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HYDROCHEMICAL AND HYDROBIOLOGICAL PROCESSES: ENVIRONMENTAL ASPECTS

Influence of Thermal Pollution on the Ecological Conditions in Cooling Reservoirs

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Abstract—The article presents the results of studying the water chemistry and the species structure of phytoplankton and higher aquatic vegetation of the cooling reservoir at the Kalinin Nuclear Power Plant (NPP), the lakes Pesvo and Udomlya being its components. It was established that the inflow of heated waters from the Kalinin Nuclear Power Plant to the lakes Pesvo and Udomlya had resulted in a significant change in the temperature conditions of the water bodies, an increase in water mineralization and the concentrations of hydrocarbonates, sulfates, calcium, and magnesium, as well as pH. The role of cryptophytae algae (Cryptophyta) has increased, and species of higher aquatic vegetation, unusual for this area have appeared.

Keywords: cooling reservoirs, hydrothermal conditions, hydrochemical conditions, phytoplankton, higher aquatic vegetation

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INTRODUCTION

The thermal pollution is any deviation from the natural temperature distribution in the environment, and it is commonly characterized by higher water temperature associated with industrial cooling [37].

In this article we consider the thermal pollution of water bodies associated with the use of natural waters for cooling of condensers at thermal and nuclear power plants.

Heated water entering the environment, can cause problems for aquatic biota in the ecosystem. Water with higher temperature shows lower dissolved oxygen content. In warmer water, oxygen consumption for breathing of organisms is higher and oxygen depletion in water is faster. The populations of some organisms may decline with increasing water temperature, as they have acclimated to definite temperature intervals, while other species may flourish changing the dynamics of the ecosystem [33].

The acceptable temperature ranges of freshwater organism species vary widely, though an optimal range can exist, i.e., the low and high limits within which they can survive. An increase in the temperature accelerates the growth up to some limit, above which the organism will suffer damage. Eventually, changes in the temperature caused by thermal pollution have an effect on the rates of processes and functions of the ecosystem, such as nutrient turnover and decomposition [37].

Water temperature increase causes the eutrophication of water bodies and changes in the species composition of aquatic organisms and higher aquatic plants.

The phytoplankton of cooling reservoirs is a major primary producer and the initial link in the trophic chain. Its nonuniform development causes various "biodisturbances," which hinder the operation of the systems of process water supply to electric power plants [2, 17]. Planktonic algae are also very sensitive to changes in water medium. Their composition is a reliable indicator of the ecological conditions in the water body. Because of this, studying phytoplankton in cooling reservoirs is of importance for both assessing and forecasting the development of the ecological situation and ensuring the safe operation of nuclear power plants [20].

The wide construction of thermal and nuclear power plants in the 1960s–1970s has caused interest among researchers in the problem of the effect warm water has on the environmental state of water bodies. The results of these studies were generalized in many publications and reports [1–3, 12, 13, 17–19, 26].

The objective of this study was to examine the current water chemistry, the state of phytoplankton and higher aquatic plants of the cooling reservoir of the Kalinin Nuclear Power Plant (Udomlya C., Tver oblast, Russia) under the conditions of permanent thermal pollution.

Table 1. The morphometric characteristics of lakes in Kalinin NPP area, according to [9, 24]

Type and name of water body		Water area, km^2	Drainage area, km^2	Depth aver/max, m
KNPP reservoir, including				
1	Udomlya Lake	10.1	400	10/38
2	Pes'vo Lake	6.3	128	2.7/5.2
Background lakes, including				
3	Kezadra Lake	8.7	120	5.6/20.7
4	Navolok Lake	12.5	105	2.3/3.4

METHODS

In 2017–2018, under regional project RFBR–Tver oblast no. 17-45-690600, field studies were carried out to analyze the effect of the Kalinin NPP on the environmental state of its cooling reservoir. The authors studied the temperature regime, macro- and micro-component water composition, the species composition of phytoplankton and higher aquatic plants, and the overgrowth of cooling reservoirs.

