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## Technoecosystem of the cooling pond of the South Ukrainian Nuclear Power Plant: group dynamics and transformation

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The results of long-term complex hydrobiological studies of the cooling pond of the South Ukrainian Nuclear Power Plant (SU NPP) are presented. The abundance of zoo- and phytoplankton increased until 1984–1985, and then in the summer of 1986, against a background of extremely high temperatures in the reservoir, there was a significant (32-fold) drop in the mean biomass of phytoplankton, coinciding with the minimum abundance of zooplankton. In subsequent years, the abundance of these groups recovered, but has not reached previous levels. At present, the zooplankton contains a considerable amount of thermophilic species. Research in recent years indicates that the zooperiphyton is dominated by the invasive gastropods *Melanooides tuberculata* (Müller, 1774) and *Terebia granifera* (Lamarck, 1822). In the epilithon, the number of LDT (lowest determined taxa) and groups of invertebrate was more than double that in the epiphyton (17 and 7, respectively). At the first stages of the development of the pond ecosystem, the periphyton communities were dominated by zebra mussel *Dreissena polymorpha* Pall. These communities were eliminated as temperature increased, and after the commissioning of the NPP, the second and third power units were not completely restored in the environment of a constantly high thermal load. Over years, with the formation of bottom biotopes, the abundance of zoobenthos increased, and with an increase in the technogenic load, it decreased. At the present stage, the zoobenthos is impoverished (9 taxa) and is dominated by mainly juvenile tubificids.

**Keywords:** technogenic succession, phytoplankton, zooplankton, zoobenthos, zooperiphyton, gastropods, invaders, river Southern Bug.

## Introduction

The phenomenon of ecological succession, a process of orderly and predictable changes in the structurally functional organization of a community, is characteristic of all ecosystems. However, for technoecosystems, anthropogenic effects are at least as important as natural processes. The effect depends on design features, the nature of operation of various water supply and water management systems of industrial facilities, power plants, etc. (Beznosov and Suzdaleva, 2005; Protasov et al., 2011). The hydrobiological regime of cooling ponds that are part of the technoecosystems of nuclear power plants and thermal power plants is influenced by such factors as changes in the hydrodynamic regime, the supply of additional heat, the influx of organic and inorganic substances with recharged water and the discharge of wastewater (Protasov and Silaeva, 2012; Protasov et al., 1991; 1994, 2011; Zdanowski and Protasov, 1998). In addition, processes related to climate change are currently of some importance. The abundant development of some aquatic organisms can cause biological hindrances in the operation of the technical systems of a power plant (Protasov et al., 2009).

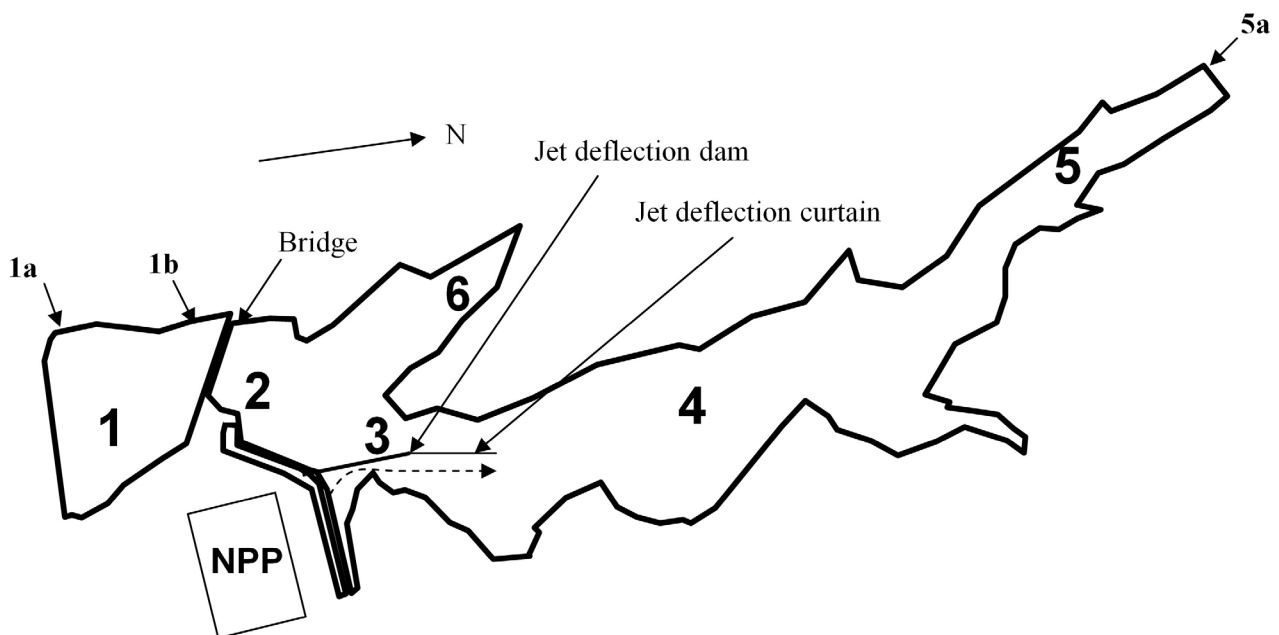
The purpose of this work is to establish the direction in the changes in a technoecosystem of the cooling pond of a nuclear power plant under conditions of technological succession.

## Materials and methods

The cooling pond (CP) of the SU NPP was constructed on the Tashlyk River (the left tributary of

the Southern Bug River, 35 km south of the city of Pervomaisk) by building a dam and filling it in 1979–1980 with the water of the Southern Bug River. At a normal retaining level, according to design data, the area of the reservoir is 8.6 km<sup>2</sup>, the volume is 86.0 million m<sup>3</sup>. The reservoir is of canyon type; the greatest depth (up to 46 m) is measured near the dam. In the central part of the reservoir and in the upper reaches, depths of 13–15 m prevail. To reduce wave abrasion, the shores are reinforced with a stone dump. Additional pumping of water is carried out from the Southern Bug River. Since 2004, continuous flushing of the CP has been carried out with the discharge of water into the Southern Bug River (water flow in this case is 0.5 m<sup>3</sup>/s). The station operates three power units with a capacity of 1000 MW each with VVR-1000 reactors, put into operation in 1982, 1985 and 1989. Cooling water is supplied through intake channels (IC). To drain the heated circulating water there is a short discharge channel (about 600 m). In 2017, a dam and a “thermal curtain” of about 500 m long, made of polymer material, were constructed near its exit. The curtain is suspended on pontoons from the water surface to the bottom directing the flow of heated water toward the head of the reservoir.

Hydrobiological studies at water bodies of the power complex of the SU NPP have been conducted more or less regularly since the early 1980s. The last sampling and observation was in July 2018. For the retrospective analysis we used our own, literary and archival materials (WaCo hydrobiological database of



**Fig. 1.** Scheme of the cooling pond of the South Ukrainian NPP: 1 – dam area, 2 – area of entry into intake channel, 3 – area of outlet of discharge channel behind thermal jet deflection curtain, 4 – middle part of cooling pond, 5 – upper part of cooling pond, 6 – corner of large bay. Dashed arrow indicates direction of heated water discharge.

the Hydrobiology Technical Group of the Institute of Hydrobiology of NASU).

