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DEVELOPMENT OF THE REGULATION OF HYDROBIOLOGICAL MONITORING IN CIRCULATION COOLING SYSTEM OF THE ZAPORIZHZHIA NUCLEAR POWER PLANT

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The article proposes a new approach to solving the problem of biofouling at the facilities of the circulating cooling system of the Zaporizhzhia Nuclear Power Plant (ZNPP) by regulating hydrobiological studies. In the course of the studies, 4 species of hydrobionts were found that formed massive fouling on water supply facilities: filamentous algae Oedogonium sp. and Ulotrix zonata with a total biomass of 123.6±18.44 g/m2, tropical molluscs Melanoides tuberculata and Tarebia granifera of the Thiaridae family with a biomass of 20.09 g/m2. The shells of dead mollusks drifted along the pipes of the circulation system with the flow of water and interfered with the operation of pumping stations. Also, the blue-green algae Microcystis aeruginosa, which dominated the phytoplankton of the cooling pond, belonged to the potential bio-hindrances. The hydrobiological regulation was developed with the aim of timely detection of hydrobionts capable of active reproduction and creation of biological obstacles. It provides for four types of monitoring: current (operational), extreme (control), deployed (research) and background (hydrobiological monitoring of the Kakhovka reservoir in the zone of influence of waste warm waters). For each type of monitoring, the subjects of control (a group of hydrobionts), control parameters (species composition, abundance, biomass) and frequency of control are determined. The regulation of hydrobiological monitoring makes it possible to minimize the consequences or prevent the occurrence of accidents and emergencies in the operation of the ZNPP cooling circulation systems associated with biological obstacles, and can be used as an example for solving similar problems at other power facilities. The article also contains practical recommendations for improving the ecological state of the cooling pond and preventing the massive development of dangerous aquatic organisms by introducing biomeliorator fish with a different food spectrum into the reservoir

Keywords: Zaporizhzhia nuclear power plant, hydraulic structures, environmental factors, problem of biofouling, hydrobiological monitoring, bioreclamation

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1. Introduction

The operation of nuclear and thermal power plants is associated with the use of significant amounts of water required for cooling power units. The facts show that in different countries the vast majority of emergency shutdowns of nuclear power plants and hydroelectric power plants related to water supply were caused by the massive development of hydrobionts. At the Khmelnytskyi nuclear power plant, the mollusk *Dreissena polymorpha* (Pallas, 1771) forms huge fouling on the surfaces of coastal concrete structures and, with water, gets on the grids of pumping stations that impede the flow of water. To prevent an emergency situation, the station is forced to suspend the operation of power units every two years and perform mechanical cleaning of underwater structures from mollusk colonies, the biomass of which reaches 900 tons [1]. At the Funil hydroelectric power plant (Rio de Janeiro), emergency stops are caused by the hydroid *Cordylophora caspia* (Pallas, 1771), which settles in the water cooling system of generating units and causes a further increase in the temperature of the system [2].

The problem of bio-hindrances is also relevant for marine man-made systems. The mass development of marine periphyton organisms (sponges, mollusks, algae) in water supply pipelines causes a reduction in heat transfer and a decrease in cooling efficiency, premature wear of objects and an increase in operating costs [3].

When using a circulating water supply system, the cooling pond serves as the main reservoir for cooling. It is the quality of the water in the cooling pond that affects the efficiency of the power plant. For cooling ponds, the problem of biofouling is particularly relevant, since the elevated temperature regime and the presence of organic matter in such reservoirs create favorable conditions for the rapid development of certain species. Examples of such phenomena are bio-hindrances caused by the massive development of phytoplankton ("blooming" of water) due to technogenic thermalization of a reservoir [4]. The most numerous bio-hindrances are created by animal periphyton organisms. For freshwater man-made systems, bivalve mollusks *M. Dreissena* are active objects of biocirculation. In the cooling reservoir of the Khmelnytskyi NPP, dreissenas are found everywhere and the biomass reaches 5 kg/m^2. It is from the cooling pond that Dreissena enters the water supply system and creates hindrances [5].

Invasive species of hydrobionts pose a particular threat as bio-hindrances. Getting into cooling reservoirs, some self-distributing species occupy a dominant position in the ecosystem in terms of their abundance and biomass in a relatively short period of time. An example is the tropical mollusk *Melanoides tuberculata* (Thiaridae), which by anthropogenic means turned out to be naturalized in the cooling pond of the Pivdennoukrainsk NPP. During the period from 2005 to 2011, its abundance increased from 400 ind/m^2 to 5800 ind/m^2 and accounted for 86 % of the total abundance of zoobenthos in the reservoir [6].

The consequences of the penetration of Thiaridae mollusks into the cooling pond of the Zaporizhzhia NPP amaze with the speed of adaptation and the scale of distribution throughout the entire circulation cooling system. In almost 3 years (2015–2018), tiarid mollusks increased their numbers in the cooling pond from single specimens to 300 ind/m^2, and in pipelines to 6340 300 ind/m^2 and became the cause of their blockage [7].

Another important hydroecological problem associated with the operation of nuclear and thermal power plants is the thermal pollution of natural water bodies that receive heated wastewater. It has been established that in the zones of influence of heated waters, the species biodiversity is much poorer compared to natural zones [1].

The results of many years of research on the functioning of water technosystems of power plants indicate the inappropriateness of using a standard approach to assess their ecological state based on reference conditions. In many cases, the biological factor had a greater impact on the quality of water in the circulation system than the man-made one [8]. Therefore, hydrobiological monitoring should be an integral part of the overall process control at hydropower facilities.

Thus, in order to prevent the occurrence of emergencies in the operation of energy facilities caused by bio-hindrances, it is necessary to develop and introduce a hydrobiological monitoring mode into the technological process for each power plant. The regime should take into account the peculiarities of the species composition and development of biocenoses of hydraulic structures, as well as the potential risks of bio-hindrances.