The Kalinin NPP is situated in the northern Tver oblast, about 120 km from Tver City. The NPP area lies on the southern shore of Lake Udomlya near the town with the same name, 2.7 km east of Lake Pes'vo. The lakes Udomlya and Pes'vo are connected by a short pass (100 m in length and 60 m in width); after the construction of the Kalinin NPP in 1984, these lakes are used as a single cooling reservoir. Since the construction of a dam on the S"ezha river in 1984, the water level in the lake is subject to regulation and the water body is referred to as Kalinin NPP reservoir. The drainage area of the reservoir is 400 km^2, its water area at normal water level of 156.25 m is 21.2 km^2, its full volume is 156.4 km^3, and its active storage capacity is 44.6 km^3.

Lake Pes'vo receives wastewaters from Udomlya town, its population being 29 thousand. The lakes are also used for commercial fish-breeding and recreation. The station contains four power units with VVER-1000 reactors with electric power of 1000 MW, which were commissioned in 1984, 1986, 2004, and 2011. To assess the changes in the environmental conditions of Kalinin NPP cooling reservoirs under the effect of thermal discharges, water samples were also taken in the background lakes of Navolok and Kezadra (Table 1), which lie beyond the zone of influence of the thermal discharges of the Kalinin NPP.

The water chemistry of the cooling reservoir was evaluated with the use, in particular, of the data of hydrochemical surveys of 2014, when water samples were taken on nearly monthly basis.

In 2017–2018, water samples were taken once per season from the surface horizon in accordance with GOST 3161-2012 "Water. General Requirements to Sampling" [10]. Water was taken into prepared dark-glass bottles 1 L in volume for analysis for oil products, into plastic canisters 3 L in volume for general chemical analysis, and into calibrated flasks with ground plugs for the analysis for oxygen. The sampling points for chemical and phytoplankton analyses are shown in Fig. 1.

Quantitative chemical analysis of water was carried out in an accredited laboratory of the Ivankovo RS and followed generally accepted procedures [29]. The methods of studies included titrimetric, iodimetric, gravimetric, potentiometric (pH-meter-ionometer Ekotest 2000I), photometric (spectrophotometer V-1100), IR-spectrometry (concentration meter KN-2m IShVZH.010). The chemical analysis of water included the determination of pH, electric conductance, turbidity, suspended matter, hydrocarbonates, calcium, magnesium, sulfates, chlorides, sodium, potassium, total iron, silicon, ammonium ions, nitrites, nitrates, phosphates, BOD_5, COD_5, PO, color index, dissolved oxygen, oil products, surfactants, and heavy metals (zinc, lead, copper, cobalt, and chromium).

Parallel to that, samples for phytoplankton were taken in accordance with the procedure accepted in algology [10]. Water samples were filtered through Vladipor membrane filters with a pore size of 1 μm. The species and intraspecific taxa were determined under Carl Zeiss Primo Star microscope at magnification 400. The number of cells was determined in Uchinskaya-2 chamber with a volume of 0.01 cm^3, the biomass was evaluated by calculation-volumetric method [18].

To assess water quality by phytoplankton species composition, Pantle–Buck saprobity index modified by Scadecek [34] was used.

Shannon and Pielou indices [32, 35] were used to assess the biodiversity.

The overgrowth by higher aquatic plants (except for submerged vegetation) was evaluated by deciphering high-resolution NASA satellite images (Landsat 8 satellite, cartographic material of Digital Globe company, 2017) at a scale of 1 : 10000.