In the pelagic part of the reservoir, samples of phyto- and zooplankton were taken over the entire water area (Fig. 1): phytoplankton from the surface horizon with a bathometer, zooplankton using the total fishing method of Apstein net (mesh size 80  $\mu\text{m}$ ) from a depth of 3 m to the water surface. At the time of sampling, we measured the water temperature and transparency using a Secchi disk. Zoobenthos sampling was carried out at the same stations at a depth of 6.0 to 8.0 m, as well as at coastal areas in the upper reaches (stations 5 and 5a) and in a large bay (station 6) at a depth of 0.6–1.1 m (Fig. 1). Soils in the South Ural NPP are currently represented by silted clay with a significant number of shells of the gastropods *Melanooides tuberculata* (Müller, 1774) and *Tarebia granifera* (Lamarck, 1822).

Zooperyphyton was studied on solid substrates (epilithon) on the stone enforcement structure of the dam (station 1a), the shore of the CP (1b), and near the exit of the discharge channel, as well as on the stalks of the southern reed *Phragmites australis* (Cav.) Trin. ex Steud, 1820 (epiphyton).

To determine the taxonomic composition, biomass, and abundance, generally accepted standard research methods were used (Arsan et al, 2006). When describing the taxonomic composition, the term “the lowest determined taxon” (LDT) was used, the designation of taxa of both species and higher rank, defined in accordance with the identification capabilities. The names and systematic affiliation of phytoplankton taxa are cited according to the Algae-base database ([www.algaebase.org](http://www.algaebase.org)). The number and biomass of epiphyton were calculated over the area of the plant substrate.

The similarity of taxonomic composition was evaluated by Sørensen and Smirnov coefficients (Pesenko, 1982). The Smirnov coefficient was also used to calculate the originality of the LDT composition ( $t_{xx}$ ). Coefficient of variation (CV) was used to assess the heterogeneity of the distribution of plankton and zoobenthos indicators over the water area (Plokhinsky, 1970). The species diversity (LDT diversity) was evaluated using the Shannon index (Pesenko, 1982).

The taxonomic diversity of hydrobiont groups (Protasov, 2002) was calculated by the LDT number in taxonomic groups using Shannon’s index.

## Results and discussion

During the research period in 2018, two nuclear power units were operating. Near the exit of the discharge channel, the temperature reached 41.2 °C, while in the rest of the water area it varied within 32.7–35.4 °C. Water temperature in the Southern Bug River in this period was 26.6–27.5 °C. Water transparency indicators ranged from 0.65 to 1.50 m. The minimum values were recorded from the “cold” side of the thermal curtain near the exit of the discharge channel, the maximum values were recorded near the dam.

Water in the CP was characterized by relatively high pH values; near the dam (station 1), this indicator varied from 8.63 at the surface to 8.42 at a depth of 30 m. In the rest of the water area in the surface layer, its value varied from 8.60 to 8.77, with the maximum at the upper reaches of CP (station 5).

The amount of dissolved oxygen in the dam area at a depth of 0.5 to 30.0 m was quite high: 7.20–7.68 mg O<sub>2</sub>/dm<sup>3</sup>.

A characteristic feature of CP of the SU NPP is a high content of sulfate ions in water (Table 1). For comparison, their content in the Zaporizhia NPP was about 70 mg/dm<sup>3</sup>, and in the Khmelnytsky NPP it reached 130 mg/dm<sup>3</sup> (2018, according to the ecological and chemical laboratories of the NPP).

High dry solids (Table 1) indicated high salinity. According to the data provided by the Ecological and Chemical Laboratory of the SU NPP, in terms of mineralization, the CP is borderline oligohaline to  $\beta$ -mesohaline brackish water basin, and in terms of the concentration of main ions it belongs to type II, sulfate class, and sodium group (S<sup>Na</sup><sub>II</sub>).

The content of nutrients (nitrogen and phosphorus) in the CP was relatively low (mesotrophic to eutrophic waters). The organic matter content in water (according to the indicators of permanganate oxidizability, PO) was also low, which corresponds to mesoeutrophic waters (Table 1).

In 2018, **the phytoplankton** of the CP included 52 LDT algae of five phyla. The richest phytoplank-

**Table 1.** Hydrochemical indicators in the cooling ponds of the South Ukrainian NPP, July 2018.

Station	pH	Sulfates, mg/dm <sup>3</sup>	Dry residue, mg/dm <sup>3</sup>	NH <sub>4</sub> <sup>+</sup> , mg N/dm <sup>3</sup>	NO <sub>2</sub> <sup>-</sup> , mg N/dm <sup>3</sup>	NO <sub>3</sub> <sup>-</sup> , mg N/dm <sup>3</sup>	PO <sub>4</sub> <sup>3-</sup> , mg P/dm <sup>3</sup>	PO, mg O <sub>2</sub> /dm <sup>3</sup>
1	8.63	350	1090	0.19	0.009	0.66	0.016	6.56
IC no. 1	8.75	354	1115	0.17	0.012	0.77	0.016	5.76
2	8.60	353	1089	0.18	0.009	0.62	0.023	7.52
4	8.67	353	1099	0.1	0.009	0.52	0.016	7.04
5	8.77	352	1084	0.1	0.009	0.54	0.016	7.52

ton occurred in the upper part, the least susceptible to heated discharges (Table 2). The floral spectrum was formed by green algae ( $59.15 \pm 0.88\%$ ), diatoms ( $18.05 \pm 1.85\%$ ), cyanobacteria ( $11.42 \pm 1.06\%$ ), charophytes ( $5.80 \pm 1.03\%$ ) and cryptophytes ( $5.58 \pm 0.66\%$ ). The composition of phytoplankton at individual stations was quite similar: the values of the Sørensen coefficient ranged from 0.50 to 0.85 (an average of  $0.68 \pm 0.01$ ). The taxonomic diversity was low ( $1.70 \pm 0.03$  bit/taxon) and did not change much over the water area of the reservoir (coefficient of variation  $CV = 3.83\%$ ). Relatively low values of taxonomic diversity of phytoplankton, associated, as a rule, with the pronounced dominance of one of the phyla in terms of the number of LDT, are a feature of cooling ponds (Novoselova and Protasov, 2015).

Quantitative indicators of phytoplankton were fairly evenly distributed over the water area of VO ( $CV_N = 35.13\%$ ,  $CV_B = 26.61\%$ ). The abundance level was determined mainly by cyanobacteria ( $58.38 \pm 6.05\%$  of the total) and green algae ( $31.70 \pm 4.68\%$ ). The cyanobacteria *Aphanocapsa incerta* (Lemmermann) G. Cronberg & Komárek, 1994 and *Merismopedia minima* G. Beck, 1897 dominated throughout the water area; at some stations, the dominant assemblage included the green alga *Binuclearia lauterbornii* (Schmidle) Proschkina-Lavrenko, 1966. At all studied

stations, the dominant biomass assemblage included *Cosmarium* sp. (Charophyta). In the upper reaches of the reservoir (station 5), near the dam (station 1) and in the large bay (station 6), *B. lauterbornii* joined the dominant assemblage. Also at some stations, *Nitzschia kuetzingiana* Hilse, 1863 (diatoms) and *Rhodomonas pusilla* (H. Bachmann) Javornicky, 1967 (cryptophytes) were among the dominants.

At most of the stations studied, the LDT diversity was quite high. At the entrance of the intake channel (station 2) and in the large bay (station 6), where *M. minima* constituted 63.9 and 57.5% of the total population, the Shannon index was slightly lower. The evenness indices testified to a fairly uniform distribution of LDT in the phytoplankton (Table 2).

