
WATER QUALITY AND PROTECTION: ENVIRONMENTAL ASPECTS

Studying Thermal Eutrophication in Cooling Reservoirs of Nuclear Power Plants

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Abstract—The processes of thermal eutrophication of the cooling reservoirs of the Smolensk and Kursk nuclear power plants (NPP) were studied. Data characterizing changes in the concentrations of inorganic forms of nitrogen and phosphates in water during its heating in the NPP cooling system were obtained. Different aspects of the effect of heated water on the production–destruction processes are discussed. The conditions under which the intensity of thermal eutrophication can substantially increase were determined.

INTRODUCTION

By thermal eutrophication (TE) we mean an increase in a reservoir trophic level due to acceleration of the circulation of biogenic elements (BE) with increasing temperature of the aquatic environment [2]. Similar processes can be observed in reservoirs used for cooling thermal and nuclear power plants, the so-called cooling reservoirs. The effect of heated water on the eutrophication of reservoirs was repeatedly discussed in the scientific literature [5, 7, 8]. The total levels of eutrophication of cooling reservoirs were most often considered in these studies. Such levels depend on the inflow of additional amount of BE compounds into the reservoir, i.e., on the processes of chemical eutrophication, and on changes in the reservoir temperature regime. Such approach did not allow one to determine the causes and sources of eutrophication, which substantially hindered the timely development of nature conservation measures during designing cooling reservoirs.

The aim of this work is to study the effect of thermal discharge from NPP on the regime of the main BE and production processes in cooling reservoirs, i.e., to study TE processes.

MATERIALS AND METHODS

The main data were during the study of the cooling reservoirs of the Smolensk (SNPP) and Kursk (KNPP) nuclear power plants in 1999 and 2000. The TE processes were studied in two directions. First, we analyzed variations in the concentrations of the main BE (P, N) in water under the effect of thermal discharge from NPP. The hydrochemical analyses were performed according to the standard techniques [6]. Second, we determined the effect of thermal discharge on production–destruction processes in cooling reservoirs.

The primary production of phytoplankton and the destruction intensity were determined by the oxygen method [12]. The biomass of algae was calculated proceeding from the cell volume of individual species.

RESULTS AND DISCUSSION

Increased ambient temperature intensifies mineralization processes. Consequently, we can expect that thermal discharge will result in an increased concentration of mineral forms of N and P. Such assumption is corroborated by the results obtained during a comparative analysis of the concentrations of phosphates (P-PO_4^{3-}) and nitrates (N-NO_3^-) in water samples taken simultaneously from the intake and discharge channels of the nuclear power plants (Table 1). However, in many cases no reliable increase was observed in the amount of these BE in the regions of discharges from NPP. The concentration of ammonium nitrogen (N-NH_4^+) in the NPP discharge water even slightly decreased (probably due to the intensification of evaporation and oxidation of ammonia compounds at increased temperature). Again, no stable regularities were observed in variations in the nitrite (N-NO_2^-) content during the water passage through the NPP cooling system. At the same time, the conclusion that water heating does not affect the concentrations of N and P-PO_4^{3-} mineral forms would be incorrect.

When studying cooling reservoirs we should take into account certain specific features of their hydrological structure [11]. Considerable part of water mass in these reservoirs circulates, periodically coming through the NPP cooling system (figure). Therefore, the water hydrochemical composition at an outlet can change insignificantly at some instant as compared with such

Table 1. BE concentration, mg/l, in the NPP intake (top number) and discharge (bottom number) channels

Month, year	P-PO ₄ ⁻³	N-NO ₃ ⁻	Month, year	P-PO ₄ ⁻³	N-NO ₃ ⁻
	SNPP			KNPP	
July 1999	0.017 ± 0.006	0.253 ± 0.030	October 1999	0.264 ± 0.023	0.350 ± 0.050
	0.026 ± 0.008	0.180 ± 0.033		0.248 ± 0.021	0.360 ± 0.045
August 1999	0.058 ± 0.004	0.250 ± 0.028	February 2000	0.098 ± 0.016	2.040 ± 0.170
	0.058 ± 0.007	0.330 ± 0.031		0.130 ± 0.020	2.100 ± 0.200
November 1999	0.100 ± 0.011	1.37 ± 0.14	April 2000	0.043 ± 0.013	0.390 ± 0.030
	0.090 ± 0.010	1.80 ± 0.14		0.053 ± 0.015	0.370 ± 0.030
February 2000	0.160 ± 0.020	1.90 ± 0.20	July 1999	0.056 ± 0.010	0.259 ± 0.025
	0.280 ± 0.030	2.40 ± 0.22		0.082 ± 0.016	0.297 ± 0.032
April 2000	0.016 ± 0.005	0.520 ± 0.040	October 2000	0.119 ± 0.019	0.405 ± 0.055
	0.018 ± 0.004	0.740 ± 0.060		0.139 ± 0.025	0.428 ± 0.029
August 2000	0.025 ± 0.006	0.312 ± 0.040			
	0.028 ± 0.005	0.395 ± 0.032			