2. Literature review and problem statement

The problem of bio-hindrances in the work of underwater communications remains relevant for many countries, despite many years of international experience in its study. Power plants that use sea water for cooling are more likely to encounter the problem of microbiological fouling. Bacteria and microalgae colonies have been reported to cause scale and corrosion of cooling towers and thereby significantly impair water cooling efficiency [9]. Marine macrofouling (colonies of sponges, mollusks) causes significant damage to pipeline systems, causing them to clog, and also create vortex vibrations and thereby reduce the energy transfer coefficient by 15–36 % [10].

In freshwater reservoirs-coolers of Ukraine, mollusks and algae become frequent culprits of biological obstacles. The greatest damage is caused by mollusks – representatives of the genus of Dreissena (*D. polymorpha*, *D. bugensis*). Dreissena is a common inhabitant of natural water bodies of the Dnipro basin. Once in the cooling ponds, where the temperature is increased and there are practically no mollusk-eating fish, this mollusk begins to multiply en masse, penetrate into other hydraulic structures of the cooling system and create bio-hindrances there. Such problems are typical for the Khmelnitskyi NPP [11].

Invasion penetration of the mollusks of the city of Thiaridae (*Melanoides tuberculata* and *Tarebia granifera*) into cooling ponds has been described for the Pivdennoukrainsk NPP [6] and Zaporizhzhia NPP [7]. In the ZNPP circulation cooling system, invasive mollusks quickly captured various biotopes and, due to their massive development in pipelines, on culverts, nets, and filters, form significant bio-hindrances [12].

Existing modern methods of combating water biocirculation have their advantages and disadvantages. The use of mechanical methods for cleaning water conduits from fouling is environmentally friendly, but laborious and ineffective, since it eliminates the problem and its consequences.

Among the chemical methods, the most common is the use of preparations containing chlorine. Chlorination to protect hydraulic structures from fouling has been used for many years and has a positive effect [13]. As disadvantages of using chlorine-containing preparations, their corrosive effect on underwater metal structures is indicated [14]. In order to reduce the corrosive effect of chlorine use, the addition of chlorine-containing compounds of a bromide-based biocidal preparation has been recommended [15]. But the main disadvantage of using chlorine and other chemical agents to combat bio-hindrances is their negative impact on the ecology of natural water bodies, where wastewater from energy facilities enters [16].

To search for non-toxic ways to combat marine and freshwater biological obstacles, it was proposed to use physical and biological methods [17]. An example of developments in this direction is the use of anode current to combat the fouling of water intake grates on mollusk Dreissena [18]. According to the technology, current is supplied to the gratings, as a result of which substances of the ferrocene class are formed in the biofilm, which protect metal structures from biotreatments.

Another direction in the fight against bio-hindrances is the use of synthetic polymeric materials for coating underwater structures. But all of them contain toxic compounds (biocides, salts of heavy metals, etc.) as antifouling agents, which are released into the water and harm the environment. The use of environmentally friendly biomemetic polymer coatings is a promising direction, but the problems of the shortage and high cost of biopolymer materials remain unresolved [19].

In order to continue the safe production of nuclear power, it is important to understand the condition of key structures, systems and components of nuclear power plants. Timely detection of malfunctions of NPP technical structures is a predictive maintenance strategy based on constant monitoring and full awareness of the state of the equipment [20].

Since cooling reservoirs are an integral part of the NPP technological ecosystem, it is necessary to include hydrobiological monitoring in the monitoring system of nuclear power plant technological processes, which has received little attention in the scientific literature.

Due to the diversity of the species composition of organisms and the characteristics of their existence in cooling ponds, there cannot be a universal way to prevent and combat biofouling. Therefore, for the timely detection of hydrobiological risks, a general concept of organizing hydrobiological monitoring in water bodies of thermal and nuclear power plants was proposed [21]. It is aimed at identifying possible and real causes of biological disturbances in the operation of NPP water supply systems. The concept uses European environmental principles for controlling the negative impact of technical ecosystems on background water bodies located near nuclear power plants [22].

An analysis of the literature indicates that the existing methods of combating water bio-hindrances, to one degree or another, have an anti-fouling effect. But a number of shortcomings infringes, and sometimes makes it impossible to use them. This applies to chemical and physical methods that use compounds or devices that adversely affect the quality of the aquatic environment and biota (chlorine-containing compounds, biocides, synthetic polymer coatings, electric current). The prospects for the use of environmentally friendly biomaterials are limited by their preciousness. Mechanical methods of cleaning underwater structures from biofouling are time-consuming and require a partial suspension of the operation of the station.

A common drawback of most of the above methods is the focus on combating bio-hindrances, and not on their prevention. This approach does not take into account the possibility of timely detection of hydrobionts – potential samples of bio-hindrances. This is especially true for species that accidentally enter cooling ponds and spread massively throughout the entire cooling system in a short time.

Thus, to effectively solve the problem of bio-hindrances in the operation of power plants, a complete approach is needed, which should be based on the concept of organizing hydrobiological monitoring. The development and implementation of a hydrobiological monitoring regime will make it possible to timely identify and prevent the development of dangerous hydrobionts that can form obstacles. The use of a system of permanent hydrobiological control in all facilities of the circulating cooling system will reduce the likelihood of hydrobiological and environmental risks in the operation of the station. Such an approach in solving the problem of bio-hindrances will have certain economic advantages compared to existing methods.

3. The aim and objectives of research

The aim of research is to develop a regulation for hydrobiological monitoring in the man-made reservoirs of the circulating cooling system of the Zaporizhzhia NPP and the background reservoir (Kakhovka reservoir) based on complex hydrobiological studies of all biocenotic groups. This will make it possible to timely identify possible biological obstacles in the reservoirs of the cooling system and prevent the negative consequences of their impact on the operation of the Zaporizhzhia nuclear power plant, as well as on the ecological state of the Kakhovka reservoir as a background reservoir.