**In the higher aquatic vegetation**, southern reed prevailed. Reed beds of this plant were noted along almost the entire perimeter of the reservoir, with the exception of the intake and discharge channels. In the dam area, individual clumps and strips up to one meter wide were found, in the rest of the water area, the strip width was 3–10 m. The overgrowing density varied from 68 to 220 stems per  $m^2$ , the average biomass in the reservoir was  $3.40 \pm 0.66$  kg/ $m^2$  with a maximum of 5.37 kg/ $m^2$  in the corner of a large bay. According to our observations, reeds have always dominated the associations of higher aquatic vege-

**Table 2.** Structural indicators of the pelagic ecological groups in the cooling pond of South Ukrainian NPP, July 2018.  $N_{Sp}$  – the number of species/LDT;  $H_{tax}$  – taxonomic diversity, bit/taxon; N – abundance, mln cells/ $dm^3$  (for phytoplankton), ind./ $m^3$  (zooplankton), ind./ $m^2$  (zoobenthos and zooperiphyton); B – biomass, mg/ $dm^3$  (for phytoplankton), mg/ $m^3$  (zooplankton), g/ $m^2$  (zoobenthos and zooperiphyton);  $H_N$  – abundance diversity, bit/ind.,  $H_B$  – biomass diversity, bit/mg (for phytoplankton and zooplankton), bit/g (zoobenthos and zooperiphyton); J/N – abundance evenness; J/B – biomass evenness.

Station no.	$N_{Sp}$	$H_{tax}$	N	B	$H_N$	$H_B$	J/N	J/B
Phytoplankton								
1	25	1.70	20.02	2.53	3.48	3.45	0.75	0.74
2	24	1.80	45.60	4.34	2.09	3.10	0.45	0.68
3	23	1.61	15.76	2.69	3.60	3.46	0.79	0.77
4	21	1.69	25.64	2.61	2.70	2.90	0.61	0.66
5	30	1.66	36.29	3.64	3.16	3.54	0.64	0.72
6	19	1.75	30.74	1.98	2.21	3.03	0.52	0.71
Zooplankton								
1	12	1.56	477841	3872.76	2.32	2.604	0.65	0.73
2	13	1.53	335957	2405.43	2.41	2.35	0.65	0.63
3	13	1.53	54130	520.52	2.44	2.78	0.66	0.75
4	11	1.57	310290	2988.29	2.32	2.07	0.67	0.6
5	12	1.56	701913	7246.79	2.48	2.15	0.69	0.6
6	10	1.30	159520	1023.64	0.64	0.3	0.19	0.09

tation in a given reservoir. This is probably due to the lack of shallow water zones, which are needed for the development of submerged taxa.

**Zooplankton** of the CP in 2018 was characterized by low richness, which is characteristic of cooling ponds with a high water temperature (Zhivotova, 2007). In total, 17 LDT of invertebrates were discovered in July 2018. Among them, eight LDT were rotifers, six were branched, and three were copepods. The taxonomic diversity was low ( $1.51 \pm 0.04$  bit/taxon) and did not change much over the water area of the reservoir (CV = 6.64%). The similarity of zooplankton in areas with different temperature regimes was high; the Sørensen index was 0.76–0.96.

On the whole, zooplankton was copepod-cladoceran dominated by individuals of the juvenile stages of copepods, as well as rotifers *Conochiloides deltaicus* Rudscu, 1960 and *Moina micrura* Kurz., 1875. The biomass was dominated by individuals of the juvenile stages copepods, the rotiforms *M. micrura*, ctenopods *Diaphanosoma dubium* Manuilova, 1964 and *D. orghidani* Negrea, 1982, and the copepod *Thermocyclops oithonoides* (Sars), 1863. The zooplankton abundance distribution, in contrast to composition, was less uniform across the water area ( $CV_N = 67.74\%$ ,  $CV_B = 80.30\%$ ).

The diversity and evenness indicators at most stations (Table 2) indicate a fairly uniform distribution of quantitative indicators in zooplankton groups. The exception was station 6 in the large bay, where low values of diversity and evenness reflect the overwhelming dominance of Copepoda (99.2% in numbers and 99.7% in biomass).

**Zoobenthos** of the CP showed extreme impoverishment of taxonomic composition. Only nine LDT of invertebrates from three groups were recorded: oligochaetes represented five LDT (four LDT of tubificids and *Dero* sp.), chironomid larvae – three LDT, and Ostracoda sp. were also recorded. Only juvenile tubificids (88%) and *Leptochironomus tener* (Kieffer, 1918) (75%) were characterized by high levels occurrence. Ostracodes were registered only in the upper reaches, however, in other areas, their carapaces were observed, according to a visual assessment, belonging to recently dead individuals. Probably, organisms of this group are reduced during the hottest summer period and resume their numbers during the fall – spring. The similarity of the taxonomic composition of zoobenthos (Sørensen index) in the stations of the CP main water area was quite high (up to 0.8), with the exception of coastal areas.

Quantitative parameters of zoobenthos were low: the abundance was on the order of a thousand ind./m<sup>2</sup>, and the biomass was on the order of g/m<sup>2</sup> (Table 3). In terms of abundance and biomass, juvenile tubificids predominated in almost the entire water area (to a lesser extent in the upper reaches).

Abundance indices were distributed fairly evenly across the CP water area (CV values were 32%), biomass was more mosaic (55%). Mature individuals of the tubificid *Limnodrilus claparedeanus* Ratzel, 1868 and *L. hoffmaisteri* Claparède, 1862 were noted, this confirms the observations (Karataev, 1990) that these species are resistant to high temperatures. Among the chironomid larvae, *L. tener* was the most tolerant to the raised temperature, and was found not only in the upper reaches, but also in the central area and near the dam, where even bottom water layers were considerably heated. In the area with the maximum near-bottom temperature in the reservoir, on the heated side of the “thermal curtain” (36 °C, depth 8 m), only *L. claparedeanus* and juvenile tubificids were recorded in the zoobenthos; abundance indices amounted to 4400 ind./m<sup>2</sup> and 2.24 g/m<sup>2</sup> with tubificids dominating the assemblage.

Thus, the zoobenthos of the CP of the SU NPP has currently a very low total biomass and is average in number of specimens (in accordance with the grades proposed by O.P. Oksiyuk with co-authors (2006)). The taxonomic composition is impoverished, at least during the hottest summer period. This state of invertebrate zoobenthos can be relatively stable over time and is characteristic of cooling ponds with significant technogenic load, in particular, thermal, which in Ukraine are cooling ponds of SU NPP and Zaporizhia NPP (Protasov et al., 2013).

A distinctive feature of the **zooperiphyton** of CP of the SU NPP in 2018 was the presence of massive populations of the invasive tropical gastropod mollusk species *Melanoides tuberculata* and *Terebia granifera* in single-species and joint colonies (Fig. 2).

In the epilithon, the number of LDT and invertebrate groups was more than double that in epiphyton (17 and 7, respectively). At individual stations, the amount of LDT ranged from 2 to 8. The richest epilithon was in the upper reaches of the CP (station 5a).

The abundance of epilithon was in the range 333–16795 ind./m<sup>2</sup>, the total biomass was 0.001–1880.37 g/m<sup>2</sup>, and without mollusks, it was 0.001–3.36 g/m<sup>2</sup> (Table 3). Settlements of gastropod mollusks with significant abundance indices: 10217–16795 ind./m<sup>2</sup> and 1739.39–1880.7 g/m<sup>2</sup> were recorded on a stone dump along the perimeter of the CP and on the dam.

In the zone of the highest temperatures (41.2 °C), invertebrates were not found in samples of periphyton from rocks; filamentous cyanobacteria with a biomass of 62.9 g/m<sup>2</sup> are recorded from here.

