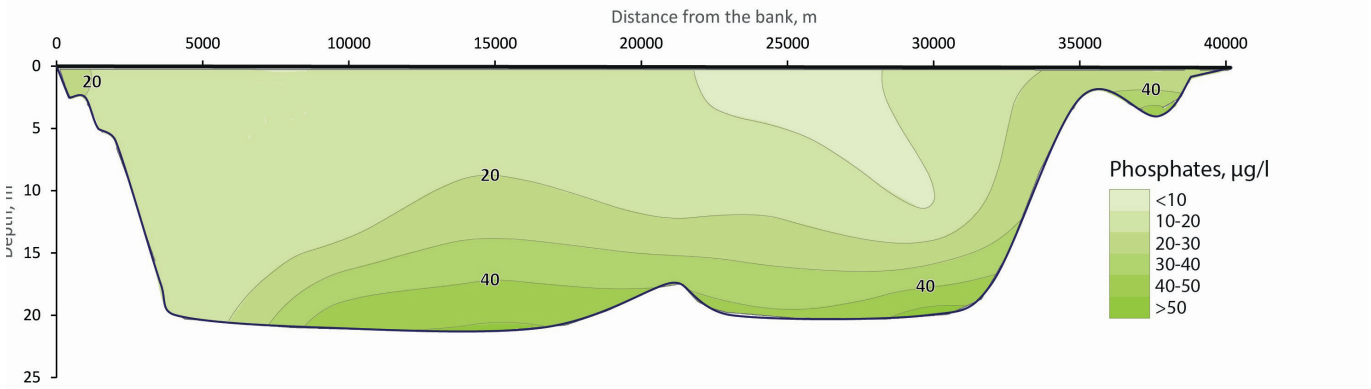


Fig. S3. Distribution of phosphates (PO_4 , $\mu\text{g/l}$) in water of Lake Gusinoye in July 2019 along profile 3 (stations 1.6, 1.5, 1.8, 3.3, 2.7, 2.6, 2.3, 2.1)

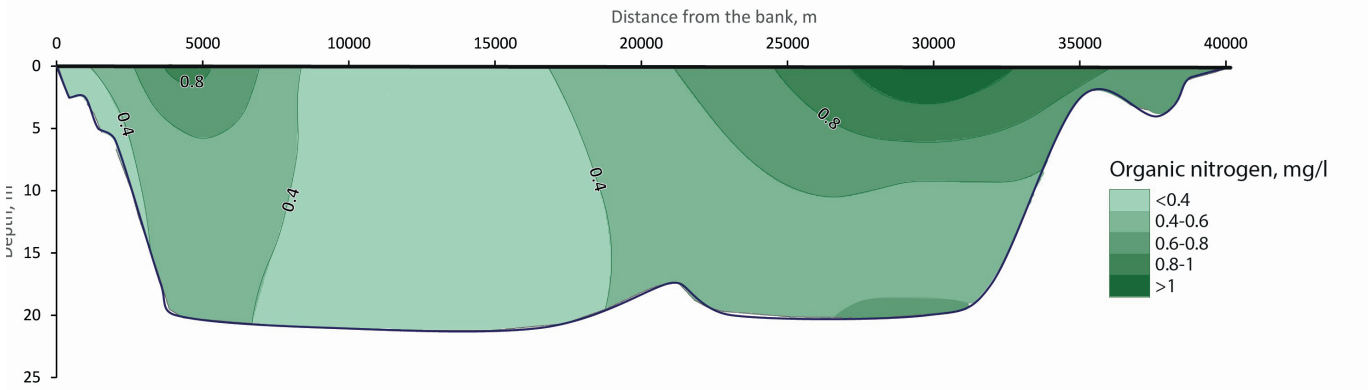


Fig. S4. Distribution of organic nitrogen (mg/l) in water of Lake Gusinoye in July 2019 along profile 3 (stations 1.6, 1.5, 1.8, 3.3, 2.7, 2.6, 2.3, 2.1)