To achieve the aim, the following objectives were set:

– to assess the hydroecological state of the ZNPP circulation system CP;

– to study the features of the development of hydrobiocenoses (grouping of plankton, benthos, ichthyofauna) of water bodies of the hydrotechnical system of ZNPP;

– to analyze the existing and possible bio-hindrances in the ZNPP water cooling circulation system;

– to develop a regime for the implementation of current, extreme and extensive control over the development of hydrobionts – potential samples of bio-hindrances, as well as to determine the parameters for monitoring the possible negative impact of the ZNPP on the background water body;

– to develop recommendations for improving the ecological state of the ZNPP cooling pond.

4. Materials and methods of research

The object of research was the real and potential bio-hindrances of the cooling reservoir and hydraulic structures of the Zaporizhzhia NPP.

As a hypothesis, it is believed that the development of a science-based hydrobiological monitoring regime and its implementation will contribute to the timely identification of potential bio-hindrances in the ZNPP cooling system and to prevent the negative impact of the mass development of aquatic organisms on the operation of the plant.

Water samples for hydrochemical analysis were taken in the surface and bottom layers; studies were carried out according to standard methods [23]. The environmental assessment of water quality for different categories was carried out in accordance with the developed methodology [24].

Samples of bottom sediments for toxicological analysis were taken from the cooling pond of the Zaporizhzhia NPP from a depth of 0–5 cm.

Zooplankton samples were taken using an Apshtein plankton net (gas No. 71), through which 100 L of water was filtered. Quantitative indicators of zooplankton were determined in a Bogorov chamber under a MICROmed XS-6320 binocular stereomicroscope (China, 2019), taking into account the number of different size and age groups of organisms [25]. Biomass was calculated using the formula for the dependence of mass on body length:

$$w=ql^{\beta}, \qquad (1)$$

where w – the mass; q – the coefficient of proportionality; l – the length of the body.

Zoobenthos samples were collected with an Ekman-Burge bottom grab and fixed in 4 % formalin. Species composition was determined using a MICROmed XS-6320 binocular stereomicroscope (China, 2019).

The collection of mollusks at hydraulic structures was carried out using a hydrobiological scraper. The number of mollusks on concrete slabs in the NPP channels was counted using a frame with an area of 1 m^2, which was installed along the edge of the water and fixed on the slope of the slabs. Within the limits of the space limited by the frame, the mollusks were selected by hand. The obtained material was counted on the spot, to clarify the species composition, some samples were fixed with 4 % formalin.

Bacterioplankton samples were taken and processed in accordance with generally accepted hydrobiological methods [23].

Samples for studying the species composition and quantitative characteristics of phytoplankton were taken with a Molchanov bathometer [26]. The selected material was fixed in 2 % formalin. For thickening, the sample was settled in a cylinder for 7–10 days, after which the sample was examined in a 0.02 cm^3 Nageotte chamber under a Carl Zeiss Jenaval microscope (China, 2019).

Ichthyological material was collected from control gear for fishing with a set of fixed nets with a cell pitch a=30–110 mm. The collection and processing of ichthyological material was carried out in accordance with generally accepted methods [27]. The age of the fish was determined by the scales [28].

Parasitological studies of fish were carried out by the classical method of complete parasitological section [29]. For the quantitative assessment of parasites, the following indicators were used: extensiveness of invasion – EI (the ratio of the number of infected fish to the total number of experimental fish of the same species, %); intensity of invasion – II (the number of parasites of one species per fish).

Statistical processing of the results was carried out by the variational-statistical method using the Statistica 6.0 software package.

5. Research results of the ecological state and hydrobiocenoses of the circulating cooling system of the Zaporizhzhia nuclear power plant

5. 1. Assessment of the hydroecological state of the cooling pond of the circulation system of the Zaporizhzhia nuclear power plant

The cooling pond is an element of the complex of hydraulic structures of the circulating system of technical water supply of Zaporizhzhia NPP. It was put into operation in 1984 with the launch of power unit No. 1 by fencing off part of the Kakhovka reservoir with an alluvial sand dam. The reservoir has the following parameters: the mirror area at the normal maximal level (NML) is 8.2 km², the volume at the NML is 47.05 million m≥, the average depth at the NML is 5.87 m, the maximum depth at the NML is 13.5 m, the length of the coastline is 11.2 km [30]. Fig. 1 shows a diagram of the CP and circulating cooling system with sampling points.

The thermal regime in CP in summer is characterized by elevated water temperatures from +32 °C to +40 °C, while the temperature optimum limit for most hydrobionts is +34 °C. High temperatures accelerate the degradation and oxidation of organic matter and thus increase the levels of biological oxygen demand (BOD_5) and chemical oxygen demand (COD_5).