At the dam, the total abundance ranged from 333 to 10217 ind./m<sup>2</sup>, biomass from 0.46 to 24.09 g/m<sup>2</sup>, the proportion of mollusks in the groups was dominant. Outside the mollusk populations, in the areas encrusted with filamentous algae (depth up to 3 m), invertebrates of the epilithon were represented only

**Table 3.** Structural indicators of the contour groupings in the cooling pond of the South Ukrainian NPP, July 2018. h – depth, m; JDD – jet deflecting dam (Fig. 1). Other explanations are in Table 2. \*Colony of mollusks with 90% substrate coverage.

Station no.	h	N <sub>Sp</sub>	H <sub>tax</sub>	N	B	H <sub>N</sub>	H <sub>B</sub>	J/N	J/B
Zoobenthos									
1	7.3	4	0.81	5200	2.66	1.38	1.41	0.69	0.70
2	6.0	3	0	5100	5.02	0.56	1.14	0.35	0.71
3	8.0	2	0	4400	2.24	0.44	0.59	0.43	0.59
4	7.0	4	0.81	2000	0.90	1.52	1.29	0.75	0.64
5	0.7	7	1.59	4602	3.84	2.25	2.13	0.80	0.75
5a	7,0	3	0.99	2300	0.61	1.34	1.15	0.84	0.72
Epilition									
	0.3	8	1.75	10217	24.09	1.92	0.99	0.64	0.33
Dam (1a)	0.5	4	1.50	1528	0.46	1.28	0.63	0.63	0.31
	3.0	2	0	333	0.001	1.00	1.00	1.00	1.00
	4.0	4	1.50	16795	1880.37	0.37	0.16	0.18	0.08
Shore filling (1b)	0	2	1.00	11905	1739.39	0.14	0.00	0.14	0.00
	0.15	3	0.92	21333	283.57	0.34	0.20	0.21	0.12
	0.15*	3	0.92	51833	5837.49	0.36	0.41	0.22	0.26
JDD	0	3	0.92	2037	0.64	1.24	1.39	0.78	0.87
5	0.1	6	1.79	2051	3.44	1.62	0.13	0.62	0.05
5a	0.15	12	1.95	5183	3.22	3.52	2.34	0.92	0.61
Epiphyton									
1b	0.5	2	1	696	13.35	0.34	0.00	0.33	0.00
6	0.35	3	0.92	428	0.004	1.50	1.33	0.94	0.83
5	0.4	4	0.81	193	0.001	1.92	0.96	0.95	0.48
5a	0.8	4	0.81	694	0.003	1.42	1.62	0.70	0.80

by two species of oligochaetes Naididae: *Pristina aequiseta* Bourne, 1891 and *P. longiseta* Ehrenberg, 1828, with minimal abundance indices.

The populations of *M. tuberculata* and *T. granifera* were represented by variously-sized individuals, which may indicate the naturalization of species in the CP, while *T. granifera* significantly prevailed in the two-species populations in terms of abundance.

At the dam (station 1a) at shallow depths, monospecific populations of *M. tuberculata* were found, the size composition of which is represented by two groups: 1–5 and 6–10 mm, with the predominance of the former (96%). At a depth of 4 m, two-species populations were found where individuals of *M. tu-*

*berculata* were recorded in six size groups: from 1–5 mm to 26–30 mm, with dominance of groups of 6–10 mm (39%) and 16–20 mm in size (29%). The maximum height of *M. tuberculata* shell reached 27 mm, the minimum – 2 mm. At the same depth, individuals of *T. granifera* are represented by three groups: from 1–5 mm to 11–15 mm, while groups of 6–10 and 11–15 mm in size (38% each) dominated; the maximum height of the shell was 13 mm, the minimum was 4 mm.

On a stone dump at the coast (station 1b), both mono- and bispecific populations of gastropod mollusks were found in the epilition. In the monospecific populations of *M. tuberculata*, the morphometric pa-



**Fig. 2.** Mollusks *Melanoides tuberculata* (left) and *Tarebia granifera* (right) from the South Ukrainian NPP cooling pond, July 2018.

parameters of the population were similar to those at the dam: individuals of size groups 6–10 mm (29%) and 11–15 mm (33.7%) dominated, the maximum height of the shell reached 28 mm, the minimum size was 2 mm (Fig. 3). In bispecific populations, the *M. tuberculata* population was represented by small-sized individuals (up to 6 mm), and the *T. granifera* population – by groups from 2–5 to 11–12 mm, with the dominant prevalence of small-sized individuals (the proportion of mollusks with a shell height of 2–3 mm was 73 %). In bispecific mass populations with 90% mollusk coverage of the substrate, the proportions of size groups of *T. granifera* (from 1–5 mm to 21–25 mm) were distributed relatively evenly.

The **epiphyton** CP (on the reeds) contained seven LDT of invertebrates from four groups (Nematoda, Oligochaeta, Chironomidae, Gastropoda). At individual stations, 2–3 LDT from two groups. The abundance of epiphyton was very low, significantly lower than that of epilithon. The abundance ranged from 193 to 696 ind./m<sup>2</sup>, biomass from 0.001 to 0.004 g/m<sup>2</sup>, including gastropods – up to 13.35 g/m<sup>2</sup>. In most of the stations, epiphyton was dominated by abundance indices of oligochaete Naididae (*P. aequiseta*, *P. longiseta*, *Nais pardalis* Piguët, 1906, *N. communis* Piguët, 1906). In the upper reaches, nematodes dominated in numbers (67%). In the coastal areas (station 1b), the structure of the epiphyton was different: the mollusk *T. granifera* dominated in numbers (94% of the total) and biomass (99%) resulting in a high biomass. The mollusk population here was represented by small-sized indi-

viduals of groups 1–5 and 6–10 mm, with the former dominating (67%). The maximum height of the shell reached 8 mm, the minimum was 1 mm.

Thus, at present, CP is characterized by a rather intense thermal regime and a rather impoverished composition of groups, especially contour ones. However, over the period of its existence, the ecosystem has gone through several stages of transformation.

### **Long-term group dynamics**

At the initial stages of research, an increase in the biomass of **phytoplankton** was recorded against a background of an increase in the power of the power plant (Fig. 4). In the summer of 1985, the recorded maximum level of indicators (mean 9.6 mg/dm<sup>3</sup>) was associated with the abundant reproduction of the diatom *Aulacoseira granulata* (Ehrenberg) Simonsen, 1979 during the entire observation period. In 1986, an increase in the mean annual air temperature by 2 °C relative to the previous year was recorded at the NPP site (Aleksienko et al., 2017). Moreover, following the accident at the Chernobyl nuclear power plant and its shutdown, in the summer months, the SU NPP was operating at full capacity. Together, these factors influenced the temperature increase not only in the area of the exit of the discharge channel, but throughout the water body. During this period, the minimum biomass of phytoplankton was recorded (on average 0.3 mg/dm<sup>3</sup>). Over the next ten years, the abundance increased, but the range of fluctuations in the summer biomass of phytoplankton did not go beyond the previously recorded values. In 2018, the abundance was low relative to the entire studied period. Thus, for phytoplankton, the general trend can be described as a decrease in the quantitative parameters.