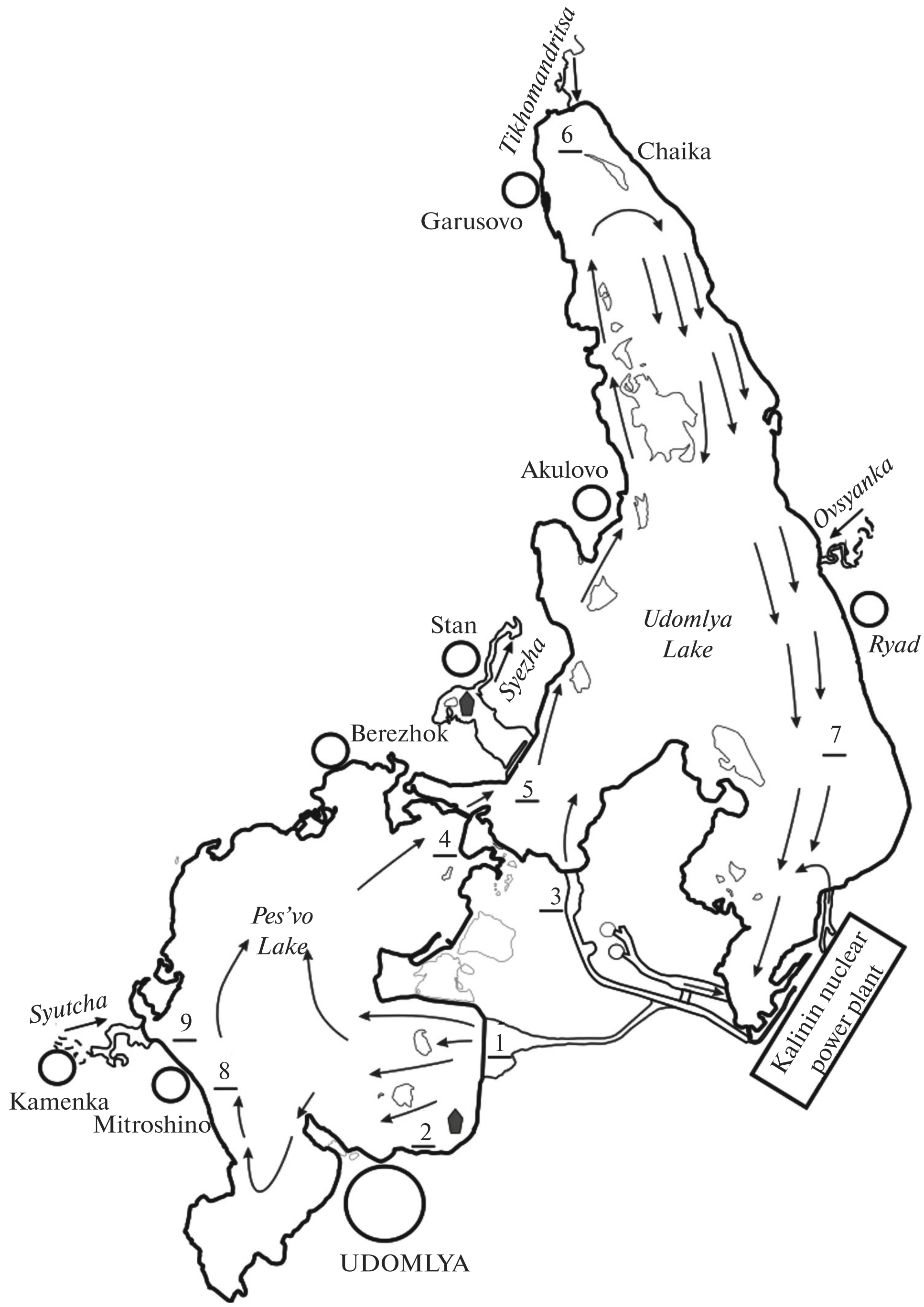

Fig. 1. Schematic map of the cooling reservoirs Udomlya and Pes'vo. Sampling points: (1) Lake Pes'vo, diversion channel from the Kalinin NPP; (2) Lake Pes'vo, discharge from Udomlya T. treatment facilities; (3) Udomlya Lake, diversion channel from the Kalinin NPP; (4) pass between Pes'vo and Udomlya lakes, Troitsa; (5) sources of the S"ezha river; (6) Udomlya Lake, Chaika (Tikhomandritsa river mouth); (7) Udomlya Lake, Dvinovo; (8) Pes'vo Lake, Mitroshino V.; (9) Pes'vo Lake, Kamenka V. (S"yucha R. mouth).

RESULTS

Lakes Pesvo and Udomlya show higher water temperature near the discharge site of heated water from the NPP and a flow-through regime. A specific circulation zone forms in the lakes (Fig. 1). Warm water is discharged into both lakes through discharge canals, and water intake is in Lake Udomlya. In drier years, groundwater is also used for cooling KNPP aggregates, contributing to a gradual increase in lake water mineralization.