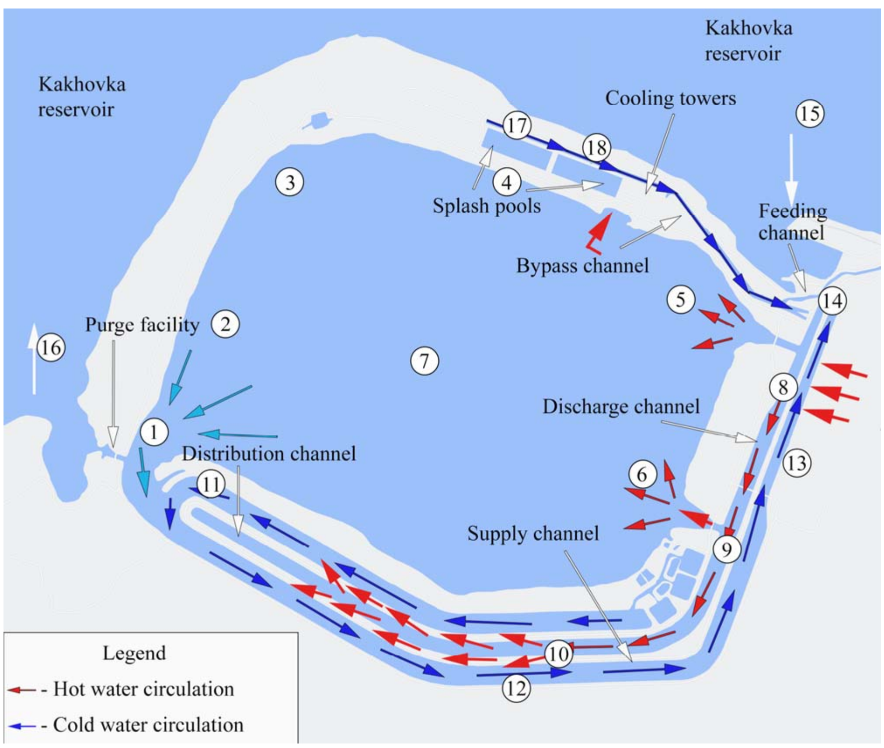

Fig. 1. Scheme of the cooling pond and circulation cooling system of the Zaporizhzhia nuclear power plant with control points of hydrobiological monitoring. Areas of the cooling pond: western: 1 — water discharge into the Kakhovka reservoir (blowing system); 2 — littoral (silty sand); 3 — littoral (silt); northern: 4 — discharge into spray pools and cooling towers; eastern: 5 — discharge of heated water into the cooling pond (eastern zone); southern: 6 — discharge of heated water into the cooling pond (southern zone); 7 — central. Channels: 8 — waste (water bypass from underground channels of power units); 9 — discharge (bypass to the cooling pond); 10 — discharge (the beginning of the distribution channel); 11 — discharge (end of the distribution channel); 12 — supply (the beginning of the distribution channel); 13 — (near the 6th power unit); 14 — channel for feeding the cooling pond; 17 —discharge channel of spray pool No. 1; 18 — discharge channel of spray pool No. 2. Of Kakhovka reservoir: 15 — water intake of the Zaporizhzhia thermal power plant; 16—500 m below the discharge of water from the cooling pond

Since fish are grown in CP for the purpose of biomelioration, it is advisable to assess the quality of water according to fishery criteria. According to the data of the ZNPP water-radiochemical laboratory in CP, there is an excess of fishery MPCs in terms of BOD_5 by an average of 21 %, COD_5 by 64 %. There is also an excess of MPC for some heavy metals: copper – 1.6 times; manganese – 1.8 times; zinc – 4.2 times and iron – 1.7 times. Other hydroecological indicators were within the limits of fishery norms [31].

The radiation state in the CP is satisfactory. The content of natural and artificial radionuclides did not go beyond the fishery MPCs and amounted to: radium-226 – 0.25 Bq/l, thorium-232 – 0.092 Bq/l, potassium-40 – 0.7 Bq/l, cesium-137 – 0.014 Bq/l, strontium-90 – 0.004 Bq/l.

5. 2. Features of the development of hydrobiocenoses of the reservoir-cooler and the cooling system of the Zaporizhzhia nuclear power plant

Bacterioplankton. Planktonic organisms were studied in the cooling pond in the following groups: bacterioplankton, phytoplankton and zooplankton. The total abundance of bacterioplankton in the CP varied widely from 3.3 million cells/mL to 7.9 million cells/mL. The greatest abundance of bacterioplankton was noted in summer, which was accompanied by the formation of a bacterial film on the water surface (Fig. 2).

Fig. 2. Bacterial biofilm

According to the environmental assessment of microbiological pollution, this corresponded to the III–IV classes of the water quality category – moderately polluted [24].

Phytoplankton. In CP, the spatial distribution of phytoplankton was not uniform. The abundance indicators ranged from 13376 million ind/m^3 to 85724 million ind/m^3, the average biomass was 7.53±0.12 g/m^3. The composition of phytoplankton was dominated by representatives of blue-green algae: *Microcystis aeruginosa*, *Aphanizomenon flos-aguae*, *Anabaena flos-aguae*. In summer, the mass development of *M. aeruginosa* caused the "water bloom" phenomenon (Fig. 3). In places of "blooming" its biomass reached 58.4±8.32 g/m^3.

According to the environmental quality classification, the water of the ZNPP CP according to the biomass of phytoplankton corresponded to class III of the 5^{th} quality category – eu-polytrophic.

Zooplankton. The number of zooplankton in different parts of the CP varied from 30193 ind/m^3 to 141580 ind/m^3 with a minimum at the points of discharge of heated waters.

Fig. 3. The accumulation of blue-green algae on the water surface

The average characteristics of zooplankton biomass in the CP are rather low and amount to 1.45±0.09 g/m^3. In terms of quantitative indicators of development, representatives of cladocerans (*Diaphanosoma brachyurum*, *D. dubia*, *Moina macrocopa*, *M. micrura*, etc.) dominated among zooplankton groups.

In the channels of the circulating cooling system (CCS), an impoverished development of planktonic organisms is observed due to the high flow rate and high temperature (more than +40 °C in summer).

According to the classification of water quality in relation to the development of zooplankton, the CP can be attributed to the 2^{nd} category "low development" in the zone of discharge of heated waters and to the 3^{rd} category – in the zone of discharge into the Kakhovka reservoir – "development below average".

Phytobenthos and phytoperiphyton. The phytobenthos in the waterways and channels of the circulation system was represented by filamentous algae *Oedogonium sp*. and *Ulotrix zonata* (Fig. 4).

Fig. 4. Phytoperiphyton

The average abundance of microphytobenthos in the ZNPP cooling pond was 32654±786.9 million cells/m^2, and the biomass was 5.5±0.65 g/m^2. The maximum biomass of phytobenthos was noted in certain sections of the CCS channels and reached 123.6±18.44 g/m^2. The coefficient of species similarity of groupings between the phytobenthos of ZNPP and the Kakhovka reservoir reached 0.92 units, which indicates the similarity of algae in the studied reservoirs.

Zoobenthos and zooperiphyton. The main biomass of zoobenthos in the CP consisted of groups of mollusks *Melanoides tuberculata* and *Tarebia granifera* (Fig. 5). The total biomass of the zoobenthos of the cooling reservoir ranged from 0.54 g/m^2 to 20.09 g/m^2 and depended on the nature of the soil. On average, the biomass of zoobenthos in CP was 11.32±1.28 g/m^2, and the abundance was 160 ind/m^2.