The taxonomic richness of **zooplankton** was low throughout the entire observation period (1981–2018), numbering from 13 to 28 LDT in different years (Aleksienko et al., 2017; Protasov et al., 2018; Sergeeva et al., 1988). Significant changes in the species composition did not occur until the beginning of the 1990s. Noticeable changes were recorded in 1997, when the similarity of zooplankton composition with previous studies (1990–1992) in the Sørensen index was 0.43. However, by 2018, the composition of zooplankton had almost completely changed: only one species in common with previous studies has been found, the rotifer *Brachionus calyciflorus* Pallas, 1776. Changes were also recorded in the dominant assemblage. At the stage of the initial filling and at the first stages of the development of the reservoir (1981–1983) under natural temperature conditions, zooplankton was represented by a copepod-cladoceran assemblage with the dominant role of *Eudiaptomus gracilis* (Sars, 1863), *Daphnia longispina* (Müller, 1776) or *D. cucullata* Sars, 1862. With the increase in water temperature and the formation of

technogenic circulations associated with the commissioning of the first power unit of the NPP, the dominant species changed to the more thermophilic species *Diaphanosoma brachyurum* (Lievin, 1848) (Sergeeva et al., 1988). In the modern period of significant development, thermophilic species with a predominantly southern distribution increased their abundance. These are *M. micrura*, *D. dubium*, *D. orghidani*, *Keratella tropica* (Apstein, 1907) (Aleksienko et al., 2017; Protasov et al., 2018). The quantitative development of zooplankton reached its greatest development after the opening of the nuclear power plants in 1984, when the biomass averaged  $5.7 \text{ g/m}^3$  (with a maxi-

imum value of  $11.5 \text{ g/m}^3$  at one of the stations). In subsequent years of research, biomass on average varied between  $0.5\text{--}2.7 \text{ g/m}^3$  (Fig. 5).

The dynamics of **zoobenthos** was also associated with the nature and mode of operation of nuclear power plants and climatic factors. In the first year of filling of the CP (1980), a sharp change in the conditions of existence (transition from a small river to a reservoir, absence of formed bottom sediments) led to a significant decrease in the richness of invertebrates, the number of zoobenthos groups decreased from 14 (in the Tashlyk River) to 2 in the CP (oligochaetes and larvae of one chironomid



Fig. 3. Dimensional structure of the *Melanoides tuberculata* population, epilithon, station 1b, July 2018.

species (*Procladius ferrugineus* Kieffer, 1919)). By 1983–1984 hydras, nematodes, amphipods and cumacean crustaceans, larvae of dragonflies, mayflies, caddis flies and midges (upper reaches) were recorded in the reservoir, and zebra mussel was found everywhere. In 1986, 48 LDT from 15 groups were recorded in zoobenthos. After a significant summer temperature increase in 1986, the species composition of zoobenthos sharply decreased (7 LDT in 1988, to 11–13 LDT in 1990–1997). After elimination of zebra mussel (not recorded in 1988), this mollusk was observed locally in 1989–1992, but since 1997 it has completely disappeared.

As the formation of CP and the formation of zoobenthos, its abundance indicators increased (Fig. 6). So, in 1980, the abundance and biomass at the dam site were only 90 ind./m<sup>2</sup> and 0.21 g/m<sup>2</sup>, and in 1981 already 7900 and 1.4, respectively. In 1983–1984 abundance ranged from 1785 to 8013 ind./m<sup>2</sup>, the biomass of “soft” zoobenthos – 0.77–2.1 g/m<sup>2</sup>, including mollusks – up to 150.87 g/m<sup>2</sup>. In the upper reaches, the main part of the “soft” zoobenthos was composed of chironomid larvae, in the central areas, chironomid larvae and oligochaetes, dominated by biomass of zebra mussel. At the discharge site in 1984–1985 oligochaetes developed in mass (up to 34929 ind./m<sup>2</sup>), and the biomass of zebra mussel reached 339.82 g/m<sup>2</sup>. In the summer of 1986, the abundance indicators decreased significantly (in shallow water, biomass decreased by more than 1000 times), and only in the upper reaches the biomass reached 139.62 g/m<sup>2</sup>. By the fall of 1987, abundance indicators remained at a low level,

although in some areas the process of zoobenthos recovery began. In 1988, its groups were represented only by chironomid larvae and oligochaetes; abundance was 1160–2120 ind./m<sup>2</sup>, biomass was 0.60–1.39 g/m<sup>2</sup>. In 1989–1992 zoobenthos CP was mainly composed of chironomid larvae and tubificids, only by 1992 locally in the central areas zebra mussel was noted (1.14 g/m<sup>2</sup>, 82% of the total biomass). In the discharge area, *Dreissena* dominated both in abundance and biomass.

In August 1997, the zoobenthos CP of the SU NPP was extremely depleted: a total of 15 LDT from six groups were registered with the predominance of chironomid and oligochaete larvae (five LDT each); the remaining groups were represented by one taxon, mollusks were not registered. In the intake channel, the hydroid polyp *Cordilophora caspia* Pallas, 1771, probably immigrating from periphyton populations, was recorded. At individual stations, the number of taxa ranged from one to six. The zoobenthos was the richest in the upper reaches of the CP (nine LDT from two groups): chironomid larvae were represented by five LDT (found only here) and oligochaetes by four LDT, which explains the significant originality of the taxonomic composition of zoobenthos of this section ( $t_{xx} = 186$ ).

The abundance of zoobenthos was low, especially its biomass, and varied significantly in different parts of the reservoir: abundance ranged from 100 to 25600 ind./m<sup>2</sup>, biomass from 0.01 to 4.37 g/m<sup>2</sup>. The maximum biomass was recorded in the upper reaches on silty gravel with plant debris of *Chironomus plumosus* L., 1758 (64% of the total) dominated by biomass, and oligochaetes of the family Naididae dominated in numbers (56%).

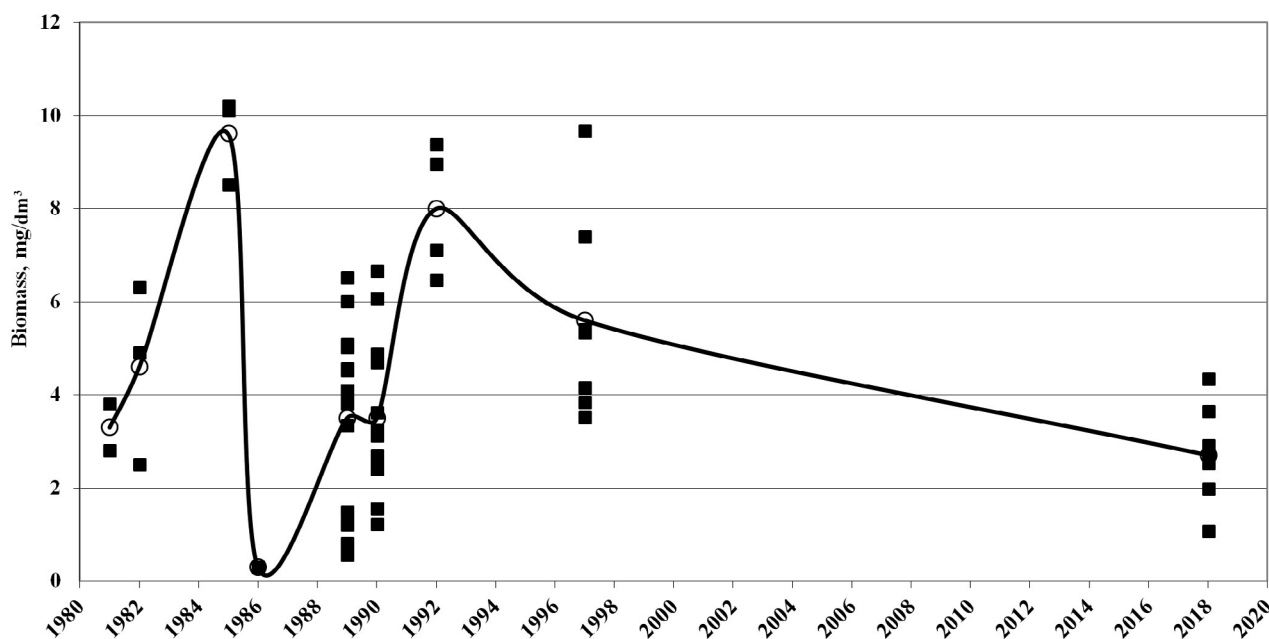


Fig. 4. Phytoplankton biomass changes during summer period 1981–2018, in the South Ukrainian NPP cooling pond. Squares show individual stations, circles show mean level of biomass throughout the pond.