Water temperature in the lakes varies widely both from season to season and over reservoir areas. In the

Table 2. Water temperature (°C) in lakes Pes'vo, Udomlya, and Navolok, summer of 2014, 2017, and 2018 (the hydrochemical data on cooling lakes are generalized in Table 3)

Year	S"ezha river source	Lake Udomlya, Chaika	Pass from Pes'vo to Udomlya lake	Lake Udomlya, o. Dvinovo	Lake Pes'vo, Mitrtoshino v.	Lake Pes'vo, KNPP discharge channel	Lake Pes'vo, Discharge from Udomlya TS	Lake Udomlya, KNPP discharge channel
2014	28.6	29.3	28.6	28.1	29.2	34.9	28.0	–
2017	–	18.9	25.0	–	23.8	32.6	28.0	33.3
2018	20.5	22.9	20.8	20.8	20.8	–	23.5	–

discharge channels, it is generally 9–18°C higher than in the areas not involved in the circulation current (Tables 2, 3).

In 2018, 115 alga species, varieties, and forms from nine divisions were identified in planktonic algaflora (Fig. 2).

Seven families were leading in terms of taxonomic diversity: Scenedesmaceae, Oocystaceae, Selenastraceae, Hydrodictyaceae, Fragilariaceae, Naviculaceae and Nitzschiaceae, embracing 29 genera and 92 taxa of algae—50% of the total composition of planktonic flora (Table 4).

The leading genera were Desmodesmus (R. Chodat) S.S. An, T. Friedl & E. Hegewald, Navicula Bory de Saint-Vincent, Nitzschia Hassal, which totaled 37 alga taxa, i.e., 20% of the overall diversity of planktonic algae. In addition to the genera mentioned above, the genera Fragilaria Lyngbye, Chlamydomonas Ehrenberg, Monoraphidium Komarkova-Legnerova, Trachelomonas Ehrenberg, Cyclotella (Kützing) Brébisson, and Gomphonema Ehrenberg, also played an important role in the algaflora, where they accounted for 37 alga taxa, i.e., also 20% of the total flora composition (Fig. 3).

Common for all sampling points were 10 alga species: Aulacoseira ambigua (Grunow) Simonsen, Aulacoseira granulata (Ehenberg) Simonsen, Cyclotella meneghiniana Kützing, Stephanodiscus neoastrea (Håkansson et Hickel) emend. Casper, Scheffler et Augsten, Amphora ovalis (Kützing) Kützing, Navicula rhynchocephala Kützing, Desmodesmus communis (E.Hegewald) E.Hegewald, Franceia ovalis (Francé) Lemmermann, Didumocystis planctonica Korschikov, and Chroomonas acuta Utermöhl.

The total abundance of phytoplankton varied from 100 thous. cell/dm^3 to 6 million cell/dm^3, which differ only slightly from the data of 2017. The distribution of the abundance over the cooling lakes was not uniform.

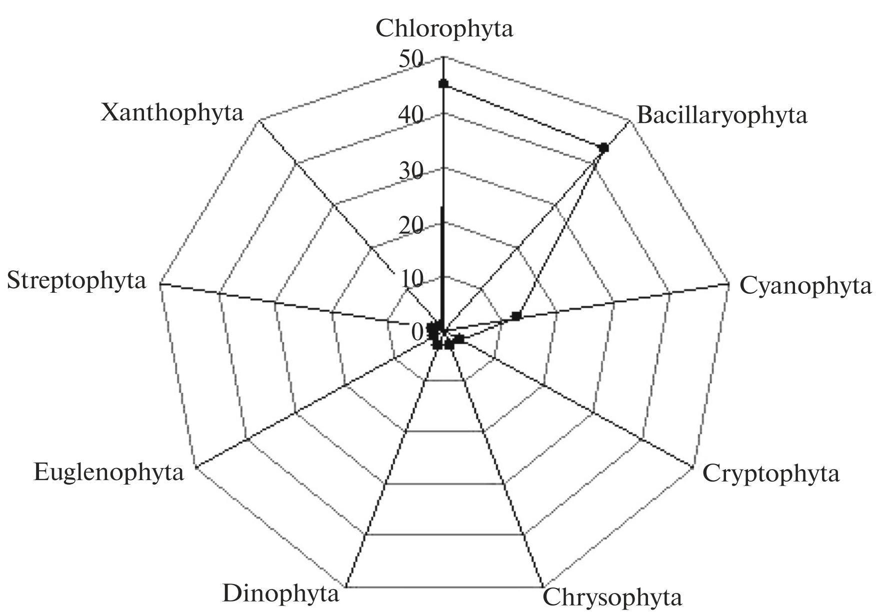

Fig. 2. Taxonomic diversity of phytoplankton in Kalinin NPP cooling lakes in 2018.