Fig. 5. Mollusks *Melanoides tuberculata* and *Tarebia granifera*

The vast majority of the zooperephyton of the discharge and bypass channels was represented by mollusks of the family Thiaridae, the abundance of which varied from 20 ind/m^2 to 80 ind/m^2. In the channels of the CCS, the enrichment of the number of species occurred due to the finding of *Planorbis corneus L*., a species of mollusks popular in the aquarium hobby.

In underground discharge channels, Trinitidae mollusks were also the main representatives of zooperiphyton. On the walls of metal pipes, their number reached 5200 ind/m^2.

Ichthyofauna. In the modern composition of the ichthyofauna of the cooling pond, 18 species of fish have been recorded. There are aboriginal species here, more or less adapted to the specific conditions of the technological reservoir (wattle, flat-billed catfish, European catfish, etc.). Introduced species introduced for bioreclamation purposes are represented by the following species: silver carp, silver carp, grass carp, Mozambique tilapia, channel catfish. There are also self-distributing species (Amur chebachok, sun perch). The latter can significantly increase their numbers in conditions of unstable ecological balance of man-made water bodies. In general, the composition of the ichthyofauna of the ZNPP includes 44 % of native species and 56 % of alien fish species.

According to the results of ichthyological studies, the individual weight of this year's silver carp in the cooling pond was 12–20 g at a rate of 25–30 g. In this regard, the yield from wintering gardens was only 40 % against the standard 70 %. The high rates of natural mortality of silver carp this summer are due to the low weight, pressure of high water temperature in summer, as well as the negative influence of fish-eating birds, which during the winter period significantly eat away young silver carp.

The maximum ichthyomass of silver carp falls on five-year-olds, that is, the maximum consumption of food resources will be observed in four-six-year-olds. In the future, the ichthyomass of this generation will gradually decrease due to natural mortality, that is, accumulated organic substances will return to the reservoir. Accordingly, it is these age groups that should be targeted at the beginning of the reclamation extraction of silver carp individuals.

An analysis of the theoretical and actual natural mortality rates also speaks of the need to introduce the herbivorous fishery. Based on the data on stocking and the estimated number of the corresponding generation after several years of stay in the reservoir, it is possible to determine the average overall mortality rates (which, as a result of the absence of fishing, will correspond to natural mortality rates).

Theoretically, the expected natural mortality of four-six-year-old silver carps should be 0.23–0.25, while in a real population it is 0.31–0.42, that is, an increased elimination of these fish species is observed in the reservoir. One of the reasons for this may be overpopulation, the growth of intraspecific competition, therefore, with a decrease in the ameliorative effect as a result of a decrease in the generation ichthyomass, it is necessary to regulate the number of ineffective age groups.

A potential consumer of benthos is carp (carp). According to the control catches, the age limit for carp was 8 years, that is, the age range is quite wide. In long-lived nets (with eye spacing a=75 mm and above), there were mainly individuals aged 5 to 7 years (43.2 %), 42–60 cm long. Fulton fatness coefficients ranged from 1.88 to 2.48 (average 2.13), which also indicates fairly satisfactory feeding conditions for this species.

The ichthyofauna in the discharge and supply channels was not numerous and was represented mainly by tilapia at the age of 1 to 3 years. Tilapia acts as a consumer of filamentous algae biomass and prevents their mass fouling on hydraulic structures. Under the conditions of the ZNPP CP, it acclimatized and formed a self-reproducing population, the individuals of which breed year-round in the warm waters of the reservoir. The average annual rate of tilapia capture from the ZNPP cooling pond is 667 kg/year.

When conducting parasitological studies of fish living in the cooling pond (carp, silver carp, silver carp, pike perch, gobies) and the bypass channel (tilapia), only single ciliated ciliates of the genera Trichodina and Apiosoma, and worms were found. All parasites were localized on the gills. The extent of fish infection did not exceed 10 %. That is, the epizootic state of the reservoir-cooler for the period of research can be considered safe.

Macrophytes. Thickets of macrophytes (higher aquatic plants) are formed in the shallow areas of the CP. The higher aquatic vegetation was represented by 17 species. The dominant species is the common reed *Phragmites australis* (*Cav.*) *Trin. ex Steud*, which creates continuous thickets about 1 m wide (Fig. 6).

Fig. 6. Common reed *Phragmites australis* (*Cav.*) *Trin. ex Steud* on the slopes of the supply channel plates

The density of reeds in some areas can reach up to 90 ind/m^2. The phytomass of reeds in CP in dense thickets was about 4.25 kg/m^2. In general, the area overgrown with heliophytes of the CP is insignificant – less than 5 % of the area of the water table.

Primary production and destruction. The average gross primary production (A) of phytoplankton in summer ranged from 6.2 g/m^3 to 22.8 g/m^3. In balanced ecosystems, production is balanced by destruction and is determined by the ratio A/R=1 or the self-cleaning-self-pollution index. In the ZNPP cooling pond in the area of warm water discharge, this indicator is 0.6, which indicates a reduced degree of water self-purification.

5. 3. Analysis of existing and possible biohindrances in the circulating water cooling system of the Zaporizhzhia nuclear power plant

Plants that can present biological obstacles are mainly filamentous greens (Cladophora, Ulotrix), blue greens and diatoms. They develop to a greater or lesser extent throughout the year. Their development requires sunlight, so in the cooling pond they can vegetate everywhere, except for the darkened areas of the water supply systems. The thermal regime plays a significant role in the distribution of various algae. The mass development of filamentous and blue-green algae coincides with the zones of discharge of heated waters.

Biohindrances of animal origin are formed by the molluscs *Melanoides tuberculata* and *Tarebia granifera*. As invasive species, they very aggressively occupy different biotopes. A sharp increase in abundance is typical for new species at the initial stages of introduction.