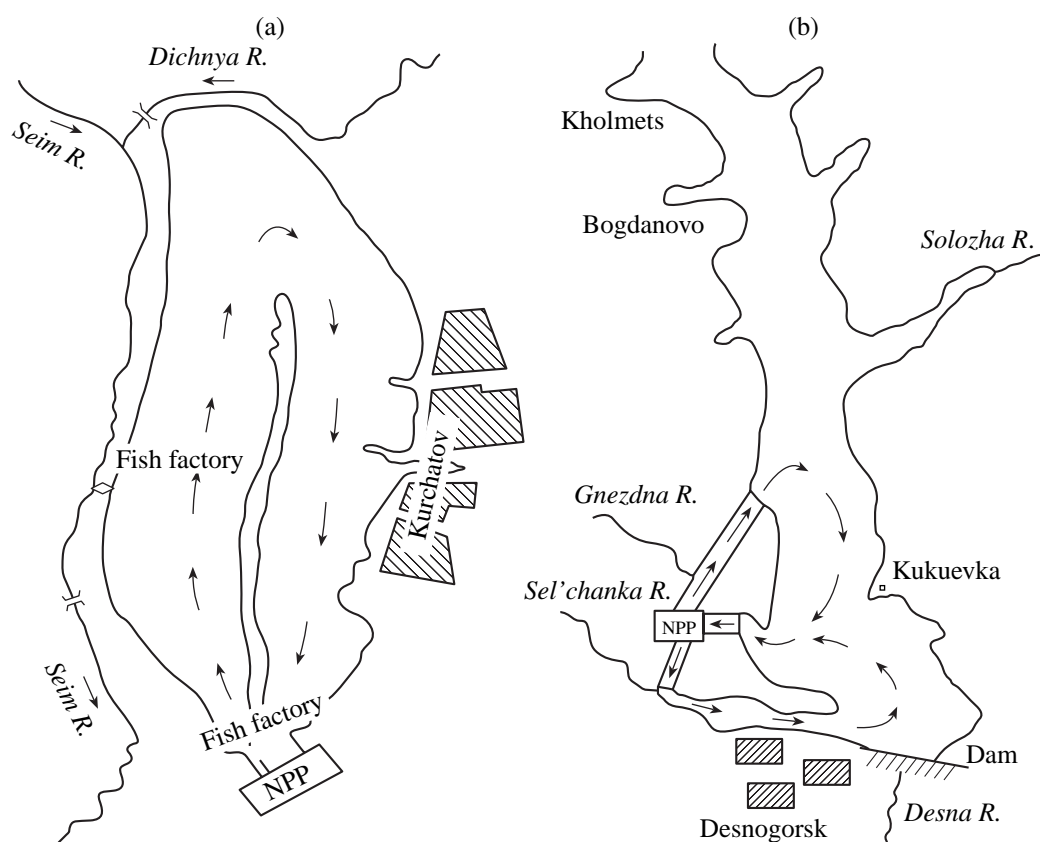
composition at an intake, although water heating in the cooling system generally pronouncedly affects the chemistry of the aquatic environment. Permanent circulation of water will smooth any heterogeneities that may form in the hydrochemical parameters [10]. Consequently, an additional amount of BE inorganic forms originated as a result of intensified mineralization cannot be constantly observed as an increase in their concentration only at an NPP outlet and should be distributed more or less regularly in the entire water mass of the circulating flow.