Table 3. Averaged hydrochemical characteristics of cooling lakes over 2014, 2017, and 2018, mg/dm^3 (except for pH, pH units; total phosphorus, mg P/dm^3; color index, deg. Pt-Co scale; PO, BOD_5, COD, mg O/dm^3, O_2, mg O_2/dm^3)

Characteristic	S’’ezha river source	Lake Udomlya, Chaika	Pass from Pes’vo to Udomlya lake	Lake Udomlya, o. Dvinovo	Lake Pes’vo, Mitrtoshino v.	Lake Pes’vo, KNPP discharge channel	Lake Pes’vo, Discharge from Udomlya TS	Lake Udomlya, KNPP discharge channel
pH	8.24	8.28	8.24	8.25	8.29	8.31	8.15	8.26
Hydrocarbonates	180.2	163.3	179.7	186.1	179.1	180.6	198.0	173.9
Calcium	46.5	44.1	46.7	48.9	47.1	48.7	49.3	46.6
Magnesium	10.8	8.6	10.0	9.1	9.5	9.2	12.7	8.5
Sulfates	13.9	12.3	15.4	15.3	14.0	14.2	15.6	16.5
Chlorides	8.7	7.8	8.3	7.6	8.6	8.8	13.0	7.8
Sodium and potassium	7.2	6.6	8.6	9.6	8.7	8.0	9.7	9.7
Silicon	2.0	1.9	2.0	2.4	1.8	2.1	2.6	2.6
Total iron	0.09	0.14	0.08	0.36	0.08	0.09	0.08	0.09
Manganese	0.04	0.04	0.04	0.20	0.036	0.039	0.039	0.040
Total phosphorus	0.078	0.080	0.080	0.083	0.082	0.089	0.341	0.087
Phosphates	0.107	0.099	0.120	0.102	0.108	0.117	0.773	0.129
Ammonium ions	0.44	0.45	0.66	0.54	0.40	0.46	2.22	0.66
Nitrite ions	0.014	0.013	0.018	0.014	0.020	0.012	0.087	0.017
Nitrate ions	1.24	1.07	1.44	1.37	1.28	1.36	4.73	1.88
Color index	44	52	48	47	43	43	44	47
Permanganate oxidability	14.8	16.7	14.9	15.1	15.0	14.8	14.1	15.7
O_2 dissolved	8.6	9.6	9.0	8.6	10.0	8.3	8.2	8.9
BOD_5	1.4	1.7	1.4	1.4	1.6	1.4	2.9	0.8
COD	35.5	38.3	38.0	35.9	39.5	36.8	34.8	33.7
Turbidity	2.0	3.0	1.7	3.3	2.5	1.8	3.3	1.9
Mineralization	271	246	273	281	270	273	308	268
Zinc	0.0177	0.0276	0.0351	0.0185	0.028	0.022	0.059	0.138
Lead	0.0074	0.0057	0.0075	0.0045	0.006	0.006	0.0065	0.0088
Copper	0.0308	0.0300	0.0307	0.0281	0.033	0.034	0.029	0.0338
Cobalt	0.0090	0.0081	0.0093	0.0088	0.009	0.009	0.0096	0.0095
Chromium	0.0196	0.0220	0.0237	0.0212	0.022	0.022	0.0224	0.0184
Oil products	0.031	0.030	0.028	0.032	2.25	0.04	0.03	0.024
Surfactants	0.016	–	0.025	0.016	–	–	0.019	–

Table 4. Taxonomic structure of the leading phytoplankton families in 2018

Divisions	Family	Number of genera	Number of taxa	Percent of the total number of taxa
Chlorophyta	Scenedesmaceae	7	25	14
	Oocystaceae	5	11	6
	Selenastraceae	5	10	5
	Hydrodictyaceae	2	10	5
Bacillaryophyta	Naviculaceae	3	14	8
	Fragilariaceae	6	12	7
	Nitzschiaceae	1	10	5
Total		29	92	50