An increase in water temperature in the return and cooling pond can lead to more intensive development of molluscs, which will develop both in the return and supply channels, and in cooling and technical water supply systems. The death of organisms associated with an increase in temperature and flow velocity in the supply channel will affect the amount of drift material, which will cause bio-hindrances in the operation of pumping stations. The shells of dead mollusks accumulate in the pools of bioreclamation sites with the flow of water and also create bio-hindrances.

5. 4. Regime for monitoring the development of potential bio-hindrances patterns

When developing the regulations for various types of hydrobiological monitoring in the ZNPP circulating cooling system, methodological guidelines for the development of hydrobiological monitoring regulations [32] and recommendations on conceptual approaches to the organization of hydrobiological monitoring [22] were taken into account. For an objective assessment of the hydroecological state of the ZNPP man-made water bodies and the background water body, it is recommended to carry out four types of hydrobiological monitoring – current, extreme, extended and background. Periodicity of ongoing monitoring of hydroecological characteristics of ZNPP CP is presented in Table 1.

Table 2 provides a list of all groups of aquatic organisms subject to current control in the cooling pond, channels and technical water supply system. Periodicity and control parameters are provided.

Table 1

Control parameters for the existence of hydrobionts in the cooling pond

Object of control	Control parameters	Control frequency
Cooling systems: CP, discharge channel, supply channel, spray pools.	Water temperature, °C	Monthly
	BOD_5, mgO_2/dm^3	
	COD_5, mgO_2/dm^3	
	Ammonium nitrogen, mg/dm^3	
	Copper, mg/dm^3	
	Plumbum, mg/dm^3	
	Manganese, mg/dm^3	
	Zinc, mg/dm^3	

Table 2

Objects of current control and frequency of hydrobiological monitoring

No.	Objects of control	Items of control	Control frequency	Control Options
1	Cooling systems: CP, spray pool channels	Bacterioplankton	Monthly in summer and once in autumn	Morphological groups, abundance, biomass
		Phytoplankton	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Zooplankton	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Phytobenthos	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Phytoperiphyton	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Zoobenthos	Once a season (summer and autumn)	Species composition, abundance, biomass
		Zooperiphyton	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Macrophytes	One time (end of August – beginning of September)	Species composition, abundance, biomass
		Ichthyofauna	One time (summer)	Species composition, fish productivity
		Primary production and degradation	Monthly in summer and once in autumn	Self-cleaning-self-pollution index
2	Technical water supply systems: siphons of underground discharge channels, fore chambers of coastal pumping stations	Phytoperiphyton	Monthly in summer and once in autumn	Species composition, abundance, biomass
		Zooperiphyton	Monthly in summer and once in autumn	Species composition, abundance, biomass

Extreme monitoring is carried out in cases of exceeding the MPC, extreme climatic events, a sharp increase in bio-hindrances. Its purpose is to determine the causes and dynamics of changes in controlled indicators, as well as to obtain initial data for the development of operational measures to prevent possible negative consequences of the influence of factors on the CP ecosystem and the growth of biological interference.

The regime of extreme monitoring of the software is introduced immediately after the discovery by the environmental protection service (EPS) of the facts of a significant excess of the standard MPC of hydrochemical indicators, significant changes in hydrobiological indicators. Also, when a threat to the life of populations and groups of aquatic organisms is detected with a sudden increase in biological interference.

Controlled hydrobiological indicators during extreme monitoring are selected based on the results of the initial survey, current monitoring and analysis of the actual hydrobiological state of the CCS and CP.

The purpose of extensive hydrobiological monitoring is to establish general trends in the development of the ZNPP hydro-ecosystem, groups of aquatic organisms, primarily potentially threatening the normal operation of ZNPP. It is also aimed at identifying the role of invasive species of aquatic organisms, the consequences of extreme situations, and correcting the current monitoring system.

Detailed hydrobiological monitoring is carried out every 2–5 years with the involvement of hydrobiologists from specialized scientific organizations (if necessary) and includes a detailed examination of the VO and CSO. Controlled hydrobiological indicators and objects of control of expanded monitoring are determined by a long-term monitoring program.

The purpose of the background hydrobiological monitoring is to assess the possible negative impact of ZNPP wastewater on the ecosystem of the background section of the Kakhovka Reservoir. It is also aimed at detecting aquatic organisms that can get from the reservoir into the ZNPP cooling circulation system and create bio-hindrances.

When choosing monitoring points in the background water body, the possible impact of ZNPP wastewater on the biocenoses of the littoral and profundal zones of the background area was assessed. Sampling points and biological objects of research are presented in Table 3.

When conducting current monitoring of the background section of the Kakhovka reservoir, it is necessary to control the following hydrobiological groups: bacterioplankton; phytoplankton; phytobenthos; zooplankton; zoobenthos.

Table 3

Points of hydrobiological sampling in the background pond

Background pond	Control points	soil, substrate	Biological objects	Research horizon, m
Kakhovka reservoir	Water intake of Zaporizhzia TPP	water column, bottom	Bacterioplankton	0.01
			Phytoplankton	1
			Phytobenthos	10
			Zooplankton	1
			Zoobenthos	10
	500 m below water discharge from CP	water column, bottom	Bacterioplankton	0.01
			Phytoplankton	1
			Phytobenthos	10
			Zooplankton	1
			Zoobenthos	10

Systematic monitoring of these biological objects will make it possible to identify changes in the biocenoses of the background section of the Kakhovka Reservoir, located in the zone of influence of ZNPP wastewater. The state of populations of other biological objects is under the control of state monitoring. An extensive monitoring of the impact of ZNPP wastewater on the Kakhovka reservoir is carried out as part of the annual state monitoring.

5. 5. Recommendations for improving the ecological state of the cooling pond of the Zaporizhzhia nuclear power plant

In order to curb the mass development of hydrobionts that interfere with the operation of ZNPP underwater communications, it is necessary to maintain the number of ameliorative fish in the cooling pond at an optimal level. Adjustment of the number of fish should be carried out by annual stocking of the reservoir and periodic reclamation of fish. In the ZNPP cooling pond, it is expedient to carry out the annual introduction of the following fish species (thousand specimens) for the purpose of bioreclamation: carp – 13.6; silver carp – 91.8; white carp – 21.7.