An increase in the BE content at an NPP outlet can not always be regarded only as the result of thermal eutrophication. Open parts of intake and discharge channels of nuclear power plants are polluted from an NPP site. Moreover, wastewater from certain domestic and industrial units of NPP and other facilities is discharged into the water-supply system. Therefore, to solve the problem of the possible effect of water heating on the biogenic element concentrations we performed a series of laboratory experiments during which we simulated the conditions that form during water passage through an NPP cooling system. A similar technique was previously used to study the effect of water heating on bacterioplankton in cooling reservoirs [9]. Each water sample was divided into two parts. One of them was pored into 250-ml flasks (up to 100 ml water in each flask). The flasks were placed into a water bath and heated for 1 h to 40°C, which approximately corresponds to the duration of water staying and the degree of its heating in the NPP cooling system. The concentrations of P-PO₄⁻³ and N-NO₃⁻ in the samples were determined when the water cooled to the room temperature. Another (check) part of the sample was pored into similar flasks but was not heated. All experiments were repeated three times.

Six variants of the experiment were performed for the SNPP cooling reservoir (Table 2). A considerable part of the water in the cooling reservoirs moves through a loop, and the thermal effect on the aquatic environment is often periodical rather than occasional. Therefore, we took water samples from the intake (variant 1) and discharge channel outlet (variant 2) in order to study the effect of repeated heating. In a number of cases, water that was not previously in contact with aggregates of the cooling system can come into an intake as a result of onsets or flooding phenomena. To estimate the primary effect of heating, we conducted a test that consisted in heating the water taken from the upper part of the Desnogorsk storage reservoir. The NPP discharge water virtually cannot come into this region. At the same time, in some periods, water from the upper part of the storage reservoir can come into the NPP intake.

In variants 4 and 5, 20 g bottom sediments (BS), taken at the points where the water samples were taken, were added to each water sample taken from the NPP intake and discharge channels, respectively. In both cases we took similar soils: slightly muddy sand. The samples were taken from the surface layer (0–1 cm). The results of these tests make it possible, first, to form a certain opinion about the possible thermal eutrophication of water due to the destruction of bottom sediments and, second, to study the effect of heating on the water containing particles of roiled soil. Such situation forms sometimes as a result of wave motion and during flooding phenomena and dredging.

Water heating can also intensify the decomposition of dying parts of near-shore vegetation. Therefore, in variant 6, we put finely cut dead parts of cat-tail (*Typha latifolia* L.)—one of the widespread forms of near-



Schemes of the (a) KNPP and (b) SNPP cooling reservoirs. Arrows indicate the direction of the circulation flow.

shore vegetation around the Desnogorsk storage reservoir—into the water taken from the NPP intake.

The obtained results indicate that, in August, heating of the water taken from the NPP intake and dis-

charge channel did not result in a reliable increase in $P-PO_4^{-3}$ and $N-NO_3^{-}$ concentrations (Table 2). According to the results of the experiment performed in November, heating of the water samples from the

Table 2. BE concentrations, mg/l, in the experiments conducted at the SNPP cooling reservoir (the data for August and November 1999 are the top and bottom numbers, respectively)

Test variant	$P-PO_4^{-3}$		$N-NO_3^{-}$	
	heating	control	heating	control
1	0.058 ± 0.011	0.054 ± 0.008	0.257 ± 0.31	0.255 ± 0.030
	0.143 ± 0.028	0.085 ± 0.009	2.08 ± 0.21	1.41 ± 0.15
2	0.022 ± 0.007	0.023 ± 0.006	0.279 ± 0.25	0.260 ± 0.34
	0.118 ± 0.020	0.098 ± 0.012	1.76 ± 0.07	1.83 ± 0.15
3	0.012 ± 0.004	0.032 ± 0.005	0.216 ± 0.12	0.338 ± 0.43
	0.161 ± 0.012	0.084 ± 0.011	1.78 ± 0.11	1.21 ± 0.08
4	1.12 ± 0.21	0.139 ± 0.022	0.825 ± 0.110	0.316 ± 0.045
	1.88 ± 0.32	0.260 ± 0.035	2.76 ± 0.34	1.85 ± 0.22
5	0.043 ± 0.008	0.037 ± 0.007	0.335 ± 0.051	0.343 ± 0.030
	0.302 ± 0.14	0.279 ± 0.025	2.32 ± 0.41	2.15 ± 0.31
6	0.125 ± 0.023	0.054 ± 0.011	0.408 ± 0.068	0.271 ± 0.032
	0.612 ± 0.080	0.105 ± 0.012	1.61 ± 0.09	1.22 ± 0.07

Table 3. BE concentrations, mg/l, in the experiments conducted at the KNPP cooling reservoir (the data obtained during heating and the control data are the top and bottom numbers, respectively)