In the summer season of 2006, zoobenthos numbered 17 LDT: Hydrozoa, Nematoda, Hydracarina, *Ecnomus tenellus* caddis fly (Rambur, 1842), *M. tuberculata* gastropod. Oligochaetes were represented by eight LDT, and chironomid larvae by four LDT.

Mean quantitative indicators for CP were 12180 ind./m<sup>2</sup> and 358.06 g/m<sup>2</sup>, the bulk of the biomass (up to 99%) was represented by *M. tuberculata* found in the middle and dam areas. It should be noted that such biomass values are close to the level of 1986. The abundance of “soft” benthos was low, on average 7220 ind./m<sup>2</sup> and 2.07 g/m<sup>2</sup>.

Thus, results of the previous studies document a depletion of the taxonomic composition of zoobenthos in the CP of the SU NPP. It should be noted that V.R. Aleksienko et al. (2017) showed that in different seasons in the period 2003–2010 the total number of LDT reached 35. It is likely that in the fall and spring some renewal of invertebrate groups may occur due to organisms with a short life cycle or secondarily aquatic organisms.

In the **zooperiphyton**, prior to the start of the operation of the reservoir as a cooling pond (1983), the dominance of zebra mussel in periphyton communities was up to 60% in number and 93% in biomass (Protasov and Silaeva, 2012). About 20 LDT from nine groups were noted in periphyton, five species of oligochaetes, larvae of chironomids, caddis flies and mayflies, gammarids, hydras, and sponges. The average number of invertebrates reached 20200 ind./m<sup>2</sup>, and biomass 1850 g/m<sup>2</sup> (Fig. 7). The diversity calculated by abun-

dance, due to a fairly high evenness, was 2.229 bit/ind.; the diversity in biomass was low – 0.396 bit/g. A fairly typical community with the dominance of zebra mussel, characteristic of reservoirs, has formed in the reservoir. Although, it was formed from organisms that immigrated from the Southern Bug River, there were no organisms typical of the river, such as gastropods *Theodoxus fluviatilis* (Linnaeus, 1758) and *Fagotia esperi* (Ferussac, 1823) in the cooling pond.

In 1984, 1985, and in the spring of 1986, the general picture of the distribution and macrostructure of periphyton remained practically unchanged. Oligochaetes, chironomid larvae and caddis flies lived in large numbers among filamentous algae. At a depth of more than 2 m, the zebra mussel community was dominant in all biotopes. The abundance of invertebrates at the dam and in the discharge area (depth of about 3 m) was similar: 64880 and 51650 ind./m<sup>2</sup>, 3850 and 4540 g/m<sup>2</sup>, respectively.

At the initial stage of the technoecosystem of the SU NPP with a relatively low degree of exposure to anthropogenic factors, the structure of periphyton was quite uniform and stable. This structure was preserved until the beginning of summer 1985. During this period, the water temperature in the discharge area was 34 °C, and the periphyton structure began to acquire features typical for areas with maximum heating in other cooling ponds. In the discharge area, zebra mussel was not found to a depth of 3 m, and only at a depth of 5 m its populations in the form of druses occupy up to 80% of the substrate.

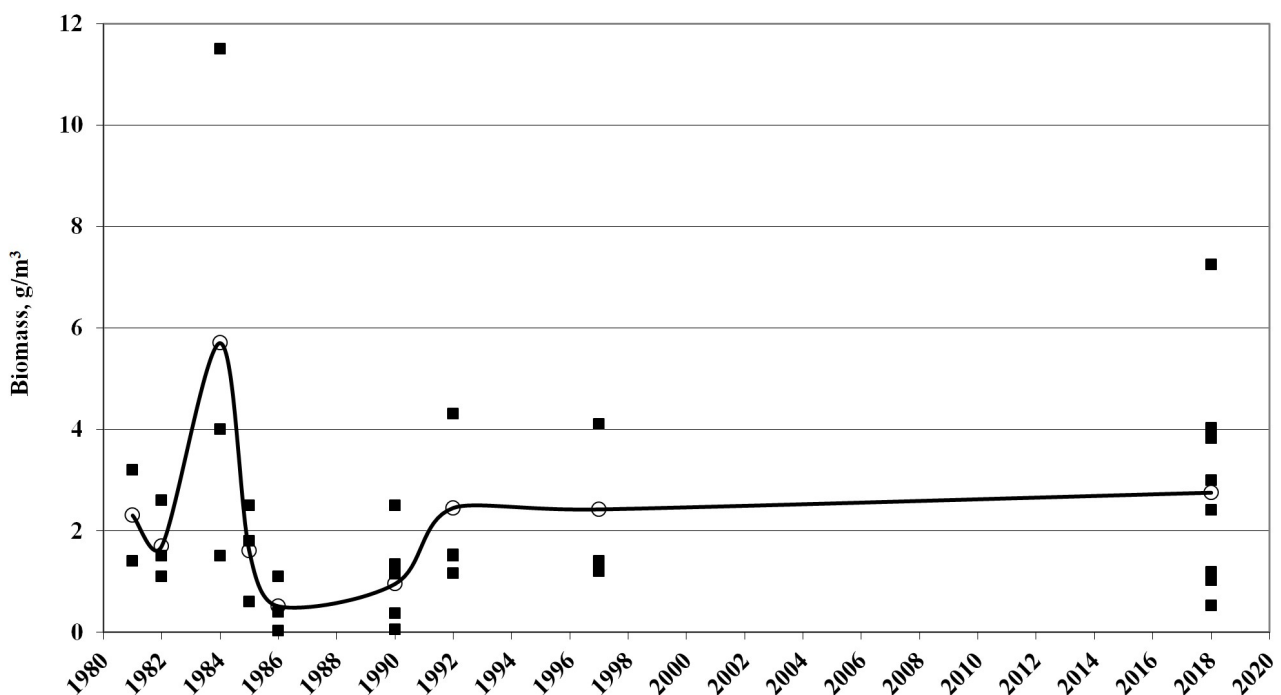
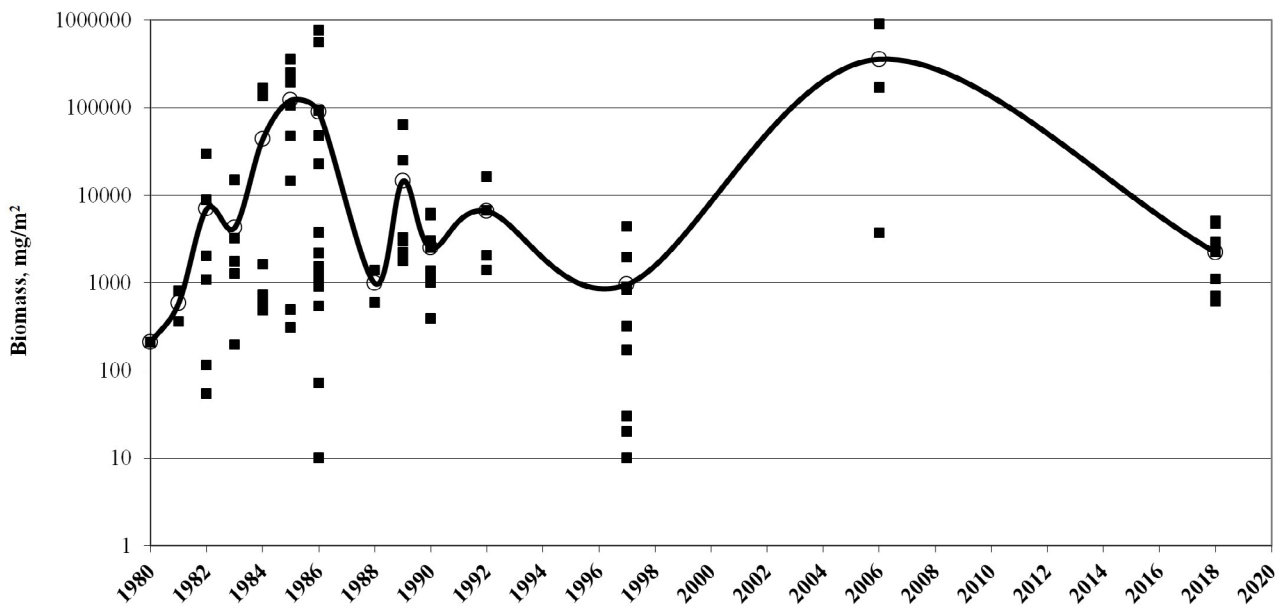