Capture of older specimens of silver carp is one of the main conditions for the successful utilization of organic matter created by phytoplankton. If the older silver carp are not removed, they will die and release the accumulated biogenic elements back into the water body, which in turn will promote the development of algae.

With the number of mollusks *Melanoides tuberculata* and *Tarebia granifera* 160 ind/m^2 and 9 months (270 days) of the vegetative season, their annual production will be 41.78 g/m^2 of the soft part of the mollusk. Taking into account the indicators of natural fish mortality, the percentage of zoobenthos consumption (70 %) and the CP area (820 ha), the total number of black carp fish should be 37.5 thousand specimens. It is advisable to stock the reservoir with two-year-old grass carp with an average weight of at least 100–130 g. The use of this black carp aircraft for stocking is undesirable, since the cost of fish will increase significantly due to an increase in the percentage of natural mortality (almost doubled).

Since tilapia grows very rapidly in the conditions of warm waters of the ZNPP, it is recommended to carry out its reclamation capture when the weight of an individual reaches more than 300–350 g.

6. Discussion of existing and possible bio-hindrances in the circulating cooling system of the Zaporizhzhia nuclear power plant

The cooling pond is a man-made reservoir, the main function of which is the cooling of waste warm water. Therefore, an increased temperature regime is its characteristic feature and is provided for by technological conditions [33]. The results of the conducted studies indicate that in summer the water temperature in the ZNPP CP is 32–40 °C. For most hydrobionts, including fish (except for tilapia), this temperature is stressful. It is known that in the embryonic and postembryonic periods, high water temperature can cause various morphofunctional deviations in fish [34]. Therefore, the weak development of the ichthyofauna in the CP is a consequence of these disturbances. In this regard, temperature control should be an obligatory measure in the hydrobiological monitoring of CP. It should be relied upon when calculating the introduction of biomeliorator fish into the CP.

The abundance and biomass of bacterioplankton are important parameters of hydrobiological control in the CP and CCS channels. There is evidence that bacterioplankton can create bio-hindrances – biofilms on the water surface or on hydraulic structures [35]. In the ZNPP circulation system, the rapid development of bacterioplankton (up to 7.9 million cells/ml) and the formation of a biofilm were observed only in summer in certain sections of the bypass channels, which was caused by an increased temperature regime and the accumulation of organic matter (Fig. 2). With such a local distribution of bacterioplankton, it is sufficient to control its development in NPP CCS once a month in summer. But an increase in the concentration of organic substances in the CCS can provoke the development of bacteria and the formation of bio-hindrances. Therefore, hydrobiological monitoring involves the determination of BOD_5 and COD_5 indicators (Table 1) to control the content of organic substances.

Among the representatives of phytoplankton in CP, a potentially dangerous bio-hindrances creator is a species of blue-green algae – *Microcystis aeruginosa*, which caused the "bloom" of water in the coastal zones of the reservoir (Fig. 3). A similar picture in the ZNPP CP was noted earlier [36]. The low content of biogenic compounds (phosphorus) in the water of the CP hindered the mass reproduction of blue-green algae. However, the presence of microcystis in the species composition of phytoplankton requires control over its development. Determining the abundance and biomass of phytoplankton once a month, as provided for in hydrobiological monitoring, will allow to calculate the optimal landing of phytoplankton-eating fish (silver carp) in the CP, which will limit the development of blue-green algae. This will avoid the risk of bio-hindrances caused by phytoplankton.

In the group of zooplankton, there were no species capable of mass distribution in CP conditions. Zooplankton biomass indicators were very low (average 1.45±0.09 g/m^3). The main factor limiting the development of zooplankton in the CP is the high water temperature. Other researchers also note the low development of zooplankton in cooling ponds and its high sensitivity to temperature [37]. Changes in the species composition of zooplankton in the zone of influence of heated waters are also reported [38]. It is the fact of the high sensitivity of zooplankton to temperature that it is expedient to use in the hydrobiological monitoring of the background reservoir (Kakhovka reservoir) to assess the impact of warm waters of the ZNPP on the ecosystem of the reservoir.

Phytoperiphyton organisms, filamentous algae of the genera *Oedogonium sp*., were found on the walls of metal pipes of underground discharge channels. and *Ulotrix zonata*, which formed dense fouling and obstructed normal water flow. The high coefficient of species similarity between the phytoperiphyton groups of the ZNPP and the Kakhovka reservoir (0.92) indicates that the reservoir is a constant source of these algae entering the cooling pond. The implementation of hydrobiological control over the development of filamentous algae in the CP will make it possible to obtain data on their biomass and calculate the number of phytophage fish (grass carp) for introduction into the cooling pond. The grass carp is an active consumer of aquatic vegetation; it will restrain the development of algae in the CP, which will limit their further spread in the CCS.

An important object of hydrobiological monitoring in ZNPP CCS should be representatives of zooperiphyton – tropical mollusks *Melanoides tuberculata* and *Tarebia granifera*. The first data on the appearance of *Melanoides tuberculata* in ZNPP CCS appeared in 2015 [39]. And already in 2017, both species completely naturalized and created bio-hindrances [40]. The rapid reproduction and distribution of *M. tuberculata* and *T. granifera* is explained by their suitability for parthenogenetic reproduction [41]. Subsequent studies showed that on the CP, mass accumulations of mollusks are formed in the periphyton at a depth of 1 m, reaching a population of 367 ind/m^2 [42]. The probable reason for its entry into the CP is considered to be aquaristic.

In CSO channels, zooperiphyton groups require special attention, since it was their objects that caused bio-hindrances. On the walls of metal pipes, the abundance of *M. tuberculata* and *T. granifera* reached 5200 ind/m^2, which led to a decrease in the throughput of pipelines and required constant mechanical cleaning.