Test variant	P-PO ₄ ⁻³	N-NO ₃ ⁻	P-PO ₄ ⁻³	N-NO ₃ ⁻	P-PO ₄ ⁻³	N-NO ₃ ⁻
	February		July		October	
1	0.114 ± 0.029	2.11 ± 0.12	0.088 ± 0.016	0.312 ± 0.025	0.140 ± 0.005	0.440 ± 0.025
	0.117 ± 0.033	2.04 ± 0.07	0.092 ± 0.010	0.265 ± 0.032	0.124 ± 0.005	0.380 ± 0.016
2	0.124 ± 0.036	2.21 ± 0.24	0.078 ± 0.015	0.305 ± 0.020	0.130 ± 0.004	0.430 ± 0.020
	0.148 ± 0.026	1.91 ± 0.21	0.081 ± 0.013	0.308 ± 0.020	0.130 ± 0.005	0.380 ± 0.016
4	2.71 ± 0.33	2.67 ± 0.27	0.264 ± 0.013	0.510 ± 0.063	0.365 ± 0.029	0.890 ± 0.110
	0.691 ± 0.045	2.20 ± 0.16	0.101 ± 0.016	0.420 ± 0.030	0.192 ± 0.007	0.520 ± 0.038
5	0.179 ± 0.029	2.31 ± 0.19	0.114 ± 0.020	0.310 ± 0.022	0.153 ± 0.004	0.460 ± 0.035
	0.153 ± 0.032	2.21 ± 0.16	0.121 ± 0.016	0.312 ± 0.020	0.160 ± 0.005	0.448 ± 0.036
6	0.140 ± 0.033	2.15 ± 0.21	0.440 ± 0.025	0.480 ± 0.050	0.440 ± 0.022	0.710 ± 0.065
	0.114 ± 0.020	2.10 ± 0.18	0.062 ± 0.004	0.285 ± 0.024	0.150 ± 0.005	0.410 ± 0.027

intake was accompanied by an increase in BE content. This is apparently attributable to the inflow into the NPP intake of water from the upper part of the storage reservoir, whose heating always had a pronounced effect. The presence of soil particles from the intake region in the flasks caused a considerable increase in the P-PO₄⁻³ and N-NO₃⁻ content as compared with the check flask. The amount of BE mineral forms also increased during heating of the water with particles of dead plants. However, heating of the water with bottom sediments from the discharge region had no such effect. We should note that reliable differences from the control data were not observed in this variant of the test even with the heating duration increased to 24 h.

In 2000, we performed five variants of studies at the KNPP cooling reservoir (Table 3). We should note that, in all cases, heating of the water samples taken near the NPP intake did not result in a reliable increase in the P-PO₄⁻³ and N-NO₃⁻ concentrations. This is apparently due to the fact that, in contrast to the SNPP cooling reservoir, such reservoir at KNPP has a ring-shaped structure and almost entire its water mass passes through the cooling system within a short time interval. Therefore, one more heating procedure in laboratory had no pronounced effect. The concentrations of P-PO₄⁻³ and N-NO₃⁻ also not increased in the experiments with cat-tail particles performed in February, probably, because the destruction of dead particles of the near-shore vegetation mainly terminated by that time.

Thus, the experimental results indicated that water heating in an NPP cooling system can sometimes result in an increase in the concentrations of P and N mineral compounds. However, the experimental results cannot be automatically extrapolated to real processes in the natural environment. To form a more or less adequate

judgment, one should add to these data the results of full-scale observations. For this purpose, when collecting data at both the cooling reservoirs we studied the effect of thermal discharge the production and destruction processes in the aquatic environment. Increased temperature generally enhanced the destruction. This tendency was especially evident in the cold season and was less pronounced in the summer (Table 4). However, we should once more draw attention to the specific features of the hydrological structure of the cooling reservoirs: destruction is intensified only in the thermal discharge areas. Thermal-discharge water circulates. Consequently, we can assume that destruction products are more or less uniformly distributed in the entire water mass of the circulation flow. The distribution of certain hydrochemical parameters indirectly corroborates this assumption. For example, the values of permanganate and bichromatic oxidizability, which adequately reflect the quantitative and qualitative composition of organic matter in the water, did not exhibit significant difference in different parts of the circulation flow in both cooling reservoirs.