Fig. 5. Zooplankton biomass changes during summer period 1981–2018, in the South Ukrainian NPP cooling pond. Squares show individual stations; circles show average level of biomass throughout the pond.



**Fig. 6.** Zoobenthos biomass changes during the summer period 1981–2018, in the South Ukrainian NPP cooling pond. Squares show individual stations, circles show average level of biomass throughout the pond.

The abundance of the zebra mussel community, which occupied rocky substrates on the dam, in the deep water part of the reinforcement area near the discharge, near the shore reinforcements, differed from that recorded in 1984: the biomass was half ( $1700 \text{ g/m}^2$ ), and the population density was about  $20000 \text{ ind./m}^2$ . Thus, the strong influence of heated wastewater on the periphyton was quite local and spread to a shallow depth.

In the summer of 1986, the thermal regime in the cooling pond was extreme. As the water temperature at the discharge raised to  $40 \text{ }^\circ\text{C}$  and higher, the communities experienced catastrophic changes, e.g., mass die-off of zebra mussel up to a depth of 6–7 m, where only individual living examples were recorded at a temperature of  $34 \text{ }^\circ\text{C}$ . The biomass of filamentous cyanobacteria exceeded  $500 \text{ g/m}^2$ , but only six invertebrate LDT (oligochaetes and crustaceans) were recorded. The oligochaete *Prigina aequisetata*, characteristic of the highest temperature zones, were observed at shallow depth at a temperature of  $40 \text{ }^\circ\text{C}$ , with the greatest abundance of about  $800 \text{ ind./m}^2$ , but deeper (at a temperature of  $39 \text{ }^\circ\text{C}$ ) their number increased to 100 thousands  $\text{ind./m}^2$ . On the dam, the *Dreissena* populations also died off. By the autumn of 1986, the zebra mussel community, so vast in previous years, was virtually eliminated.

Later, the community to some extent recovered. In the summer of 1988, the general structure of communities dominated by zebra mussel was quite similar to the one that existed earlier. The water temperature in the upper layers at the discharge reached  $33 \text{ }^\circ\text{C}$ , in the deep horizons at a temperature of  $30 \text{ }^\circ\text{C}$  and

below, the coating of the substrate with zebra mussel reached 80–100%. In 1989 and 1990 the periphyton community structure also continued to recover, however, in summer, at high temperature, the zebra mussel was again eliminated to a depth of 6–8 m. The community size in these years was  $3600 \text{ ind./m}^2$ , and the biomass was only  $0.45 \text{ g/m}^2$ , with ostracodes dominating in number and biomass. Only six invertebrate LDTs were reported. In the summer of 1997, studies showed that the zooperiphyton remained qualitatively impoverished. Only three LDTs were recorded in the intake channel, five at the discharge of the heated water, and 17 in the cooler area.

The abundance of zooperiphyton was extremely low: in the intake channel, the number reached  $2700 \text{ ind./m}^2$ , biomass  $0.05 \text{ g/m}^2$ . In the discharge area at a depth of 2.5 m, the biomass reached  $1.17 \text{ g/m}^2$  mainly due to large tubificids, but in other microhabitats (near-surface zone, the sides of the stones at a depth of 0.5 m), it amounted to only  $0.03\text{--}0.15 \text{ g/m}^2$ . On the dam at a water temperature of  $32 \text{ }^\circ\text{C}$  on the upper sides of the stones with 100% coverage by filamentous cyanobacteria, only two invertebrate LDT were recorded, with a population density of  $4500 \text{ ind./m}^2$ , and the biomass  $0.03 \text{ g/m}^2$ . At a depth of 2.5 m, three LDT were recorded; biomass was  $0.08 \text{ g/m}^2$ , biomass indicators were also low at a depth of 6–7 m  $0.02 \text{ g/m}^2$  with Ostracoda dominating.

Studies conducted in 2005 (Volikov et al., 2006) showed that the composition of periphyton continued to be impoverished: 17 LDTs were recorded (from 2 to 6 at individual stations). Oligochaetes and chironomid larvae were represented by five species each.