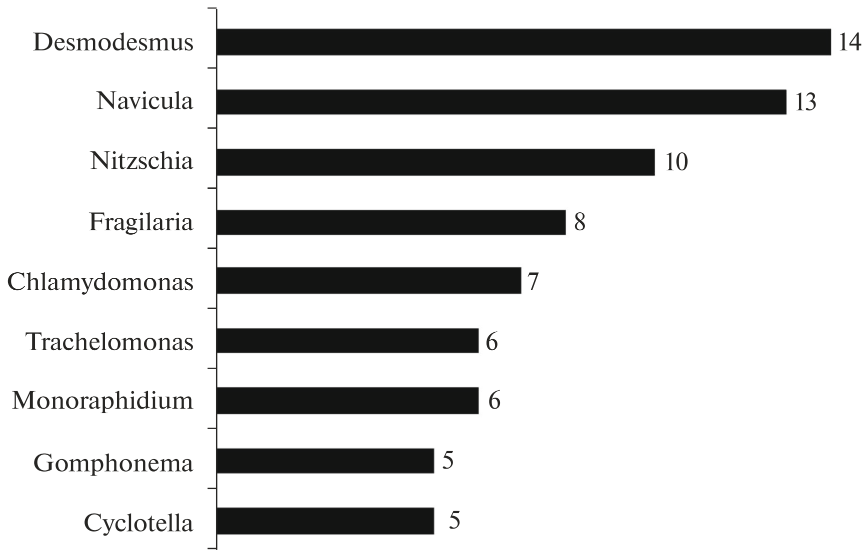

Fig. 3. Number of taxa in the major genera of planktonic algaflora.

The least values of this characteristic were recorded in Udomlya Lake. The major contributors to alga abundance in 2018 were diatom and green algae, with the participation of cryptophytes in the spring, blue-green and green in the summer, and green with the participation of cryptophytes and, partly, dinophytes in the autumn. Dominating in terms of abundance in the spring season were diatoms Aulacoseira ambigua (Grunow) Simonsen and Aulacoseira granulata (Ehrenberg) Simonsen, green algae Dictyosphaerium pulchellum H.C. Wood and Desmodesmus commuinis (E. Hegewald) E. Hegewald, and cryptomonade Chroomonas acuta Dujardin. Dominating in the summer were blue-green algae Merismopedia tenuissima Lemmermann, Microcystis aeruginosa (Kützing) Kützing, Microcystis incerta (Lemmermann) Lemmermann, Oscillatoria tenuis C. Agardh ex Gomont, Oscillatoria planctonica Woloszynska, Planktolyngbya limnetica (Lemmermann) Komárková-Legnerová, Chroococcus turgidus (Kützing) Nägeli, green algae Desmodesmus communis, Desmodesmus armatus and Pediastrum simplex Meyen. Dominating in the autumn were cryptomonade Chroomonas acuta, blue-green Merismopedia tenuissima, and diatoms Stephanodiscus neoastrea Håkansson & Hickel and Aulacoseira ambigua.

Semisubmerged vegetation occurs in local areas and tolerates water level drop in the lake, living on the land. These are often common reed and sedge. In shallows, at river mouths and at the sites of wastewater discharges, our data and data in [23] show the presence of diverse species of higher aquatic plants, including common reed Phragmites communis Trin., cattail Typha, yellow water lily Nuphar lutea (L.) Smith., arrowhead sagittifolious Sagittaria sagittifolia L., frogbit Hydrocharis morsus-ranae, duckweed little Lemna mínor, filamentous alga and other species.

Lakes Udomlya and Pes'vo show adventive species of higher aquatic plants: myrtleflag Acorus calamus L., bulrush Juncus tenuis Willd., reed Phragmites australis (Cav.) Trin. ex Steud, and Canadian pondweed Elodea Canadensis.

RESULTS AND DISCUSSION

An increase in water temperature caused by heated-water discharge deteriorates its quality, primarily, because of a decrease in oxygen solubility, which decreases by one third at temperature of 30°C.