In the formation of bio-hindrances in the ZNPP CCS, *T. granifera* occupied the main place, and *M. tuberculata* played a secondary role. In samples of zooperiphyton, the abundance ratio between the two species was 3–4:1. An in-depth study of the biological characteristics of the two species revealed disagreements in the structure of their gill apparatus and digestive system, which allow *T. granifera* to better adapt to new living conditions compared to *M. tuberculata* [43].

A similar penetration and mass distribution of the mollusk *M. tuberculata* was noted in the software of the Pivdennoukrainsk NPP. But there, in contrast to the ZNP CCS, this mollusk did not form bio-hindrances in the cooling system, although its abundance in the CP reached 12.6 thousand ind/m^2 [6]. The results of the studies, as well as the literature data, confirm the fact that the creation of bio-hindrances in the ZNPP CCS is due to the aggressive distribution and adaptation of the mollusk *Tarebia granifera*. The data obtained make it possible to develop evidence-based recommendations for the introduction of mollusk-eating fish into the CCS to curb the development of dangerous species.

An analysis of the ichthyofauna of the cooling pond indicates that the fish species existing in the reservoir cannot be considered as effective consumers of mollusks and they are ineffective in combating biological obstacles. It is necessary to carry out the stocking of mollusk-eating fish in CP. The black carp is an active consumer of mollusks. Regarding the black carp, there is a report that it consumes about 19 grams of melania per day [44]. In contrast to the classical recommendations for stocking the cooling pond with phytomeliorators [45], additional stocking of the CP with black carp will allow controlling and limiting the growth of mollusk populations. With an annual stocking of 37.5 thousand specimens of grass carp in the UA, it will consume about 256.5 tons of mollusks per year. Thus, the stocking of UA with black carp will reduce the number of mollusks in the ZNPP circulation water cooling system from 342.5 tons to 86 tons per year and maintain their population at a safe level.

Higher aquatic plants –heliophytes – can also act as potential creators of bio-hindrances. The area of overgrowth of the ZNPP CP by heliophytes was insignificant – less than 5 % of the water surface area, but an increase in the area of overgrowth will reduce the cooling capacity of the CP. In addition, decaying plants degrade water quality and serve as a source of organic matter. Submerged plants can be transported to water intake areas and create biological obstacles. Air-water plants (reed, cattail, etc.) serve as a place of accumulation of mollusks and nesting of birds, which is undesirable for the ZNPP industrial ecosystem. In order to control the state of CS overgrowth by heliophytes in hydrobiological monitoring, it is planned to assess the number and phytomass of plants once a year at the end of the growing season (August–September). These indicators must be taken into account when calculating the introduction of an active phytophage, grass carp, into the CP. The estimated number of planting two-year-old grass carp in the CP is 14.8 thousand copies.

Thus, the conducted studies testify to the presence of active and potential samples of bio-hindrances in the composition of hydrobiocenoses of the ZNPP CCS. Existing methods of combating bio-hindrances do not provide their prevention and have low efficiency. The proposed regulations for hydrobiological monitoring will make it possible to control the development of populations of dangerous aquatic organisms, timely identify species that create bio-hindrances and develop appropriate recommendations for their elimination. The regulation includes four types of monitoring – current, extreme, deployed and background, each of which has its own goals and objectives. The systematic implementation of all types of monitoring will prevent any dangers associated with the mass development of aquatic organisms. Background monitoring will make it possible to control the ecological state of the biocenoses of the Kakhovka Reservoir (background reservoir) in the ZNPP warm water discharge zones. The developed hydrobiological monitoring is universal in nature and can be adapted to other energy facilities, taking into account the characteristics of their man-made water cooling systems.

7. Conclusions

1. According to the results of the hydroecological analysis of the cooling pond of the ZNPP circulation system in the summer period, there is an excess of fishery MPCs in terms of water temperature (by 6 °C), biological and chemical oxygen demand (BOD_5 – by 21 %; and COD_5 – by 64 %). Also, an excess of copper (1.6 MPC), manganese (1.8 MPC), zinc (4.2 MPC) and iron (1.7 MPC) was noted, which is associated with the technological features of the station.

2. In the study of plankton groups of biocenoses in CP and CCS channels, local development of bacterioplankton with a maximum abundance of 7.9 million cells/ml was revealed; the number of phytoplankton varied widely (13376–85724 million ind/m^3) with the dominance of blue-green algae, which caused the "bloom" of water; groups of zooplankton were few in number (30193–141580 ind/m^3) with minimal indicators at the points of discharge of heated waters. Mollusks of the Thiaridae family dominated in the benthos groups, the biomass of which varied widely from 0.54 to 20.09 g/m^2; filamentous algae *Oedogonium sp.* dominated in the composition of phytobenthos. and *Ulotrix zonata*, the biomass of which reached 123.6±18.44 g/m^2 in some parts of the CCS canals. The ichthyofauna of ZNPP CS was represented by native species (44 %) and alien species (56 %), among which 7 species were introduced for the purpose of bioreclamation; in the discharge and supply channels, the main ichthyomass was introduced tilapia.

3. The main groups of hydrobionts that create biological obstacles in the ZNPP cooling circulation system are filamentous algae *Oedogonium sp.*, *Ulotrix zonata* and molluscs Melanoides tuberculate and *Tarebia granifera* of the Thiaridae family. The shells of dead mollusks form drift material with the flow of water, which accumulates in the basins of the bioreclamation site and creates obstacles in the operation of pumping stations. The blue-green algae *Microcystis aeruginosa* is a potentially dangerous organism that causes water blooms in the CP.

4. The developed regime for monitoring the development of potentialbiological hindrances generators provides for four types of hydrobiological monitoring – current, extreme, extended and background to ensure control over the hydro-ecological state of ZNPP man-made water bodies and the background water body (Kakhovka reservoir) and prevent the risks of bio-hindrances.

5. Recommendations for improving the ecological state of the cooling pond provide for the introduction of biomeliorator fish with a different food spectrum (silver carp, grass carp, carp, black carp) into the pond to prevent the mass development of hydrobionts –potential creators of bio-hindrances.

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