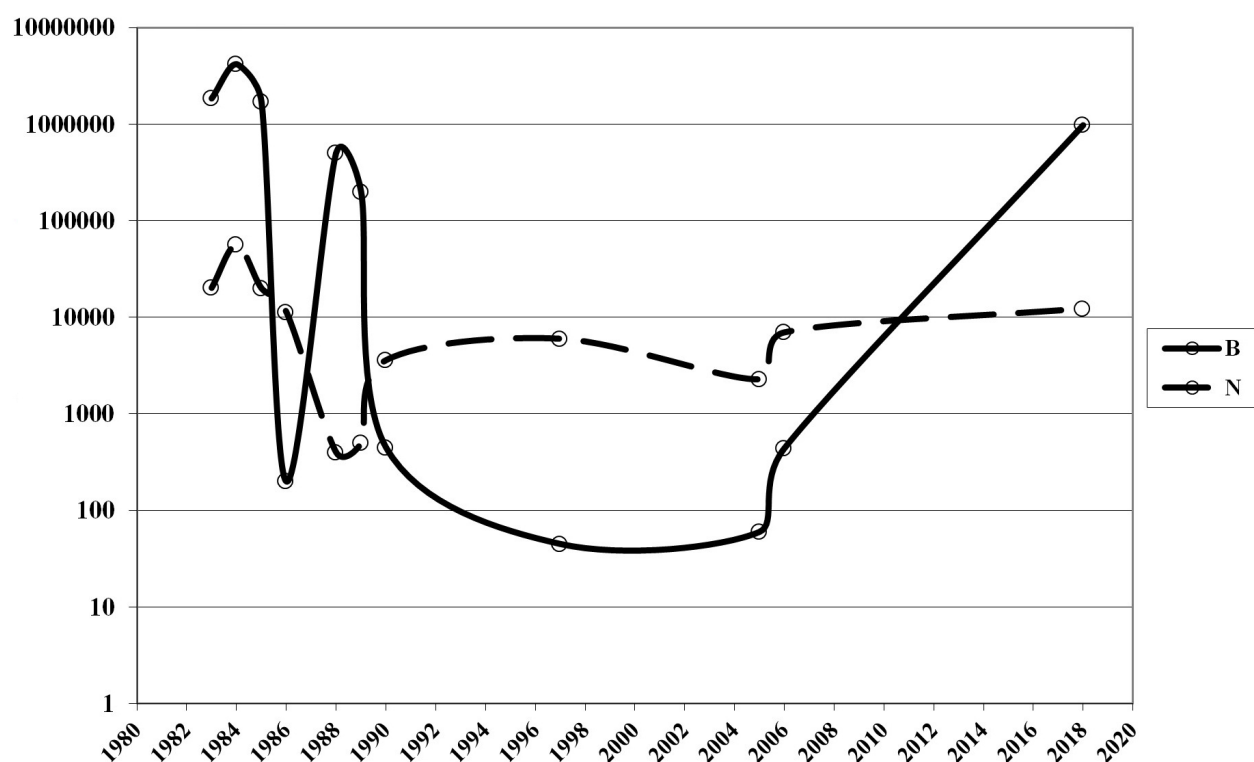


Рис. 7. Quantitative indicators of zooperiphyton of the South Ukrainian NPP cooling pond in different years of research. N – abundance, ind./m<sup>2</sup>, B – biomass, mg/m<sup>2</sup>.

The abundance was low, the population density was 9800 ind./m<sup>2</sup> (in the upper reaches of the reservoir), the maximum biomass was up to 1.85 g/m<sup>2</sup> (in the middle part of the CP). At the dam, biomass values were among the lowest (0.26 g/m<sup>2</sup>). The average biomass for the reservoir was 0.54 g/m<sup>2</sup>.

In 2006, the diversity and richness of the periphyton slightly increased, with 21 LDTs recorded. Oligochaetes were represented by nine species, chironomid larvae by six. Of crustaceans, two species of gammarids, corophiids, and mysids were recorded, of gastropods – only one species, *M. tuberculata*. The abundance at individual stations varied from 3230 to 10760 ind./m<sup>2</sup> and from 0.05 to 8.14 g/m<sup>2</sup>. The increase in biomass compared to the previous year was mainly due to oligochaetes, chironomid larvae, and gastropod mollusks in the middle part of the reservoir (Volikov et al., 2007). In 2018, as already indicated, the periphyton communities were dominated by invasive Gastropoda.

## Conclusions

As noted above, in the summer of 2018, an extremely high temperature of about 40 °C was observed near the discharge channel. Under these conditions, only occasional specimens of oligochaetes were recorded in the periphyton. According to the available data (Protasov and Silaeva, 2012; Protasov et al., 1991), quite stable and vast communities are formed in the zones of maximum temperatures in

cooling ponds. For example, in the Chernobyl reservoir in the discharge channel, where in summer the temperature reached 37–39 °C, quite abundant communities developed in the summer period with dominance of the bryozoan *Plumatella emarginata* Allman, 1844. The *Plumatella emarginata* + *Aelosoma hempi-chi* community (recognized based on the dominance of the index taxa) was established near the discharge of circulation water in the pond of the Krivoi Rog Power Plant. Here, at temperatures up to 33 °C, 10–12 species of invertebrates were found; the biomass was 2–40 g/m<sup>2</sup>. In 1986, at a temperature of 40 °C, oligochaetes were found in filamentous cyanobacteria in the cooler pond of the SU NPP. With a decrease in temperature of only one degree, their numbers increased. Thus, the zone of the highest temperatures is by no means lifeless. It is possible that with a more stable regime, a richer community of thermophiles could have formed here.

In technoecosystems, high temperature (33–36 °C) in bottom assemblages is rather rarely recorded and is observed for only a short time (during the hottest period of summer), most often in local areas. According to the results of our long-term studies, high temperatures lead to extreme depletion of the taxonomic composition of zoobenthos, only juvenile tubificids are often observed in such areas, and abundance indicators vary considerably, from minimal to quite high.

The maximum temperature zone in the cooling ponds is localized directly in the discharge channel and in a small area around the exit of the discharge channel. Pelagic groups are not tied to these biotopes for hydrodynamic reasons, namely, homogenization by anthropogenic flow. At the same time, contour groups in areas subject to maximum heating form unique communities. Thus, it was found that in the cooling ponds of TPPs and NPPs of Ukraine in the maximum temperature zones the same type of phytoperiphyton communities are formed, which belong to the *Lyngbyo putealis* – *Oscillatorietum brevis* association (Shevchenko, 2012). A characteristic feature of this association is the presence of thermophilic species of cyanobacteria among the diagnostic taxa.

The ecosystem of the reservoir-cooler as part of the water technoecosystem of the NPP has passed certain stages over the decades of its existence. Considering the development of such technoecosystems from the point of view of environmental risk analysis (Rosenberg et al., 2019), they should be assigned to the group of systems with an extremely high level of environmental risk. If, following these authors, we assume that the degree of environmental risk is inversely proportional to the likelihood of a climax state, then it is evident that risk assessment tends to the maximum, since it is unlikely that the ecosystem will reach climax (in the classical sense). It will be more accurate to say that a certain more or less stationary state (pseudoclimax) is determined not so much by the combination of climatic conditions, but by a complex of technogenic factors. The state of the technogenic pseudoclimax can remain for a sufficiently long time, while the technical conditions are relatively stable; in this case, the stable operation of three nuclear power units, with constant pumping and purging of the reservoir. At the same time, one should not lose sight of the fact that technogenic factors are superimposed on changing climatic conditions.

According to the initial design, this CP was supposed to be included in the power complex and connected with a pumped storage power plant (PSPP), performing, in fact, the functions of both a cooler and a reservoir at the PSPP. However, the abandonment of such a scheme after the accident at the Chernobyl nuclear power plant led to the fact that with a relatively small cooling surface CP, its temperature in the summer period increased significantly with the introduction of the second and third power units. Already in 1986, a radical restructuring of the CP ecosystem began. There was a sharp decrease in the average biomass of phytoplankton (32 times): from 9.6 mg/dm<sup>3</sup> in the summer of 1985 to 0.3 mg/dm<sup>3</sup> in the same period in 1986. The minimum average biomass of zooplankton (0.51 g/m<sup>3</sup>) also occurred in the summer of 1986. Elimination of filtering mollusks not only changed the appearance of periphyton communities, but also affect-

ed other ecosystem blocks. The introduction of exotic fish (*Oreochromis mossambicus* (Peters, 1852)) and gastropods (*M. tuberculata*, *T. granifera*) has led to invasive species becoming the most significant components of the aquatic ecosystems.

Until 1986, the ecosystem was in a more or less stable state. The species composition of phyto- and zooplankton did not undergo significant changes; the plankton similarity coefficient over the years of research was rather high (62–65%) (Sergeeva et al., 1988). Here, as in other cooling ponds (for example, in the reservoir of the Chernobyl nuclear power plant), in zones of small influence of heated discharges on the periphyton and benthos, communities dominated by zebra mussel formed (Protasov and Silaeva, 2012; Protasov et al., 1991). Currently, the ecosystem is also in a quasi-stationary state, but its long term stability is undoubtedly extremely low.

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