Water of the Kalinin NPP Reservoir was found to belong to the hydrocarbonate class, calcium group; it is fresh by its mineralization, and soft by its hardness; in terms of pH, it is weakly alkaline and alkaline. The concentrations of sulfates, on the average, vary within the interval 12.3–16.5 mg/dm^3, and those of chloride, within 7.8–13.0 mg/dm^3. In the background Lake Navolok, the concentration of sulfate averages 4.2 mg/dm^3, and that of chlorides, 1.6 mg/dm^3. The highest concentrations of total iron and manganese were recorded at the mouth of the Ovsyanka River. The concentrations of ammonium and nitrate ions were highest near the discharge sites of wastewater treatment facilities of Udomlya T. Water color index never exceeds 90 degrees Pt-Co scale. The concentration of organic matter of natural origin is relatively high; the permanganate oxidability, on the average, varies within the interval 14.1–16.7 mg O/dm^3.

As noted in [7], the concentrations of hydrocarbonates, sulfates, calcium, and magnesium, as well as pH have considerably increased since the NPP com-

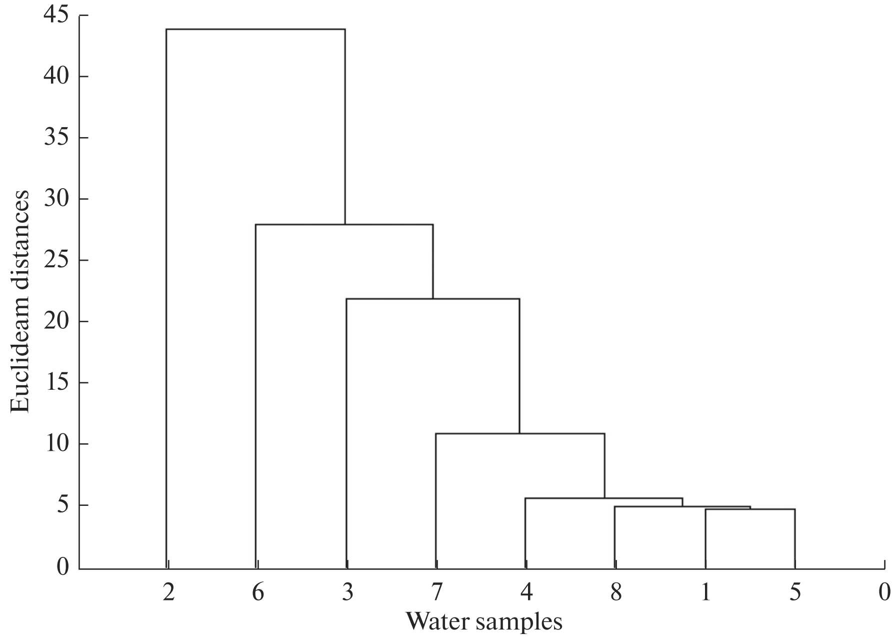

Fig. 4. Dendrogram of the difference between water chemistry at study stations (in accordance with Fig. 1).

missioning to the 1990s. Our study shows that these characteristics continue increasing.

At the moment of commissioning of the first unit of the Kalinin NPP, the phytoplankton of the lakes included 102 alga taxa lower than genus. After the start of NPP operation, the diversity increased to 152 taxa in 1985, most likely, because of water heating and the elongation of alga vegetation season. However, the further rise in water temperature and the commissioning of the second unit in 1986 caused a decrease in the number of species, which gradually diminished to 75 taxa in 1991, and 51 taxa in 2003 and 2005. Since 2007, the species diversity steadily increased from 136 to 174 taxa in 2010. Since 2014, our studies showed a decrease in phytoplankton species diversity from 167 to 115 taxa in 2018. This may be due to the commissioning of the fourth unit in the late 2011 and an increase in the temperature load onto the cooling reservoir.

The ratio of the total number of species to the total number of genera (the genus factor) was 2.0. Similar values of this characteristic are typical of the rivers under strong anthropogenic press in urban environment or under hard ecological conditions of the Extreme North [4–6, 8, 22, 25]. In the Volga reservoirs, this characteristic is 3.0–4.6 [15]; and in the Tvertsa, it is 2.4 [14]. A gradual decrease in the genus factor from 2.3 to 1.2 was found to accompany a decrease in water pH from 2.7 to 1.9 at an increase in lake mineralization [16, 21, 27]. The genus factor shows a reliable positive correlation with the species diversity, which decreases under extreme conditions [28].