The phytoplankton production in the regions of thermal discharge was often far below that in the NPP intake (Table 4). The value of this characteristic sometimes decreased to zero, which testifies to a virtually complete suppression of photosynthesis, apparently, because phytoplankton cells are damaged when water passes through process aggregates and its temperature sharply increases [4]. Such assumption is corroborated by experimental results obtained in other cooling reservoirs [1, 3]. At the same time, heated water often stimulated the production of plankton algae. However, in such cases the data were mostly obtained in the entire zone of heating of the cooling reservoir (areas into which the discharged water comes over a time sufficient for algae to restore their vital functions) rather than in the area of thermal discharge.

Table 4. Average values of the phytoplankton destruction and primary production, mg O₂/(l day) in the NPP intake (top number) and discharge (bottom number) channels

Month, year	Destruction	Production	Month, year	Destruction	Production
	SNPP			KNPP	
July 1999	$\frac{7.7 \pm 0.6}{8.1 \pm 0.5}$	$\frac{8.2 \pm 3.1}{0}$	October 1999	$\frac{5.2 \pm 0.6}{6.2 \pm 0.4}$	$\frac{1.5 \pm 0.2}{0}$
August 1999	$\frac{9.6 \pm 0.7}{10.7 \pm 0.8}$	$\frac{6.2 \pm 3.0}{0}$	February 2000	$\frac{0.8 \pm 0.3}{1.8 \pm 0.4}$	$\frac{0.8 \pm 0.3}{0.5 \pm 0.3}$
November 1999	$\frac{3.2 \pm 0.5}{6.5 \pm 0.3}$	$\frac{2.7 \pm 1.1}{0.9 \pm 0.4}$	April 2000	$\frac{3.3 \pm 0.5}{2.9 \pm 0.3}$	$\frac{9.6 \pm 0.4}{2.5 \pm 0.5}$
February 2000	$\frac{0.5 \pm 0.1}{4.0 \pm 0.2}$	$\frac{0.5 \pm 0.3}{0.6 \pm 0.2}$	October 2000	$\frac{2.4 \pm 0.3}{5.0 \pm 0.4}$	$\frac{2.9 \pm 1.4}{1.5 \pm 0.6}$
April 2000	$\frac{3.8 \pm 0.3}{4.6 \pm 0.3}$	$\frac{10.5 \pm 3.5}{10.5 \pm 3.5}$			

In spring, the intensification of photosynthesis due to thermal discharge caused a pronounced increase in the phytoplankton biomass. However, the alga biomass increased not only in the zone of heating. In most cases algae were rather uniformly distributed in the entire water mass of the circulation flow (their concentrations in the discharge zones as a rule insignificantly differed from their concentrations in distant areas where the temperature regime slightly differed from the natural one). At the same time, in this season, the phytoplankton biomass was substantially smaller in the areas located much closer to discharge outlets but outside circulation flows.

CONCLUSIONS

Under certain conditions, water heating results in an increase in the concentrations of P and N mineral forms in water. However, these processes are insignificant if the circulation flow is sufficiently closed. Similar conclusions can also be drawn concerning the effect of heated water on bottom sediments. Since the circulation character changes insignificantly, the zones, where submerged soils are constantly in contact with heated water, and the bottom areas, where sediments are not in contact with the NPP discharge water, are present in the cooling reservoir. In the first case the effect of heated water is not accompanied by a pronounced increase in BE concentration. Thus, water heating did not affect soil samples taken in NPP discharge regions, since these soils are constantly washed by heated water and subsequent heating does not result in an increase in BE leaching rate. The effect of heated water on bottom sediments taken from other parts of cooling reservoirs is most often very strong. However, heated water virtually cannot come into these parts of cooling reservoirs. At the same time, under certain conditions, BS particles from these areas can fall into a water body as mud and

can be sucked in an NPP cooling system as part of suspension.

Thus, in a long-lived cooling reservoir with a recirculating water supply system, water heating in process aggregates can cause a pronounced increase in BE concentration only if water comes in an NPP intake from water area parts that are usually not involved in the circulation flow or if suspended soil particles from unheated areas fall in the cooling system. Such phenomena are occasionally observed in all the studied cooling reservoirs during onsets, wave and flooding phenomena, and dredging.

At the same time, thermal eutrophication intensifies production processes. Indeed, heating of water in a considerable part of its area sometimes results in an increase in the level of primary production. These phenomena are especially pronounced early in spring when the level of photosynthesis in a heated zone is substantially higher. We should note that the level of primary production increases both near the NPP discharge and at a considerable distance from it. Since constant circulation flow tends to smooth any irregularities that may originate, the increase in the phytoplankton biomass due to the intensification of bioproduction proceeds rather uniformly in the entire body of circulating water.

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