The similarity of sampling stations, evaluated by Sörensen coefficient [36], was 24–61%, at an average over the water area of 41%. The largest similarity in the species diversity was observed between the local floras of Lake Pes'vo.

The dendrogram obtained from the clusterization of the stations by taxonomic characteristics of phytoplankton proved to be identical to the dendrogram by the difference between water chemistry at sampling stations (Fig. 4).

The saprobity index in the examined water area varied from 1.82 to 2.30, which corresponded to a betamesosaprobic zone and demonstrated a moderate pollution of water in the lakes. These values are in agreement with the data obtained earlier [11].

Shannon's species diversity index was 3.20–4.71, with minimal values recorded in Lake Pes'vo and maximal, in Lake Udomlya. Pielou's community leveling index varied from 0.61 in Lake Pes'vo to 0.80 in Lake Udomlya.

The total phytoplankton biomass in 2018 varied from 0.02 to 0.86 mg/dm^3, which is 25% lower than the values obtained in 2017. As was the case with the abundance, the least values of plankton alga mass were recorded in Lake Udomlya. The major portion of the biomass throughout the year was due to the magnocellular forms of diatom algae, mostly centric, with a minor contribution of cryptophyte and green algae.

Dominating in terms of biomass were diatoms Aulacoseira ambigua, Aulacoseira granulata, Cyclotella meneghiniana Kützing, Stephanodiscus neoastrea, Navicula viridula (Kützing) Ehrenberg, Melosira varians C. Agardh. In the spring and summer, they were supplemented by green algae Desmodesmus communis and Pediastrum duplex; and in the autumn, by cryptophyte algae Chroomonas acuta and Cryptomonas erosa. These data are comparable with the results obtained in other cooling reservoirs in Russia, but they somewhat differ from the data on European cooling reservoirs. For example, Lake Stechlin shows the predominance of cyanobacteria with a mass development of filamentous forms [31].

The role of cryptophyte algae was found to increase, maybe, because of the higher anthropogenic load onto the ecosystem of the cooling lakes. Representatives of this alga division are very tolerant to environmental pollution; they can persist in a wide range of temperatures, and, under unfavorable conditions, can change to heterotrophic nutrition regime.

By phytoplankton biomass, lakes Pes'vo and Udomlya can be classified as oligotrophic–mesotrophic.

The interpretation of satellite images showed that the higher aquatic vegetation now occupies as little as 4.5% of the area of lakes Udomlya and Pes'vo, while in the mid-1990s, the overgrown areas accounted for about 10% of the water area of the lakes [7]. The decrease in the overgrowth degree of the lakes is due to the hydromelioration works in the water areas and on lake shores, including clearing and shore protection.

The removal of the near-shore vegetation from the water areas of water bodies contributes to thermal pollution, as it considerably increases the penetration of solar radiation and rises water temperature [30].

The overgrowing by higher aquatic plants has both positive and negative effect for the water body. The positive effect is the launching of self-purification mechanisms in the water body, accompanied by the removal of a part of biogenic and organic substances from water. The negative effect is the enhancement of the process of eutrophication, the secondary pollution of the water body because of plant biomass decay, and the formation of oxygen-deficient areas, which is redounded by higher temperature.

CONCLUSIONS

The discharge of heated water from the Kalinin Nuclear Power Plant into lakes Pes'vo and Udomlya has caused a considerable change in the temperature regime of the water bodies.

After the commissioning of the first unit of the NPP, the species diversity of phytoplankton was found to increase, thought this characteristic has been appreciably decreasing since 2014, most likely, because of the increasing thermal load after the commissioning of the 4th unit of the power station.

The increase in the thermal pollution has caused an increase in the abundance of cruptophyte algae.

Adventive species of higher aquatic vegetation were found to appear in lakes Udomlya and Pes'vo.

The area occupied by higher aquatic plants was found to have decreased compared with that before the construction of the Kalinin NPP; this results in a decrease in the self-purification capacity of the water bodies.

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